

# New Energy Carriers in Tunnels

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## ABSTRACT

Environmental issues such as climate change and scarcity of resources have forced the development of new energy carriers for vehicles. This also means that there will be an increase in the number of vehicles running on these new energy carriers in tunnels and other confined spaces. New energy carriers do not necessarily mean higher risks, but they do represent a new situation and imply *new* risks. These risks need to be evaluated and considered. The mixture of different energy carriers (flammable liquids, gases lighter than air, gases denser than air, batteries, etc.) can also constitute a risk itself, since there are situations where different safety measures need to be taken depending on the energy carrier used and the scenario in question.

In this paper some selected new energy carriers are described, in terms of trends and properties. Some countries have restrictions on the use of some energy carriers in confined spaces. These restrictions are presented. Vehicles are involved in accidents, so also vehicles running on new energy carriers. Some vehicle fires involving new energy carriers are presented and discussed in the paper. It is important to learn from these accidents. It is also important that safety issues related to the use of new energy carriers in tunnels are considered, investigated and reported. Systems, not only components, need to be tested to study different possible scenarios and to develop models for these scenarios. When the scenarios are described in a representative way, technical safety solutions, mitigations systems, and rescue service tactics can be developed. It is also important to study how the different systems (detection, ventilation, mitigation) interact and how the models should be altered depending on the scenario.

**KEYWORDS:** tunnels, vehicles, biofuels, energy carriers, underground garage

## INTRODUCTION

Climate change and a greater awareness of the over exploitation of earth's finite resources puts politicians, industry, authorities and the public under increasing pressure to move towards a resource-efficient society that uses renewable energy and maximum resource recovery. A global increase in energy demand and a cry for the reduction of western dependency on imports of oil, which is considered as a political and economic risk, has also increased pressure for changes in the present energy system. This has already led to major changes in society and further changes are expected. On the energy side, it means a shift from fossil fuels to various types of renewable energy sources, alternative fuels and new energy carriers.

Unless this trend is accompanied by an appropriate risk assessment and the development of risk mitigation measures, there is great potential that we end up with systems that can become very costly in terms of direct and indirect damage from fires, explosions, etc., because of the absence of necessary understanding of system performance and limitations. This can also be the case for the use of new energy carriers in tunnels and underground constructions. Lack of knowledge can also lead to erroneous decisions concerning restriction of use, tactics, and safety and mitigation measures.

The European Community has under the Kyoto Protocol committed itself to greenhouse gas emission targets for the period 2008-2012. In the context of an international agreement together with other

developed countries, the European Community aims also at committing itself to a 30 % reduction in greenhouse gas emissions by 2020 (compared to 1990). Until such a global agreement is concluded, the Community has, however, made an independent commitment to achieve at least a 20 % reduction in greenhouse gas emissions by 2020 [1].

Transport fuel use makes a significant contribution to overall Community greenhouse gas emissions. The combustion of road transport fuel is responsible for around 20 % of Community greenhouse gas emissions. One approach to reducing these emissions that the Community has adopted is through reducing the life-cycle greenhouse gas emissions of the fuels for light and heavy duty road vehicles. The regulation of fuel specifications and the promotion of use of energy from renewable sources are ways to reach these reduction aims.

According to the directive 2009/30/EC suppliers should, by 31 December 2020, gradually reduce life cycle greenhouse gas emissions by up to 10 % per unit of energy from fuel and energy supplied [2]. The reduction should by 31 December 2020 be at least 6 % compared to the EU-average level of life cycle greenhouse gas emissions per unit of energy from fossil fuels in 2010. This reduction can be obtained by different means, i.e. through the use of biofuels, alternative fuels and reductions in flaring and venting at production sites.

On the other hand some older vehicles might not run satisfactorily on fuels with high biofuel content and therefore petrol suitable for these older vehicles should still be available, at least for a transitional period. According to the directive, the maximum volume fraction of biofuel components (FAME, fatty acid methyl ester) in Diesel is 7 % (B7), but the directive also encourages the development of a standard for allowing higher levels of biofuel components, e.g., the development of a standard for 'B10' is explicitly mentioned.

The selected path for the development and use of biofuels and new energy carriers is different for different countries. Weather conditions also mean that different fuel properties are needed in different parts of the world. Countries with low ambient summer temperatures allow higher maximum vapour pressure of petrol during the summer period compared to other countries. Member states with low ambient summer temperatures are in the directive defined as Denmark, Estonia, Finland, Ireland, Latvia, Lithuania, Sweden and the United Kingdom.

*Table 1 Maximum concentration of oxygenates in petrol [2].*

<b>Oxygenate</b>	<b>Maximum vol-%</b>
Methanol	3.0
Ethanol <sup>a)</sup>	10.0
Iso-propyl alcohol	12.0
Tert-propyl alcohol	15.0
Iso-butyl alcohol	15.0
Ethers containing five or more atoms per molecule	22.0
Other oxygenates <sup>b)</sup>	15.0

a) Stabilising agents may be necessary

b) Other mono-alcohols and ethers with a final boiling point no higher than that stated in EN 228:2004.

