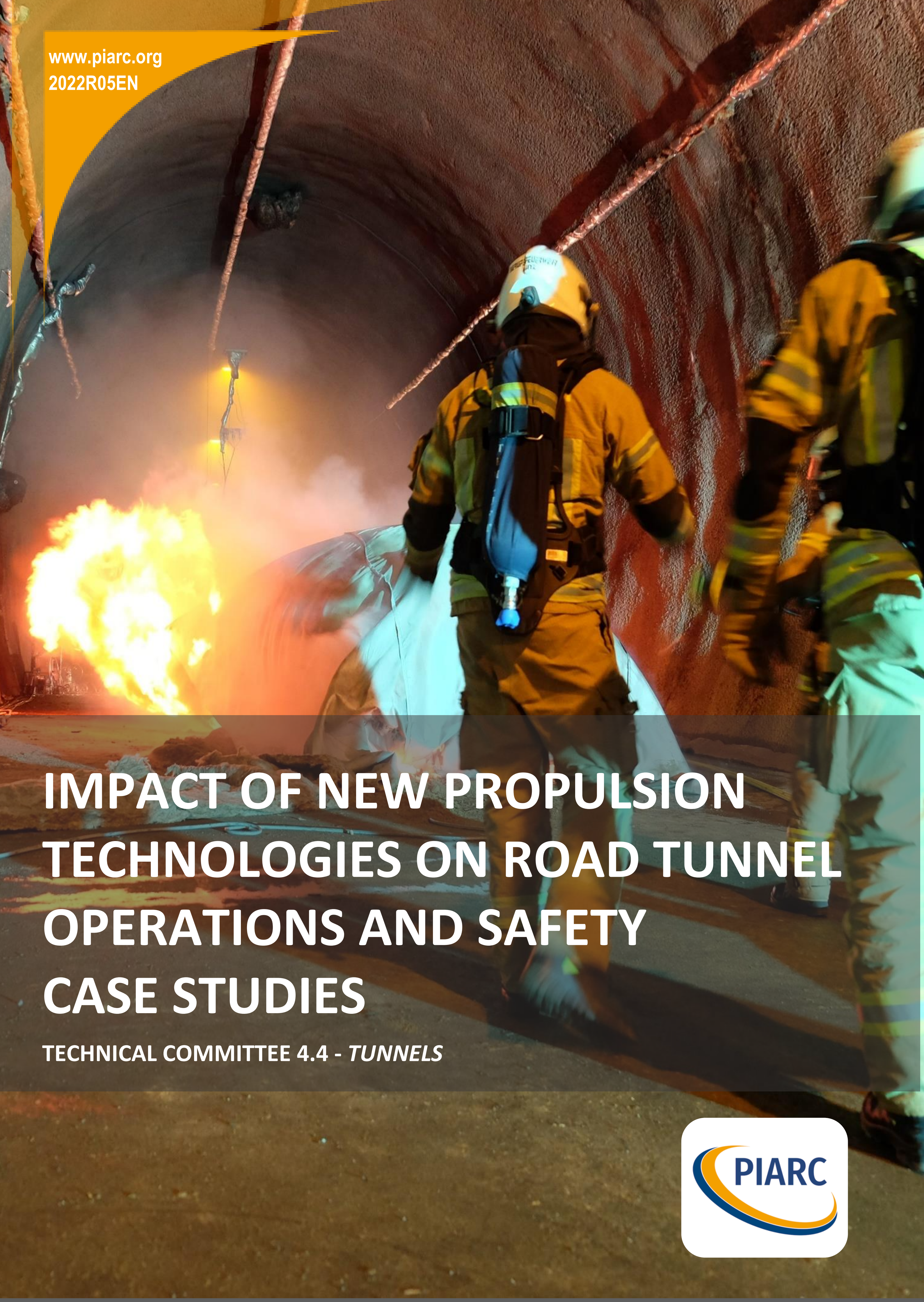

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IMPACT OF NEW PROPULSION TECHNOLOGIES ON ROAD TUNNEL OPERATIONS AND SAFETY CASE STUDIES

TECHNICAL COMMITTEE 4.4 - *TUNNELS*

STATEMENTS

The World Road Association (PIARC) is a nonprofit organisation established in 1909 to improve international co-operation and to foster progress in the field of roads and road transport.

The study that is the subject of this report was defined in the PIARC Strategic Plan 2020–2023 and approved by the Council of the World Road Association, whose members are representatives of the member national governments. The members of the Technical Committee responsible for this report were nominated by the member national governments for their special competences.

Any opinions, findings, conclusions and recommendations expressed in this publication are those of the authors and do not necessarily reflect the views of their parent organisations or agencies.

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TECHNICAL COMMITTEE 4.4 *TUNNELS*

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EXECUTIVE SUMMARY

2022R05EN

IMPACT OF NEW PROPULSION TECHNOLOGIES ON ROAD TUNNEL OPERATIONS AND SAFETY - CASE STUDIES

LITERATURE REVIEW ON NEW ENERGY CARRIER STUDIES, RESEARCH PROJECTS AND EXISTING DATA

Alternative **propulsion technologies**, including battery-electric vehicles, are becoming more prevalent. Whilst such vehicles remain a small overall proportion of the vehicle fleet, the combination of impacts of Government policy and technological advances in alternative fuels is expected to accelerate their increase in numbers on the road and in tunnels in coming years. There may also be particular initiatives in certain geographical areas, such as on airport land for example, where higher proportions of alternatively fuelled vehicles are seen sooner than on the open road.

As a result of these changes, the nature of tunnel safety risk (including from fire) is expected to change with time, and detailed consideration of the risk of significant incidents involving such vehicles is required. This should include the evaluation of incident consequences with particular attention paid to fire characteristics and toxic emissions and their impact on tunnel users and on emergency intervention strategies.

PIARC TC4.4 has prepared this report to present findings from preliminary case studies related to this issue, in advance of the final report at the end of the current PIARC cycle.

The topic has too few incidents to be able to make statistically relevant statements about the effects of accidents with vehicles propelled by new propulsion technologies, commonly called new energy carriers (NEC) on the tunnel design and infrastructure. It is also currently not possible to derive specific instructions from experience gained from incidents of such vehicles. Hence, this report collates currently available information on existing or just finished research programs and highlights the most important findings from these projects.