## **DIFFERENT ENERGY CARRIERS AND ALTERNATIVE FUELS**

It is difficult to find global or sometimes even regional statistics from comparable sources concerning all new energy carriers. In this section, therefore, different examples are given to illustrate a number of significant trends. Some interesting properties of the energy carriers are also presented.

Diesel and petrol fuels still dominate. However, the use of alternative fuels is rapidly increasing. According to The Swedish Petroleum Institute the use of renewable fuels in Sweden in 2008 corresponded to 4.9 % of the total volume of vehicle fuels.

The traditional fuels together with the increasing renewable fraction mean that we will have a mixture of different types of fuels and energy carriers in the vehicles on our roads, and in tunnels and underground constructions. This also means a new situation when it comes to safety since these energy carriers have very different properties and present different risks.

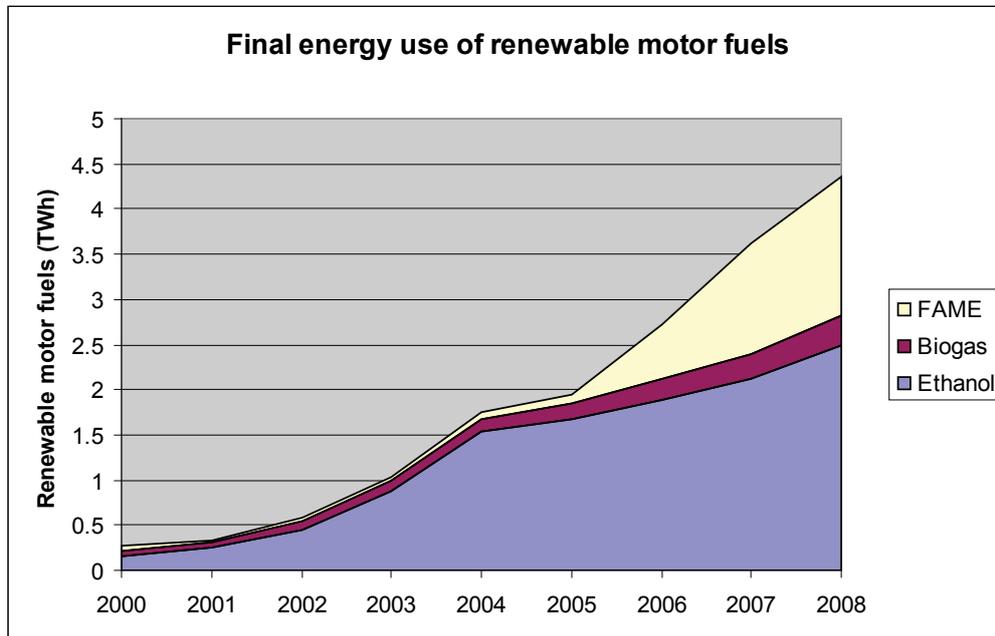


Figure 1 Development in energy use of renewable motor fuels in Sweden 2000 – 2008 [3].

In Sweden three alternative fuels presently dominate: Ethanol, FAME, and Biogas (see Figure 1), but several other energy carriers are under development globally and much research is underway to improve the characteristics of all such energy carriers. In the rest of this section, different energy carriers are described. The treatment is not exhaustive as other energy carriers do exist (the following are for example listed as biofuels in the Directive 2003/30/EC: bioethanol, biodiesel, biogas, biomethanol, biomethylether, bio-MTBE, synthetic biofuels, biohydrogen, and pure vegetable oil [4]). The compounds selected for discussion have been chosen based on the fact that they are either widely used at present or are of special interest for the future.

#### *Ethanol*

Ethanol is widely used, both as a blending component for petrol (described in EN 15376) and in the production of a variety of ethanol based fuels ranging from E5 to E95 (where the number corresponds to the approximate percentage ethanol in the mix). The fuel E85 (Swedish standard SS 155480) is common in flexifuel vehicles in Sweden, for example, and has seen wide distribution at Swedish pump stations in recent years. To some extent ethanol has also been used to replace diesel fuel for buses. In that case the fuel consists of 95 % ethanol and 5 % ignition-enhancing additives, denaturants, etc.

The full name of the vehicle fuel E85 is Ethanol E85. The fuel mixture is different depending on whether the fuel is sold during the summer (E85S) or winter (E85W), defined by the standard SS 155480:2006 [5]. E85S contains at least 75 % ethanol and an allowed percentage of petrol of 14 % – 25 %, while E85W contains at least 70 % ethanol and an allowed volume percentage of petrol of 14 % – 30 %.

The number of flexifuel cars bought in Sweden has increased significantly every year 2005 – 2008 (see Figure 2). Flexifuel means that different fuels can be stored in the same fuel tank of a vehicle, e.g. ethanol and petrol. The number decreased in 2009 by approximately 30 % compared to 2008. This change can be compared to the number of new registered cars, which decreased by approximately 17 % from 2008 to 2009 (statistics from Statistics Sweden). The overall decrease in new vehicle registrations

is probably due to the financial crisis. The larger decrease in new registrations seen for flexifuel cars no doubt depends on a variety of parameters including the price of the vehicles, the price of E85 (relatively high compared to petrol during 2009) and a reduction in tax subsidies for such vehicles.

Today, Scania is the only producer of ethanol busses. Scania has built approximately 600 Ethanol busses. Of these, 400 are in operation in the public transport fleet in Stockholm. Outside of Stockholm, ethanol buses can also be found in several cities, e.g. in Umeå, Gävle, Örnsköldsvik, Östersund, Falun, Borås in Sweden and in Madrid, La Spezia, Slupsk, Sao Paolo, Oslo, Nottingham, Redding and Milan outside of Sweden [6].

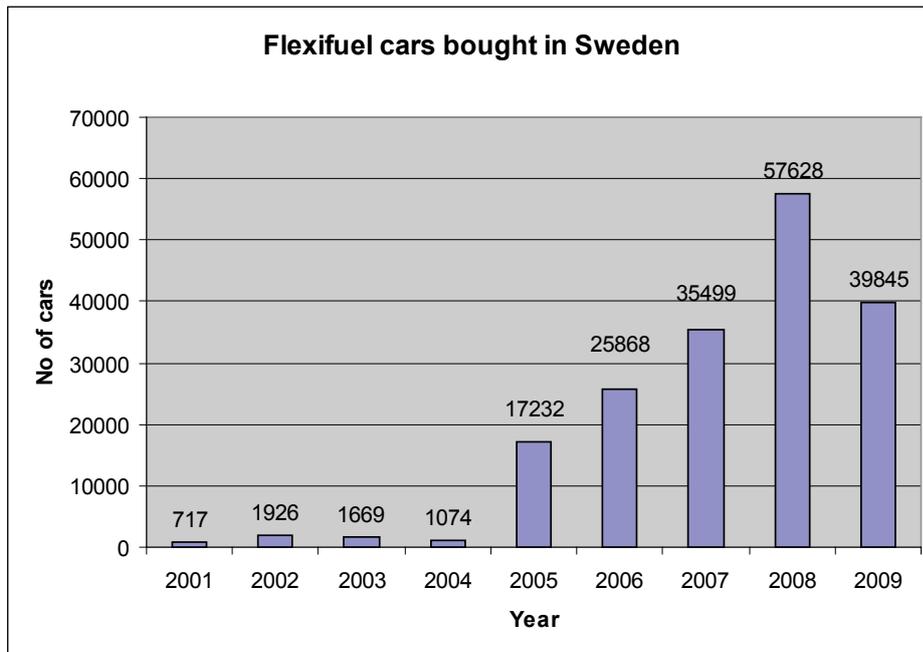


Figure 2 Flexifuel cars bought in Sweden, total per year [7].

#### Other alcohols

Experiments with methanol fueled cars were carried out in Europe and USA during a period from the 70's to the 90's. After these experiments the interest from the car industry, fuel industry and governments has been low. Methanol is produced in large amounts from natural gas, but there is some hesitation towards methanol as vehicle fuel since it is toxic, corrosive and not as soluble in petrol as ethanol is. There are, however, according to de Serves *et al.* technical solutions to these problems [8]. Experiments with M85 in the 1980s caused severe material problems in vehicles [9]. Some people, however, mean that methanol is better than ethanol since the energy efficiency during production from forest material is higher for methanol.

The company Värmlandsmetanol in Sweden is planning to build a plant which will produce methanol from wood-chips. Their aim is that the produced methanol will be blended in commercial petrol. According to Directive 2009/30/EC, it is acceptable to have 3 % methanol in the petrol is today [2]. Similar production plants are also planned in China. China aims to produce methanol in these plants by gasifying coal [8].

Research is also underway on heavier alcohols, e.g. biobutanol. Biobutanol has several advantages compared to ethanol, e.g. low vapour pressure resulting in lower emissions, better energy content, and the advantage of biobutanol being able to use the existing distribution infrastructure of the industry [9]. The longer hydrocarbon chain of biobutanol causes it to be fairly non-polar. This means that it is more similar to gasoline in terms of physical properties than it is to ethanol.

### *Compressed natural gas (CNG) and compressed biogas (CBG)*

CNG is a fossil fuel, mainly composed of methane, which is a gas lighter than air. Biogas can be said to be a renewable natural gas. The composition in its original form is, however, not the same. Biogas contains approximately 45 % – 85 % methane and 15 % – 45 % carbon dioxide, depending on the conditions during production, but also small concentrations of other gases (hydrogen sulphide, ammonia, hydrogen, nitrogen, carbon monoxide, saturated or halogenated carbohydrates and oxygen) [10-12]. This means that biogas needs to be “cleaned” from carbon dioxide, hydrogen sulphide and water, and upgraded to meet the same requirements as the natural gas before it can be used as vehicle fuel.