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1. INTRODUCTION

Alternative propulsion systems, including battery-electric vehicles, are becoming more prevalent. Whilst such vehicles remain a small overall proportion of the vehicle fleet, the combination of impacts of Government policy and technological advances in alternative fuels is expected to accelerate their increase in numbers on the road and in tunnels in coming years. There may also be particular initiatives in certain geographical areas, such as on airport land for example, where higher proportions of alternatively fuelled vehicles are seen sooner than on the open road.

As a result of these changes, the nature of tunnel safety risk (including from fire) is expected to change with time, and detailed consideration of the risk of significant incidents involving such vehicles is required. This should include the evaluation of incident consequences with particular attention paid to fire characteristics and toxic emissions and their impact on tunnel users and on emergency intervention strategies.

1.1. Purpose of the report

PIARC TC4.4 has issued this report to present preliminary findings from case studies related to this issue. The report represents the current levels of understanding, but it is acknowledged that the issues are considered as emerging, and further work is needed.

The topic has too few incidents to be able to make statistically relevant statements about the effects of accidents with vehicles propelled by new propulsion technologies on the tunnel design and infrastructure. It is also currently not possible to derive specific instructions from experience gained from incidents of such vehicles. Hence, this report collates currently available information on existing or just finished research programs and highlights the most important findings from these projects.

1.2. Structure of the report

This report contains an evaluation of

- Incident consequences from collation and review of incident records;
- Case studies; and
- Current research on the fire characteristics and toxic emissions of involving fires of NEC vehicles.

The report places a particular focus on battery-electric vehicles (BEV) because at the time of issue of this report these are the most common vehicles using new propulsion technologies.

1.3. Definitions

The term *alternative propulsion systems* refers to vehicles which differ from conventional diesel and gasoline fuelled vehicles in terms of propulsion unit (engine) and energy carrier (fuel).

Remark: It should be noted that the term ‘new (or alternative) drive technology’ is mostly replaced today by the term ‘New Energy Carriers (NEC)’. For a better reading this document follows this trend.

The alternative fuels considered in this document are limited to those thought to be most relevant on the roads worldwide at the time of writing and in the near future, as far as it is reasonable to predict. These include:

- Battery electric vehicles (BEV);
- Hydrogen fuel cells electric vehicles (FCEV); and
- Compressed or liquified gas (CNG, biogas, LPG).

Table 1 gives an overview of the categories of vehicle propulsion systems. While vehicles propelled with internal combustion engines (ICE) dominate the current vehicle fleet, BEV are penetrating the market. BEV are most commonly used in urban areas and for relatively short driving distances. Hybrid vehicles try to combine the positive aspects of both propulsion systems, the ICE and liquid or gaseous fuels for long distances and the BEV for short distances.

System	Internal Combustion Engines			Battery electric vehicle		Fuel cell electric vehicle
Propulsion concept	ICE	Full hybrid	Plug-in hybrid	Range extender	E-car	Fuel cell
Main energy storage	Tank			Battery		Tank
Main energy source	Fossil fuels, bio-fuels, hydrogen, synthetic fuels			Electricity		H_2
Main propulsion unit	ICE			E-motor		E-motor
Difference	-	Possibility to drive fully electric, recuperation during breaking	As full hybrid, but with external E-charging unit	ICE as range extender	-	-
Secondary energy storage	-	Battery		Tank	-	Battery
Secondary energy source	-	Electricity		As ICE	-	Electricity
Secondary propulsion unit		E-motor		ICE	-	-

Table 1 : Categories of propulsion systems for motorized vehicles

It is noted that there is a technical distinction between a battery and an accumulator. A battery is not rechargeable whereas an accumulator is rechargeable. In all applications considered in this report the BEV main energy storage system is an accumulator. However, this distinction is not widely used and indeed the BEV manufacturers refer to the main energy store as a battery. This report has maintained this convention to aid understanding by the reader.

Within this document, the term *alternatively fuelled vehicles* is used for vehicles powered by NEC. According to Figure 1), BEV will dominate short range driving, while FCEV will be used for medium to long range transport for commercial vehicles. Long range mass transport (freight and passenger) might be propelled by bio- and H_2-based synthetic fuels (e-fuels).