The expression CNG is used for both these types of fuels throughout the remainder of this paper since they are used in the same way in vehicles and because CNG is still the more widespread fuel of the two, even if in Sweden the amount of biogas used as vehicle fuel is increasing and since 2006 constitutes a larger fraction than natural gas. CNG is usually stored in a fuel tank at a pressure of 200 – 250 bar. Italy has used natural gas as a vehicle fuel and developed the associated technologies since the 1930s [13]. The use of CNG is accelerating all over the world and in 2008 there were more than 9 million CNG vehicles and 13000 refuelling stations worldwide [14]. The countries with the most CNG vehicles 2008 were Argentina, Pakistan and Brazil with together over 50 % of the CNG vehicles in the world. In Europe there were in total approximately 1 million CNG vehicles, with more than half (580 000) in Italy.

Clearly, interest in buying and using vehicles running on biogas is increasing. The problem right now is to meet the increasing demand for biogas. There are not enough fuelling stations and it is not uncommon that fuelling stations run out of biogas. If the implementation of CNG vehicles is to increase, supply issues must be resolved.

### *Hydrogen*

Hydrogen is a colourless, odourless, tasteless, non-toxic, non-corrosive gas approximately 14 times lighter than air. It differs from the other gases used as energy carriers for vehicles in some ways that have significant for safety. Examples of these differences are the low ignition energy of hydrogen (approximately 20  $\mu$ J [15]) and its very broad range of flammability (4 % - 75 %). The fact that hydrogen molecules are very small makes the construction of hydrogen tight canisters difficult which can result in unwanted leakages, even through seemingly intact materials due to diffusion. Hydrogen is often stored in tanks at either 350 bar or 700 bar.

Much research and development is presently devoted to hydrogen and its feasibility as a vehicle fuel, but in most cases only demonstration models are available. Hydrogen can be used either for internal combustion engine (ICE) vehicles or fuel cell (FC) vehicles. According to the association Hydrogen Sweden the commercial breakthrough is to be expected sometime after 2015, and fuel cells seems to be the main option. There are some hydrogen vehicle projects running. One such example is HyFLEET:CUTE, which is a project that involved 47 hydrogen powered buses in regular public transport service in 10 cities on three continents (Beijing, Perth, Amsterdam, Barcelona, Berlin, Hamburg, London, Luxembourg, Madrid, and Reykjavik) [16]. The aim of the project, which started in 2006 and ended in 2009, was “to diversify and reduce energy consumption in the transport system by developing new, fuel efficient hydrogen powered bus technology, plus clean, efficient and safe production and distribution of hydrogen as a transport fuel”. The project included both FC and ICE buses. Main issues studied were availability, efficiency, etc., but safety issues were also included. During the test period no major safety related incidents occurred related to the FC buses, while for the ICE buses there was one unexpected release of hydrogen when a check valve within the tank nozzle failed.

According to Hydrogen Sweden there are presently 600 – 700 hydrogen FC vehicles running in the world (e.g. in USA, Japan, Germany, China, Canada, and Iceland). In addition to this there are a number of hydrogen ICE vehicles. The vehicle corporations Daimler, Ford, General Motors, Honda,

Hyundai/KIA, Renault/Nissan, and Toyota, signed in September 2009 a Letter of Understanding saying that from 2015 onwards a significant number of FC vehicles could be commercialised, aiming at a few hundred thousands units on a worldwide basis [17]. In many countries, including Sweden, there is no regulation for legalising hydrogen vehicles on a general basis. The Road Administration can, however, permit a certain car model for a limited period of time. In 2009, an amendment to Directive 2007/46/EC was published concerning type approval of hydrogen-powered motor vehicles [18]. This now needs to be implemented in national legislation.

There are also some research activities of special interest. There is a Network of Excellence called HySafe with the aim of introducing hydrogen technologies and applications in a safe way. This network has led to a number of projects, e.g. HyTunnel and InsHyde. The aim of HyTunnel is to develop codes, standards and regulations so that additional risks due to the introduction of hydrogen vehicles in tunnels can be handled. The effect of the ventilation on destratification and dilution of hydrogen is discussed [19]. The results also indicate that higher tunnels and tunnels with horseshoe cross sections (compared to equivalent rectangular cross section) present lower hazards. In InsHyde many different aspects of hydrogen safety in confined spaces are evaluated and discussed, such as regulations, detection, ventilation, fire and explosion. Both computer modelling and experiments were performed to study different parameters and effects. In the study it was noted that among hydrogen incidents the ignition source could not be identified in 86 % of the cases and was probably caused by spontaneous ignition, e.g. due to transient shocks [20]. In yet another research project, Wu showed that conditions of oxygen deficit can be reached for high release rate of hydrogen [21]. This can lead to high temperature ceiling flows and damage to tunnel structure.

#### DME

DME (dimethyl ether) is a colourless gas that is easy to liquefy and transport. DME is denser than air as is LPG. This is important for the behaviour in case of a release and is therefore of significant for the analysis and mitigation of potential risks associated with accidental release in a tunnel or other underground construction. In Table 2 the properties of DME are compared to corresponding properties of propane and butane.

Table 2 Properties of DME compared to propane and butane [22].