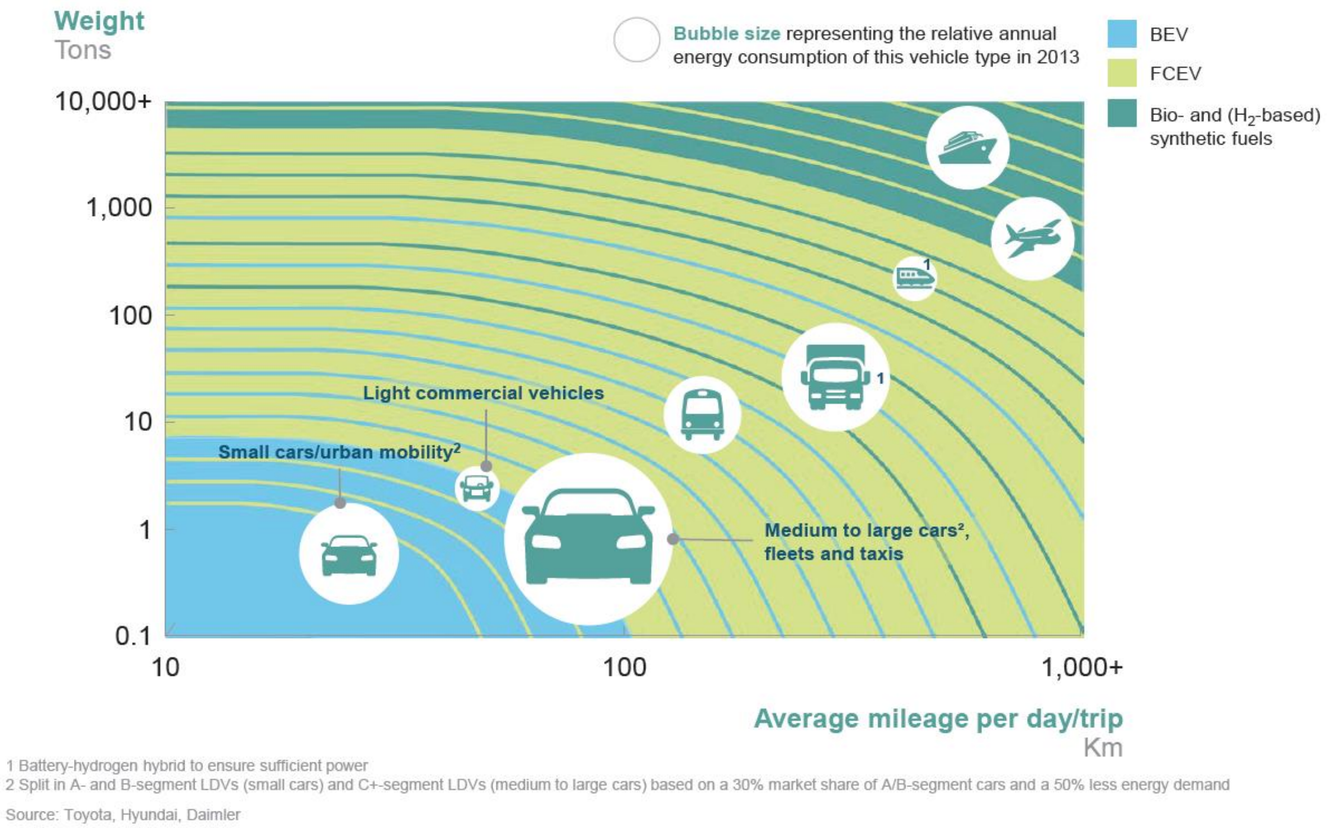

Figure 1: Application range of vehicles with NEC technology as a function of travel distance and vehicle weight [1]

2. RECENT RESEARCH ON ALTERNATIVELY FUELLED VEHICLES AND PROPULSION SYSTEMS

2.1. Study regarding new hazards created by NEC vehicles in Tunnels, CETU / INERIS

CETU (Centre d'Études des Tunnels, part of the French Ministry of Transportation) and INERIS (National Institute for the Industrial Environment and Risk) conducted a wide-ranging study regarding the new hazards created by NEC vehicles in tunnels. The study considered Li-ion battery electric, compressed and liquefied natural gas and hydrogen fuel cell propulsion systems. The main objectives were to:

- Identify the new hazards associated with NEC vehicles such as thermal runaway in batteries, gas cloud explosions, etc.
- Estimate the probability of occurrence for those events, based mostly on the experience of INERIS on industrial safety (including battery and compressed gas safety); and
- Assess the possible consequences of those events for users in typical scenarios in tunnels. The intervention and safety of fire-fighters was not examined in detail.

Some possible mitigation measures were examined, such as the use of ventilation, but mitigation was not the main subject of the study.

All risks were described by comparing them to the existing risks in tunnels from conventionally fuelled vehicles, most notably the fire risk. In particular, the probabilities of occurrence for the various events were compared to the probability of fire events (approximately one fire per 10^8 vehicle km). Additional information concerning this work can be found in [2] and [3].

2.1.1. Battery Electric Vehicles

BEV were not found to create significant new risks for tunnel users.

Available data tends to show that fires are far less frequent in electric vehicles than in conventionally fuelled vehicles (ICE). This is as expected, given there are significantly more ignition sources in a conventionally fuelled vehicle than in an electric one. However, many vehicle fires without human consequences do not get reported widely and thus do not show up in statistics. BEV have been introduced comparatively recently, and their proportion of the overall fleet is still very low. So, it’s difficult to draw general conclusions from limited available data. In addition, the absolute number of events is very low which further complicates the process of drawing statistically valid conclusions. It is also noted that risks associated with new technologies attract more attention than risks from traditional technology. It was therefore considered that the probability of fire in electric vehicles is the same as for traditional vehicles.

Fires resulting from thermal runaway in Li-ion batteries do not significantly increase the fire size for the whole vehicle, which already contains a large fire load (tires, seats, etc.). The same conclusion applies to toxic emissions: the toxicity of the gases emitted by burning batteries is actually lower than the toxicity of gases produced by other parts of a burning vehicle. Gas cloud explosions from batteries require that the fire and the subsequent thermal runaway quickly vaporizes a large quantity of electrolyte which subsequently encounters an ignition source. This is regarded as a highly unlikely scenario because a fire will vaporise and then burn small quantities of electrolytes successively, and batteries have internal walls to slow down fire propagation.

2.1.2. CNG and Hydrogen Vehicles

Compressed natural gas and hydrogen vehicles create qualitatively similar risks, related to the gas container: jet fire, tank rupture and vapour cloud explosion (VCE). The consequences for each event depend on the thermophysical properties of the gas.

The most critical hazard was found to be the VCE, particularly on buses, since many people are likely to be present in the dangerous area. Due to the properties of hydrogen, events involving hydrogen vehicles are expected to be significantly more severe.

Tank ruptures due to the fire rapidly increasing the internal pressure would have severe consequences. However, pressure-relief devices are simple and reliable, and this risk is therefore considered to be unlikely. Moreover, any tank rupture would happen between approximately 8 and 20 minutes of tank exposure to a developed fire. The tunnel is likely to be evacuated at that time and therefore there would be minimal risks to the evacuation.

Jet fires are very localised phenomena, and their typical duration is very short. They mostly happen when the tank is exposed to a developed fire, which should have triggered a tunnel evacuation. The most dangerous scenario is where a jet fire occurs on a bus in the direction of the evacuation routes. With the majority of tanks located on the upper part of the vehicle it is possible that a jet fire could be triggered while the temperature at head-height remains tenable. Orienting thermally-activated pressure relief devices (TPRDs) vertically was suggested as a way to reduce the possible impact on people on evacuation routes.

2.1.3. Liquified Natural Gas Vehicles

Liquefied natural gas (LNG) tanks operate at a much lower temperature and pressure than CNG or hydrogen tanks. As a result, LNG tanks are likely to generate less severe events than CNG or hydrogen, except for the tank rupture on HGVs, which may have catastrophic consequences due to the large quantity of fuel in the tank.

2.1.4. Indirect Risks

Indirect risks, such as a jet fire occurring on a gas-powered vehicle because of a fire on another vehicle, were also examined. This type of event was considered to be relatively significant especially in the case of buses. If a jet fire was triggered by hot smoke passing over the bus this could present a significant hazard to evacuating passengers. This risk should be considered both by operators and fire-fighters.

2.2. E-Tox and other Projects

In recent years, the Research Institutes of Sweden (RI.SE) dealt with two research areas related to NEC. These are works on battery fires and CNG containers. The CNG research also considered the impact in subsurface structures.

2.2.1. Battery fires

Work related to battery fires is found in the following reports:

- Toxic Gases from Fire in Electric Vehicles by Willstrand et. al [4]
- Fire Safety of Lithium-Ion Batteries in Road Vehicles by Bisschop et al. [5]
- Li-on Fire: Extinguishment and mitigation of fires in Li-ion batteries at sea by Andersson et. al [6]

The E-TOX[1] research project has focused on battery fire tests that measure heat release rates, toxic production and extinguishment. These questions are all important for the safety of personnel fighting fires and users of tunnels. One of the additional risks that fires involving electric vehicles has created is the potential release of toxic gas.

The work at RI.SE includes literature reviews, conventional vehicle fire tests, battery fire tests and numerical simulations to gather and present data on gas and heat release during fire in BEV. In the tests carried out, one BEV and one conventional vehicle of the same model and from the same manufacturer were used. Peak heat release rate and total heat release were affected by the fire scenario and vehicle model. The vehicle powertrain did not significantly impact the outcome (Figure 2).

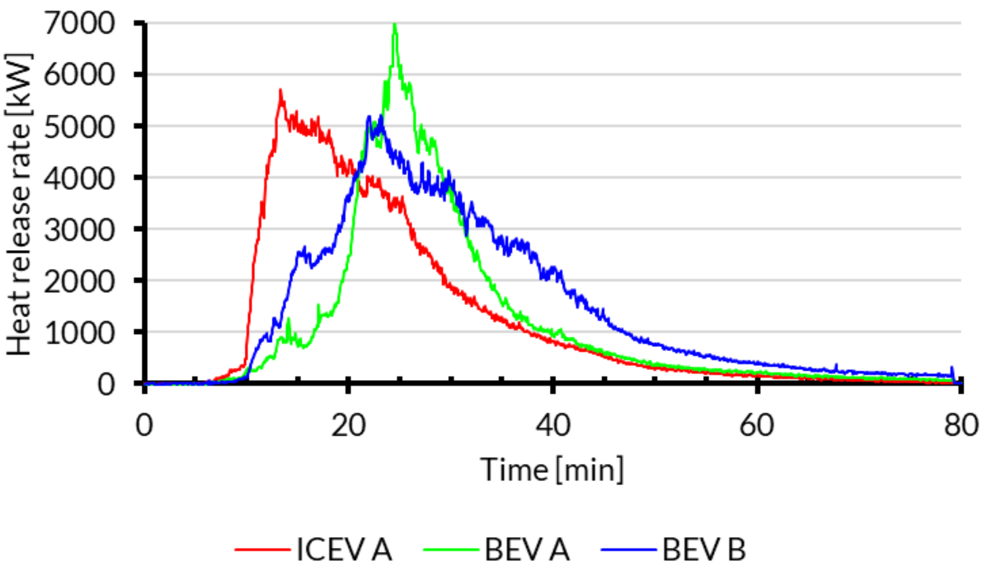

Figure 2: Heat release rate (oxygen consumption calorimetry) for the three vehicles [4]

There are many toxic gases released by a vehicle fire that do not depend upon the powertrain involved. The largest difference between electric vehicles and traditional vehicles was the release rate of hydrogen fluoride. There are also some specific metals present in the smoke from a battery vehicle fire which are not present in a traditional vehicle fire. The work is presented in the RI.SE Report 2020:90 [7], and funding for continuation of this work in ETOX II project has been granted.

Further work on battery fires is presented in the RI.SE Report 2019:50 [5]. The report addressed concerns on the fire safety of road vehicles with lithium-ion batteries (LIBs). Fundamental

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[1] *Toxic gases from electric vehicles (E-TOX)*

information on BEVs and LIBs is presented, and matters related to fire risks and safety solutions were investigated. Battery pack integration in vehicles, identification of fire hazards and means for preventing and controlling LIB fires were all considered.

The suitability of fixed fire suppression and detection systems in BEVs and measures to prevent consequences to the surroundings in case of a BEV fire were also investigated. Statistics show that the demand for BEVs has increased strongly in recent years and that this trend continues. The report points out that first responders and post-crash handlers need to be aware of the possible risks posed by BEVs and how to handle them. It is important that first responders are able to identify BEVs and their LIB easily; a task which can be challenging given current standards. Only after this, can the risk be assessed and appropriate guidelines and working procedures followed. Incidents involving BEVs continue to attract considerable media attention, which could increase caution among responders and the public.

The work at RI.SE is not only related to road vehicles but also to new propulsion methods using batteries at sea. A test compartment was constructed to simulate a battery room and a commercially available LIB cell was positioned inside a cubic box that mimicked a battery module. By heating the battery cell, combustible gases were generated, and these gases were ignited by a pilot flame inside the simulated battery module. The tests indicated that fire extinguishment of a battery cell fire inside a battery module is unlikely when using total compartment water spray or water mist fire protection systems. The water droplets are simply not able to penetrate the battery module and reach to the seat of the fire. Direct injection of the fire extinguishing agent inside the battery module is necessary. The tests also showed that agents such as water and low-expansion foam, with a high heat capacity, provide rapid cooling and fire extinguishment. The reduced water surface tension associated with low-expansion foam may improve the possibilities for water penetration whilst agents with a high viscosity may not be able to spread to the seat of the fire. Agents with less heat capacity, such as high-expansion foam and nitrogen gas, provide less cooling but fire extinguishment can still be achieved if designed correctly.

2.2.2. CNG containers

Work related to CNG containers is found in the following reports:

- CNG vehicle containers exposed to local fires by Gehandler, J and Lönnermark, A. RI.SE Report 2019:120. [7]
- Fire exposure of empty CNG storage tanks by Gehandler, J., Lönnermark, A. and Anderson, J. RI.SE Report 2019 [8]

The majority of CNG research has focussed on CNG tanks and the benefits and impacts of TPRD (thermally-activated pressure relief device). This is important due to the safety issues and how the jet flames behave if released, especially in tunnels.