Property	DME <sup>a)</sup>	Propane	Butane
Boiling Point, °C	-25.9	-42.1	-0.5
Vapor pressure @ 20 °C, bar	5.1	8.4	2.1
Liquid density, @ 20 °C, kg/m <sup>3</sup>	668	501	610
Specific density, gas	1.59	1.52	2.01
Lower heating value, kJ/kg	28.430	46.360	45.740
Ignition <sup>b)</sup> temperature @ 1 atm, °C	235-350 <sup>c)</sup>	470 <sup>c)</sup>	365 <sup>c)</sup>
Flammability limit in air, vol%	3.4-17 <sup>d)</sup>	2.1-9.4 <sup>d)</sup>	1.9-8.4 <sup>d)</sup>

a) The properties of Fuel Grade DME will differ from neat DME depending on the amount and type of other oxygenates and water [22].

b) Presumably referring to spontaneous ignition temperature data

c) The spontaneous ignition temperature may differ depending on measurement method. According to Glassman the values are for dimethyl ether: 350 °C, propane: 450 °C – 504 °C, and butane: 405 °C – 430 °C [23].

d) Note that the flammability limits varies in the literature, depending on experimental method. Glassman report the following limits for dimethyl ether, propane and butane: 3.4-27, 2.1-9.5, and 1.8-8.4, respectively [23].

#### Batteries

Electric cars with batteries as energy carriers are seen by some people as the single most promising future energy carrier, at least for city traffic. One problem is the relatively short available driving distance before recharging is needed. Therefore, hybrid solutions are of greatest interest at the moment. A hybrid vehicle in most cases means that it has both a conventional internal combustion engine and an electric motor. There are several different types of hybrid drive trains and the details will not be presented here. There are also plug-in electric vehicles, which means that the batteries can be plugged in, e.g. to house electricity, for charging, in addition to being charged while running.

Presently, Nickel-metal hydride batteries (NiMH) are the most common in hybrid vehicles. These are robust, but have a relatively high self-discharge rate. Therefore, most interest is now given to lithium-ion batteries, for a variety of reasons. Lithium-ion has a high energy density and a high cell voltage. The maintenance need is low and there are no memory effects. However, to limit the peak voltage during charging for safe operation, a protection circuit is built into each battery pack. This also limits the discharge current. Other safety features are also needed for lithium-ion batteries and these measures also the batteries rather expensive.

Two main types of risks should be considered with vehicle batteries. One is that the battery (system) itself is the cause of the incident, i.e. an electrical fault (e.g. short-circuit or overcharge), which could result in a fire. The other is that the battery is exposed to an external risk, either some mechanical force or a thermal attack (e.g. fire). There are examples of batteries exploding or giving off jet fires in some situations where these risks have been realised. Burning and exploding lap-tops have made big news in recent years [24] and it is imperative that suitable safety measures are taken concerning such batteries, but scientific data is scarce and more research is needed. According to Andersson and Johansson electric cars is the group of cars experiencing the largest number of fires in relation to the number of cars within the group [25].

Caution should also be taken concerning toxic fumes, e.g. hydrogen fluoride, and oxides of carbon, aluminium, lithium, copper, and cobalt [26] can be emitted in a fire. The lithium salts used in the electrolyte contain fluorine or chlorine compound, which mean that hydrogen fluoride or hydrogen chloride can be produced during a fire.

## **REGULATIONS AND RESTRICTIONS**

Some restrictions presently exist concerning alternative energy carriers, especially for compressed or liquefied gases. Regarding underground constructions most restrictions concern underground garages, but some also specifically address tunnels. Many of the restrictions can be related to LPG (liquefied petroleum gas), which cannot be considered as a new, alternative energy carrier as it has been used since the 1930's. It is, however, interesting for several reasons. LPG is a fuel that is different from the most traditional fuels, i.e. petrol and Diesel, and some new energy carriers are quite similar to LPG, e.g. DME which can be stored as a liquid at low pressure. According to the Energy Policy Act of 2005 in the USA, LPG is also considered to be an alternative fuel, together with LNG, CNG, hydrogen, propane, methanol, ethanol, and biodiesel [27].

Different countries have different regulations for handling and storage of gases in underground structures. Regulations are continuously under discussion and revisions. This means that the situation might have changed in some of the regions discussed below since the references were published. However, this still gives an overview of the different approaches adopted in the different regulations. In Table 3 restrictions of the use of gaseous fuel in some European countries are presented. The corresponding information for some non-European countries is given in Table 4.

As can be seen in Table 3 and Table 4 there are restrictions of the use of LPG and other gases in some countries or regions. In other countries there are, on the other hand, no such bans (e.g. Japan). In some countries there are no general restrictions, but there are certain safety requirements to follow for the underground construction and/or the vehicles. In many countries it is also up to the garage owner to decide what vehicle fuels to allow in their garage. The table is not comprehensive, but gives a good picture of the diversity in approaches taken in different countries and regions concerning the legislation on gaseous vehicle fuels.