The reports give an overview of the research carried out in this field. Fuels with a high energy density have contributed to the development of modern communities and can contain energy that, during certain conditions, can result in incidents, not least within transportation. CNG vehicles are designed according to safety standards of the UNECE, including consideration of events such as fire. In case of a fire, a TPRD should empty the container before a pressure vessel explosion can occur. CNG tanks are, according to UNECE regulation 110, tested against a 1.65 m long pan fire. However, local fires, which expose only one part of the tank are not included in these tests. The RI.SE report

2019:120 [7] presents fire tests of CNG containers performed both with a UNECE compatible fire source and with a local fire source. Any pressure vessel explosion and jet flames were characterized for two different types of CNG containers, namely steel and composite. In five out of six tests the safety of the CNG containers prevailed also in the event of a local (0.24 m by 0.24 m) pan fire, meaning that no pressure vessel explosion occurred. In real vehicle fires, where the fire extends from its local characteristics to a more developed fire that exposes the CNG containers to a larger extent, these tests support that TPRDs most likely will activate. In four out of the six tests with local fire the TPRD activated (much later than with the UNECE fire) and released the gas in a jet flame (Figure 3). In one case nothing at all happened and the tank was punctured with riffle shooting. In one test a composited gas tank ruptured in a pressure vessel explosion after 20 min local fire (0.48 m by 0.24 m) exposure. The experience from running these test series calls for the fire source to be more accurately defined with regards to fuel and dimensions, and a local fire should be included in the UNECE Regulation 110.

Figure 3: Test of a gas container under fire condition [7]

2.2.3. Subsurface infrastructure – tunnels and mines

Tunnels and mines are of great interest and research has been carried out on battery incidents related to these areas. Two studies presented in Swedish have been carried out related to this subject, but they are not presented here. Work related to the risks of NEC in tunnels and underground garages was published in *SP Report 2017:14* [9].

The SP research project comprises primarily a literature review that was intended to identify the risks involved in using alternative fuels in road tunnels and underground garages. Gaseous fuels and electric vehicles pose new risks that are less familiar. 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 battery fires undergoing thermal runaway.

2.3. BRAFA

Within the BRAFA[2] research *project [10], [11],* the effects of fires in BEV on the safety of tunnel users and the tunnel infrastructure were examined, and methods for fighting fires in BEV were

[2] *Brandverhalten von Fahrzeugen mit alternativen Antrieben (BRAFA)*

evaluated. Real fire tests were carried out in suitable test tunnels in the Austrian tunnel research facility 'Zentrum am Berg'.

Figure 4: Full scale fire test of a BEV [10] © TUG/Lunghammer

The main results from these tests can be summarized as follows [12]:

In car fires, the heat release rates increased slightly compared to fires with conventional fuels. However, if the whole battery-pack is affected in a spontaneous fire over a very short time, a noticeably higher rate of heat release could be expected.

The gases that were released during the fire showed a noticeable increase in CO, HF and H_3PO_4 (phosphoric acid) concentrations. However, due to the thermally induced gas stratification, the high concentrations were observed in the soffit area of the tunnel. In the area less than 2 m above the roadway, critical limit values were generally not exceeded for all cases tested.

With regard to firefighting, it was found that water continues to be the most effective extinguishing agent due to its cooling effect. As part of the tests, alternative extinguishing methods such as the use of extinguishing lances for direct cooling in the battery housing or fire blankets were also investigated (Figure 5).

Figure 5: Use of a fire blanket (left) and an extinguishing lance (right), [10]

With regard to the assessment of the risk for tunnel users, it emerged that with a noticeable proportion of BEV in the car and bus fleet-segment, the overall tunnel safety risk tends to increase by just a small percentage, while the fire risk can increase more significantly.

2.4. HYTUNNEL-CS

The aim of the HyTunnel-CS[3] project [13] is to perform pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces.

The main ambition is to facilitate hydrogen vehicles entering underground traffic systems at risk below or equivalent to the risks for fossil fuel transport.

The project started in 2019 and is scheduled for completion in 2022.

The consortium —composed of 13 partners from 11 European countries— is conducting interdisciplinary and intersectoral research to achieve the following partial objectives:

- Critical analysis of the effectiveness of conventional safety measures for hydrogen incidents;
- Generation of experimental data using the European hydrogen safety research facilities and real tunnels;
- Understanding of relevant physics to underpin the advancement of hydrogen safety engineering;
- Innovative explosion and fire prevention and mitigation strategies;
- Development of new validated CFD and finite element models for consequence analysis;
- Development of new engineering correlations for novel quantitative risk assessment methodology tailored for tunnels and underground parking;
- Harmonised recommendations for intervention strategies and tactics for first responders;
- Recommendations for inherently safer use of hydrogen vehicles in underground transportation systems; and
- Recommendations for Regulations, Codes and Standards (RCS).

The project outcomes are intended to be reflected in appropriate recommendations; models and correlations could be directly implemented in relevant regulations codes and standards.

HyTunnel-CS also has a Stakeholders Advisory Board (SAB) which includes National Networks authorities, practitioners and experts from different countries within and outside Europe. Its objective is to ensure that the work and results of the project are valuable and usable by the different stakeholders involved in the safety of tunnels and similar confined spaces.

Figure 6 shows the structure of the workflow within the project.

[3] *Pre-normative research for safety of hydrogen driven vehicles and transport through tunnels and similar confined spaces (HyTunnel-CS)*

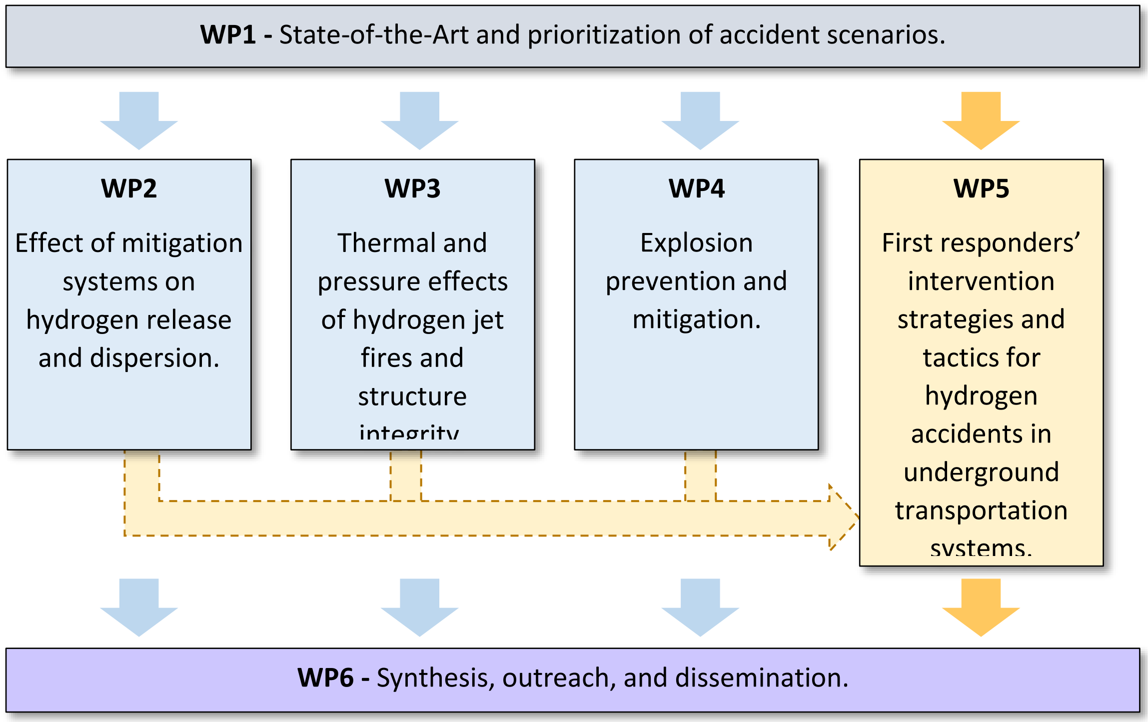

Figure 6 : Structure of the work packages in HyTunnel

WP1 State-of-the-Art and prioritization of accident scenarios.

Study of existing safety provisions in tunnels and their relevance to hydrogen, hydrogen hazards and risks in confined spaces; critical analysis of current Regulations, Codes and Standards.

WP2 Effect of mitigation systems on hydrogen release and dispersion.

Develop analytical, numerical, and experimental studies of unignited leaks, hydrogen dispersion and the effect of mitigation systems like ventilation and water spray and mist.

WP3 Thermal and pressure effects of hydrogen jet fires and structure integrity.

Develop analytical, numerical, and experimental studies of jet fires, including pressure peaking estimation, effects of fire suppression and mechanical ventilation, and effects on concrete and metallic structures and other elements.

WP4 Explosion prevention and mitigation.

Develop analytical, numerical, and experimental studies of explosions, including blast wave and fireball of tank rupture, overpressure during spurious operation of TPRD (thermally-activated pressure relief device), shock wave attenuation, and safety technology to prevent tank rupture.

WP5 First responders' intervention.

Compilation and revision of intervention strategies, tactics, and procedures of first responders. It also involves a critical analysis of the QRA methodology for tunnels and confined spaces.

WP6 Synthesis, outreach and dissemination.

Compile, order and present the results of all the other work packages. Use these results to develop a general understanding of hydrogen interaction with safety equipment and geometries of confined spaces. Using this understanding, the development of recommendations for safer use of hydrogen vehicles, prepare performance-based requirements to regulators and disseminate project results to stakeholders.

Further information about the deliverables from the HyTunnel-CS project as well as related publications can be found at the project webpages [14] and [15].

2.5. SuverEin-2 Project

SUVEREIN-2[4] [16] was a German research project lasting from 2017 until 2020 and was funded by the German Federal Ministry of Education and Research (BMBF). Partners in the SUVEREN consortium were the German Federal Institute for Materials Research and Testing (BAM), the Study Association for Tunnels and Transport Facilities e.V. (STUVA e. V.) and FOGTEC Fire Protection. Associated partners from both Germany (Deutsche Bahn Netze and the Munich Fire Department) and France (INERIS Development and CETU) provided input. The experimental tests were carried out by IFAB of Germany.

The project addresses the risks associated with NEC in partially or fully enclosed underground facilities like road tunnels, car parks or bus depots. Fire risks related to LIBs were the focus. The goal was to get a better understanding of heat release rates, combustion products, other gases released during a fire incident, toxicity aspects and the impact of battery fires on humans and nearby assets like building structures and other vehicles. The burning behaviour of LIBs was studied by carrying out real-scale fire tests with LIBs common in the automotive industry. A specially designed calorimeter (>32 m³) allowed for fire tests with both battery modules and complete battery packs, resulting in a large amount of new data on gas and surface temperatures, gas species concentration, battery-mass loss and other aspects and parameters. For the gas monitoring and analysis, Fourier-Transform Infrared Spectroscopy (FTIR) was applied. An updated design fire curve representing both conventional and battery electric vehicles was developed. Based on this design fire curve, a reference fire load and mock-up were developed representing the burning characteristics of a modern passenger vehicle.

The capabilities of most commonly used detection and firefighting technologies were tested in a second series of fire tests. The project included tests with faulty and healthy LIB modules as well as tests with the newly developed reference fire loads, and a passenger car mock-up. The detection tests covered systems based on temperature, smoke and gas as alarm parameters. Firefighting systems based on water (sprinklers, high and low-pressure water mist), gas (Nitrogen, Carbon Dioxide, Novec) as well as on water with additives, foaming agents and aerosols were tested. In addition to the direct comparison of the effectiveness against fires of these systems, measurements of temperatures and gas concentrations were carried out and taken into account in the analysis and evaluation.

During a third fire test series, sprinklers and high-pressure water mist were tested against an electric vehicle fire in the form of a mock up in a test room representing a parking garage. A concept for the protection, especially of charging stations in parking garages, was developed.

The project further included extensive computer simulations on the combustion level, for real scale fires and on evacuation.