*Table 3 Summary of restriction of use of gaseous fuel in underground constructions in different countries in Europe.*

<b>Country</b>	<b>Type of underground construction</b>	<b>Fuel</b>	<b>Comments</b>	<b>Ref.</b>
Italy	Multilevel garage	LPG	Allowed down to the first underground level. If to park in garage, the vehicle must have safety equipment (ECE/ONU 67-02) and the garage must have prevention actions from the rescue services.	[28, 29]
	Tunnel	LPG	Vehicles using LPG or gas should be labelled before entering the Mont Blanc tunnel or the Frejus tunnel, respectively.	[30, 31]
Germany	Garage	LPG	Allowed according to federal regulations, but still a ban of LPG vehicles in underground garages in two of the states.	[32-35]
France	Tunnel	Gases	Vehicles running on gas are prohibited in the Euro tunnel	[36]
	Garage	LPG	Vehicles with safety valves are allowed, both in tunnels and underground garages.	[37-39]
Luxembourg	Garage	LPG, H <sub>2</sub>	Vehicles running on LPG or hydrogen gas are not allowed to be parked in underground garages	[40-42]
UK	Garage, tunnel	Gases	No restrictions except the Euro tunnel (see France above). Private owners of underground garages can, however, forbid gas driven vehicles in their garage	[36, 43]
Czech Republic	Garage	LPG, CNG	Vehicles running on CNG or LPG may not be introduced into closed storage buildings, underground garages or similar facilities unless specifically stated otherwise. For garages permitting the gases, specific safety measures must be taken.	[44, 45]
Switzerland	Garage	Gases	The garage owner has the final decision on what vehicles may park in their garage.	[46]
Austria	Garage	LPG, CNG	The provinces of Austria have autonomy regarding rules on car parking, e.g. LPG is banned in garages in Oberösterreich and in the city of Mürtzschlag. In other regions the garages should fulfil certain requirements and be clearly signed to allow LPG (e.g. Niederösterreich, Salzburg, Steirmark); for Salzburg certain requirements also for CNG	[47-51]
	tunnel	LPG, CNG	LPG and CNG are not permitted in the Tauern rail tunnel	[52]
Sweden	Garage	LPG	LPG cannot be stored in underground garages below apartment buildings, or in multi-car garages. Local municipal bans also exist.	[53, 54]
Finland	Garage	LPG	LPG cannot be used or stored in underground premises	[55]

Table 4 Summary of restriction of use of gas in underground constructions in some different non-European countries.

Country	Type of underground construction	Fuel	Comments	Ref.
Canada	Garage	LPG	No federal law, but laws on municipal level exist, e.g. in Ontario vehicles must have stop-fill valve to be parked in underground parking facilities and in Calgary LPG tanks are forbidden in underground garages.	[56, 57]
USA	Tunnel	LPG	No federal law, but state wise restrictions, e.g. in Maryland LPG is forbidden in the Baltimore Harbor and McHenry tunnels. LPG is also forbidden in the Summer, Callahan, Prudential and Dewey Square tunnels in Massachusetts and in the Holland, Lincoln, Brooklyn Battery and Queens Midtown tunnels in New York and New Jersey. In the state of Texas there is a total ban on LPG vehicles in tunnels, while in Virginia the only LPG ban is for the Chesapeake Bay tunnel	[58-63]
Hong Kong	Garages	LPG	No restrictions on parking LPG fuelled vehicles in underground garages. However, the installations must be factory made, i.e. no converted vehicles are allowed.	[64]
Japan	Garage, tunnel	LPG	No restrictions on the use of LPG	[65]

### FIRE INCIDENTS

Vehicle fires can have several different causes: collisions, over-heating, leakage of flammable liquids, electrical faults, etc. For new energy carriers it is difficult to find any representative statistics. Therefore, this section is focused on some selected incidents exemplifying the risks. Again LPG is included to represent vehicles running on liquefied gas denser than air and incidents with LPG vehicles also constitute a large part of the selected incidents, see Table 5. Further details on the incidents are given below. Not mentioned in Table 5 (which focus on vehicles running on LPG or new energy carriers) is the car crash in a highway tunnel near Palermo in Italy 18 March 1996. In that accident, involving a tank truck transporting LPG, propane was released through a crack leading to a burning gas cloud causing critical burns to 25 persons. The subsequent BLEVE caused five fatalities [66]. This has not been included as the cause of the accident was not strictly a new energy carrier but a vehicle transporting fuel for a new energy carrier.

The night of 31 January 1999, a vehicle fuelled with LPG was put on fire by an arsonist in Venissieux outside Lyon [67]. The LPG system was not equipped with a safety valve. This led to an increase in pressure in the tank during the fire and later the tank exploded. Six fire men trying to extinguish the fire were severely injured during the fire. This incident led to the opinion that something needs to be done to avoid this kind of incident in the future and later requirements of safety valves were introduced.

Table 5 Summary of incidents involving cars running on LPG or new energy carriers.