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[4] *Safety of Urban Underground Structures due to the Use of New Energy Carriers (SUVEREIGN-2)*

The approach of SUVEREN was to generate new and relevant data on LIB fires in a systematic and scientific manner. These data were used to work out concepts for how to deal with fire risks related to LIBs. The data were intended to provide the basis and input for further research work and data. Major findings derived will be summarized and published in a publicly available guideline.

Further information can be found in the references [17] to [26].

2.6. BEV IN UNDERGROUND TRAFFIC INFRASTRUCTURE, SWISS RESEARCH ACTIVITIES

BEV fires with LIBs lead to new types of pollutant emissions. New studies from Switzerland show that this changes the toxicological risks in underground traffic infrastructure because these pollutants do not occur in fires in conventional vehicles [27], [28], [29]. These battery specific contaminations will not impair technical operations in underground car parks or road tunnels, but they will make careful handling of fire-fighting and cooling water essential.

The latest experiment [29] was carried out in 2019 in the underground facilities of Versuchs-Stollen Hagerbach AG, which provide a real environment for fire tests related to both underground car parks and road tunnels. The experiment focused on lithium-ion batteries (type NMC) used in a BEV that had been approved for traffic. The analysis of fire residues and their impact on infrastructure was the main focus. Neither fire nor crash tests were conducted with full BEV, nor were there any analyses on the probability of such damage.

The hypothesis that the emissions from electric vehicle fires in underground traffic infrastructure lead to lasting effects cannot be confirmed. The study concluded that, for typical infrastructure components in underground car parks and road tunnels, no damage was observed. Therefore, it was considered that any impact to infrastructure from electric vehicle fires will be no greater than those associated with traditional vehicle fires. However, the battery specific emissions will lead to contamination which is of toxicological importance especially for decontamination and disposal works. Based on the findings, six risk-reducing measures can be derived (

), which are primarily of an organizational nature; two of them are urgent.

#	Measure	Type	Influence on risk
1	Mandatory retention and environmentally correct and professional disposal of firefighting water in accordance with the applicable provisions	Organisational / technical	Minimises damage
2	Definition of a safe process for handling cooling water and immediate implementation in practice	Organisational	Minimises damage
3	Standardisation of the handover process for accident-damaged traction batteries	Organisational	Minimises damage
4	Risk-based siting of charging stations in multi-story car parks	Organisational	Preventative
5	Consideration of further fire protection measures in smaller infrastructures	Technical	Preventative / minimises damage
6	Integration of new propulsion technology into risk models	Technical	Preventative

Table 2 : Measures for minimising the risks of electric vehicle fires in underground traffic infrastructure

Fire-fighting and cooling water resulting from an electric vehicle fire is highly contaminated. Since the concentrations of lithium and the heavy metals cobalt, nickel and manganese exceed current thresholds for discharge into the sewerage system many times over, appropriate pre-treatment must be implemented. Regarding the cooling water, which is typically produced in the after-treatment of damaged batteries, standardised handling needs to be defined. The other recommendations include additional preventive measures that allow an appropriate handling of the changing risk landscape.

Concerning electric mobility in underground infrastructure, two aspects should be investigated in greater depth:

- The effectiveness of high-pressure water mist systems, which are used internationally, especially under the argument of new energy carriers. Since these systems are hardly or not at all used in underground infrastructure in Switzerland, they should be reassessed in the course of the increasing use of lithium-ion storage systems.
- The risks of fuel cell electric vehicles, especially in the case of heavy goods vehicles in underground infrastructure, are still not clear. A risk assessment with experimental methods is recommended.

2.7. SANDIA REPORTS

SANDIA published two reports concerning NEC vehicles and tunnel safety ([30], [31]).

The Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study [30], published in 2017, gives a first insight into the FCEV topic. The report about alternatively fuelled vehicles in tunnels [31], published in 2020, provides a good overview of the risks that such vehicles can pose in the event of incidents in tunnels. The report covers all types of commonly used propulsion systems, mainly ICE with gasoline or diesel, LPG and CNG but also BEV and FCEV. The information provided is based on literature from the last two decades.

The report concludes as follows (cited from [31] pp 161, 162):

Battery Electric Vehicles

> *Overall, BEVs have a variety of research gaps due to the complexity of scaling battery systems to power the various classes of vehicles. Additionally, the wide variety of cell chemistries, battery pack designs, and battery management systems make it difficult to assess specific safety metrics for BEVs as a whole.*
>
> *One large-scale test [86] showed that BEVs have comparable heat release rate (HRR) and total heat release (THR) to ICE vehicles, but with a higher hydrogen fluoride production during a fire.*
>
> *Specific modelling for BEVs in tunnels was not conducted, and modelling for LIBs is still at the cell and module level. A tunnel experiment was conducted which looked at various failure scenarios and the effect of this inside a tunnel downstream of the failed battery cells [86]. The release quantities were measured which included toxic aerosols such as cobalt, lithium, and manganese. Data from mechanically and thermally failed modules were analysed to understand the fire effluents and required ventilation in the space [91].*
>
> *A systems safety approach from the cell level, to modules, battery system, and complete BEV should be studied to further understand how the components and sub-components interact. Using a system safety V-diagram to define testing and safety requirements for each system level (cell, module, and battery system) would help further understand how to safely design these systems. This will directly tie into understanding consequence metrics for further evaluations in tunnels. Future work characterizing fire spread within a BEV and tactics to slow or stop thermal propagation would be beneficial.*

Natural Gas Vehicles

> *Multiple studies for both CNG and LNG powered vehicles have been conducted, including experiments to understand flame speed and overpressure and the effects of congestion on these hazard metrics. Vapour cloud explosions and heat flux from flames have also been studied. Modelling to understand CNG dispersion has been conducted for various tunnels. An FMEA of CNG-powered buses has also been completed to understand the risk of these vehicles. However, the majority of these studies involve CNG only, showing the need to further understand LNG hazards and the differences for this liquefied fuel. Continuous release of LNG compared to CNG showed that the harmful and lethal distances for CNG exceed those for LNG due to the higher storage pressures. Further studies to understand and compare the hazard difference between LNG and CNG should be considered. A variety*

of tunnel studies have used CNG release quantities that are considered equivalent to the amount of CNG used in a city bus and passenger car. Other classes of vehicles should be further studied for release characteristics for both CNG and LNG.