Date	Place	Type of premises	No of vehicles	Fuel	Ignition	Consequences
31 Jan. 1999	Venissieux, France		1	LPG	Arson	Explosion; 6 fire fighters severely injured
Sep. 2002	USA		1	CNG	Car fire	Rupture of gas cylinder
9 Nov. 2002	Seine-et-Marne, France	Garage	1	LPG	Unknown	Explosion; building of origin collapsed; in total 39 buildings affected.
28 Aug. 2005	Firenze, Italy	San Donato tunnel		LPG	Engine fire	Dense smoke
June 2006	Collatino, Italy	Parked on the street	1	LPG	Arson	Explosion, several cars, 2 garages, shops, fire spread to apartments
March 2007	Seattle, USA	Row of parked vehicles	12	One with CNG	Arson	12 cars damaged or destroyed; CNG tank exploded when fire fighter were approaching; Debris approx 30 m away
May 2007	Carson, CA, USA	Refuelling	1	CNG		Driver killed
16 Dec. 2007	Salerno, Italy	Under-ground garage		LPG	Leakage of gas from vehicle	Explosion; one 3 store building totally destroyed; 5 other building affected
7 June 2008	USA	Running on the high way	1	Hybrid converted to plug-in	Short circuit	One burnt out car
19 Sept. 2008	Rovigno, Italy	Under-ground garage		LPG		Fire spread to neighbouring garage and threatened the building
Oct. 2008	South Yorkshire, UK	Running on the road	1	LPG	Lighting of cigarette	Explosion, Burns, broken windows
8 Nov 2008	Mallaca, Malaysia	Filling station	1	LPG		Explosion of vehicle; passengers severely injured
28 Dec. 2008	Sampford Peverell, UK	Running on the high way	1	LPG	Unknown	One burnt out car
28 Oct. 2009	Marigliano, Italy	Parking	6	One with LPG	The cause of the initial fire unknown	Large explosion, damaged vehicles and buildings

On Saturday 9<sup>th</sup> November 2002, a vehicle fuelled with LPG started to leak LPG in a garage in Seine-et-Marne in France [68]. The high density of the gas made it spread over a large area and down into the

basement. At 11 p.m. the gas was ignited and an explosion occurred. The building collapsed, burying a couple and their two children, who were later saved. The explosion affected in total 39 buildings within a radius of 200 m. The roof of the LPG vehicle was found 150 m from the place where the vehicle was parked. In June 2006, an LPG fuelled vehicle in Collatino, Italy, was ignited by arsonists [69]. The car was parked together with other vehicles on the street outside an apartment building. The fire started in the rear part of the vehicle, where the LPG tank was positioned. Subsequent explosion of the tank led to an intense fire igniting several other cars. The pressure wave destroyed two small garages and shops located in the apartment building. The fire damaged the façade and several balconies.

In March 2007, an arsonist set fire to a row of vehicles parked under a highway bridge in Seattle [70, 71]. The first responders were not aware that one of the cars was CNG-fuelled. When they were 15 m – 20 m from the burning vehicles the CNG tank exploded. The fuel tank landed 30 m from the CNG vehicle and other large pieces of debris were found a similar distance from the vehicle. The tank was equipped with a safety valve but exploded before the valve released pressure. In May 2007, a CNG tank in a vehicle in Carson, CA, USA ruptured [71]. The rupture occurred during refuelling. The driver, who was killed in the accident, had the day before regained the vehicle from the repair shop after a collision three weeks earlier. In June 2008, a fire in a hybrid car converted to a plug-in, started while the car was running [72]. The car used a lithium-ion battery, which was partly damaged during the fire, but still gave power. The most probable explanation of the incident, according to the investigation, is erroneous electric wiring leading to heat generation. The heat destroyed some cells in the battery leading to a short circuit and the fire.

In October 2008, a car running on LPG suddenly exploded in South Yorkshire, UK [73]. The driver (amazingly) survived and could after the accident describe the event. He had just recently refuelled his car and drove slowly when he smelled LPG. He had been told that this is normal after refuelling. When he lit a cigarette the gas was ignited and filled the car with flames. Due to the increase in pressure the windows broke and the bonnet and the trunk were opened. The driver suffered minor burns to the face and body, but the seat absorbed most of the energy of the explosion, saving the driver. The most likely explanation of the explosion is a leakage in the tube between the filling valve and the tank. The car was bought second-hand three weeks earlier, but had been checked and approved twice at workshops. The most recent incident in this summary occurred 28 October 2009 in Marigliano, Italy [74]. A fire started in a parked car running on a traditional fuel. The fire developed quickly and spread to nearby vehicles. In total six cars were involved in the fire, including one using LPG. The LPG vehicle quickly exploded after it was included in the fire. The explosion damaged cars in the vicinity and the building outside which the cars were parked. Debris from the exploded car was found on the balcony of the building and windows were broken up to the eighth floor. Stores at street level sustained severe damage.

In addition to the car fires presented above, some conclusions can be drawn from some bus fires. Perrette and Wiedemann described three bus fires involving CNG tanks [75]. The first responders did not manage to extinguish these fires. The first conclusion from these fires is that the pressure relief devices (PRD) do not always release. This is the case when there is local thermal exposure, e.g. from an impinging jet flame, which leads to insufficient heat up of the PRD. For buses it is, therefore, important not to have areas with weaker fire protection, e.g. sun roof, which could lead to such localised fire exposure. Another important issue is the time to completely empty the tank. In the incidents described it would be preferable to have early PRD opening and fast emptying of the tank, but this could be completely different if the buses had been located in a confined environment such as a tunnel or underground garage. One main conclusion was that the safety of this type of vehicles should not rely on component tests only. It is important to test the entire system where, for example, the tanks and other components are tested using relevant and realistic scenarios.

The incidents summarized and described above should not be interpreted to mean that all vehicles running on new energy carriers will explode when used or when exposed to fire. The presentation is rather an attempt to illustrate a variety of situations. In some cases the fire or incident had very severe outcome, while in other cases the outcome was no worse than a fire in a traditional vehicle. It is,

however, important that when strategies for new energy carriers are developed one considers worst case scenarios. It is also important to realise that all risks are not eliminated by introducing PRDs. The outcome still depends on the design of these devices and on the fire scenario.

## **DISCUSSION**

Despite a significant amount of research on new fuels and energy carriers, not much attention has been paid to the risks associated with their distribution and use. Even less attention has been paid to the potential risks associated with their use in tunnels and other underground constructions. It seems that most organisations are either waiting for the use of the energy carriers, and problems associated with them, to increase, or for someone else to deal with the potential problems and find a solution. This reluctance to take action is not unusual within fast developing areas. There can be several reasons for this. One reason is a common situation in expansive new areas where attention is firmly focussed on the opportunities offered by the new technology and there is an unwillingness to see the risks. Another reason can be that it is difficult to properly evaluate the situation: what are the emerging trends concerning use and what risk scenarios are possible or most likely?

Even if there are some statistics available, it is not easy to foresee which new energy carrier will increase fastest. This depends on many different factors: the development of new energy carriers themselves or ways of producing them, the development of new technologies for exploiting energy carriers, environmental issues, political decisions and policies, public opinion, safety issues, etc. Trends can also change rapidly meaning that predictions are often short term at best. One thing seems certain, it is not likely that only one new energy carrier will replace all others and in the future we will have numerous different energy carriers.

The question is, therefore, how this diverse situation should be handled. New energy carriers do not necessarily mean higher risks, but they do imply a new situation and new risks. These risks need to be evaluated and considered. The mixture of different energy carriers can also constitute a risk itself, since there are situations where different safety measures need to be taken depending on the energy carrier used and the scenario in question. This can for example be a problem for the rescue services since they will no doubt face incidents involving different types of fuels and energy carriers. This means that they must have information concerning not only the situation itself but also the energy carriers involved. Further, they need prior knowledge of how best to tackle any given situation including mitigation tactics. Some vehicles have signs saying what energy carrier is used, but these signs are often small and sometimes missing. A common information system is needed to reliably provide this information to those who need it, when it is needed. As described above, some tunnels require drivers of vehicles running on gas or LPG to report this before entering the tunnel and to label their vehicle, but as the diversity increases, an overall system is still to be developed.

In this paper, the focus has been on the individual vehicles. Of course there will also be bulk transport of such energy carriers, which will also constitute an increased risk when transported through tunnels. As described in the section on regulations and restrictions, there are a variety of views on how vehicles running on LPG, CNG or similar fuels should be treated and what safety measures are needed. It is important that restrictions are based on correct information. Therefore, systematic research is needed concerning new energy carriers.

## **CONCLUSIONS**

A review of common new energy carriers and alternative fuels has been presented in this paper. It is important that the safety issues related to the use of new energy carriers in tunnels are considered, investigated and reported and that the development of such vehicles and the risks associated with them are studied in a scientific way. The future use of different energy carriers will not only depend on technological development, but also on public opinion and political willingness. It is, therefore, important that correct and detailed information concerning safety issues and the behaviour of these energy carriers in case of fires is developed. Unless this occurs in a timely manner, there is a risk that decisions will be based on too little or erroneous information. There is also a pedagogical aspect to this

research in that the implementation of new technology is dependent on the development and distribution of correct information to avoid unnecessary fear and insecurity in the public which constitute potential users.

Systems, not only components, need to be tested to study different possible scenarios and to develop models for these scenarios. When the scenarios are described in a representative way, technical safety solutions, mitigations systems, and rescue service tactics can be developed. It is also important to study how the different systems (detection, ventilation, mitigation) interact and how the models developed should be altered depending on the scenario.

The incidents analysed show that new energy carriers can lead to explosions with catastrophic consequences in case of fire. The outcome does, however, vary with the scenario. It is important that we learn from incidents that have occurred and that experiments and relevant research are performed to maximise our understanding of the risks. The incidents also show that safety systems do malfunction, especially in used vehicles. Such malfunction can be due to accidents, mistakes, conversions, or erroneous repairs, but the consequences of such malfunction are always potentially serious.

The field of new energy carriers is very diverse and constitutes many different fields of research. This makes a detailed review of all aspects of risks associated with new energy carriers and safety in tunnels, impossible. On the other hand this is exactly why this issue is so important. When new energy carriers are developed and used in vehicles travelling through tunnels a variety of different safety aspects converge and need to be dealt with properly. Clearly, more research is needed concerning how safety in tunnels is affected by the introduction and development of new energy carriers, preferably before a major incident in a tunnel including new energy carriers causes a major setback in political and public willingness to adopt such technologies.

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