LPG Vehicles

There are relatively few studies evaluating the failure modes and consequences associated with LPG vehicles in tunnels. A scenario identification study was conducted that estimated the likelihood of different consequences of a tunnel incident through expert elicitation, but a more rigorous evaluation of failure modes should be completed. One study focuses on creating and using a failure tree to inform release scenarios for an LPG vehicle. This then helped inform the experimental setup where six different tests using different ventilation and releases were used. The experimental data was then compared with a CFD model for validation. This model can be further used to understand the gaseous dispersion characteristics of LPG from vehicles failing in tunnels and other confined spaces. Additionally, experiments have been conducted to determine the effect of ventilation and tunnel slope on smoke dispersion in a tunnel using a propane fire. Modelling helps understand the dispersion and evaporation phenomena of an LPG spill.

Hydrogen Fuel Cell Vehicles

A variety of studies and experiments have been completed for hydrogen FCEV, specifically in tunnel applications. Just as for CNG, batteries, and other fuels, industry plans to use hydrogen fuel cells for larger class vehicles (e.g. class 8 trucks). Therefore, studies to understand how the increase of vehicle class affects the hazard should be considered. Consequence models for tunnel safety studies have been conducted using CFD models and should be further used to evaluate larger classes of vehicles. Future work and studies to improve characterization of the risks include the HyTunnel-CS project. This project will use experiments in tunnels, modelling using tools such as CFD, and analysis using risk assessment methodologies. Through this work, over-conservatism will be reduced which will help increase effectiveness of safety systems along with cost savings of tunnel and confined space safety systems.

2.8. Research in The Netherlands

Intense research was carried out in The Netherlands concerning the impact of new energy carriers on traffic infrastructure and buildings (garages). The individual investigations were mainly based on literature studies and many of the final reports have already been published. Annex 8.2 contains a list of the main relevant activities.

3. RESEARCH ON IMPACT OF FIRES GENERATED BY ALTERNATIVELY FUELLED VEHICLES ON INFRASTRUCTURE

Although not being a core topic of this working group, some recent results from research activities concerning the influence of fires generated by vehicles with alternative fuels are listed in the following section. The main subject of concern is the exposure to heat in case of a fire and high pressure in case of explosions. When considering heat, the parameters temperature and duration of the exposure are of particular interest.

Concrete is a poor heat conductor, which means that in the event of a fire there is a considerable temperature gradient from the concrete surface to its core area. The mechanical properties of the concrete change with increasing temperatures and reduce the load-bearing capacity of the building elements. Spalling at high temperatures reduces the protective effect against the fire and accelerates material failure. The current thermal requirements are defined in regulations and require the components to be functional against exposure to high temperature-time loads. Typical curves are given in a variety of references e.g. the ISO-834 curve (EN 1364-1, EN 1991-1-2) or similar curves such as HC, HC_{inc}, RWS etc. The problems arising from NEC fires relate to the issues of temperature requirements and exposure of the surface to air pollutants and acids.

Tramoni et al. [32] investigated the fire development and the temperature exposure of unprotected steel structures in an underground car park under various scenarios with different cars with alternative fuels under fire. The tests used diesel cars as the reference case, and tested BEV, FCEV as well as CNG and LPG fuelled cars. The set-up for each test always consisted of two vehicles, one NEC and one ICE placed side by side. Ignition happened always inside the NEC vehicle (except in the base case with two diesel fuelled ICE vehicles). The FCEV was equipped with a 77 MPa hydrogen tank and a standard TPRD directed to the floor. The LPG car was equipped with an overpressure valve (2.7 MPa) and a TPRD (110°C). The CNG car was equipped with a TPRD. The BEV (model year 2010) contained a Lithium Metal Polymer (LMP) battery and represents a technology which is outdated at the time of this report.

Fire dynamics as well as the temperatures on the steel structures were observed. They authors concluded as follows:

> *Global analysis showed that the structure heated in a similar way in the different tests. Temperatures were slightly higher than 900°C for the reference, H2 fuel cell and LPG tests. The main difference is the location of this maximum. Reference, NGV* (CNG) *and LPG cases showed maximum temperatures above the first car while the H2 fuel cell case mostly heated the beam above the ICE car. The electric case showed a uniform but lower heating. These tests suggest that the stability of the structure is not adversely affected by the type of vehicle.*
>
> *Finally, despite the test conditions and severe thermal stress, the thermal runaway of the battery was not observed. In addition, the activation of the safety devices of the gas tanks led to a significant increase in the heat received by the structural elements. The duration was however too short to observe a real impact.*

4. RECORDED INCIDENTS WITH NEC VEHICLES

Incidents with NEC vehicles on roads are quite rare, mainly due to the relatively small proportion in the vehicle fleet. In addition, for some of the energy carriers like CNG and LPG, the safety standards of the storage systems are high and well established.

4.1. BATTERY ELECTRIC VEHICLES

BEVs have been used on the road for a decade at the time of writing this report. However, they have only made up a notable proportion of new registrations in recent years. While incidents with first generation BEVs mainly occurred during the charging process, the vehicles of the new generation already have a very sophisticated charging and monitoring process to avoid damage during this phase.

For many of the events that resulted in battery fires, the cause was relatively trivial such as the collision with a guardrail (Figure 7). Incidents involving fire of a BEV in a road tunnel have not yet been recorded due to the small numbers of such vehicles. In 2017, there was a vehicle fire in the immediate vicinity of the entrance portal of a tunnel on the Arlberg expressway (A), which was due to a collision of the vehicle with a concrete guide wall (Figure 8).

Figure 7 BEV on fire after the car hit the guard rail [33]

Figure 8 Fire of a BEV at the entrance portal to the tunnel Pians, A [34]

4.2. FUEL CELL POWERED ELECTRIC VEHICLES

Fire tests performed some time ago, showed that the fire characteristics during release of H_2 is quite unspectacular [35]. Figure 9 shows images at different time steps of the experiment. While H_2 is fully burnt within a very short time interval and without igniting the whole vehicle, the gasoline fire covers the whole vehicle and lasts much longer. It has to be mentioned that in this experiment only the fuel was ignited, however, any gas release due to pressure relief would only happen in case of external heat exposure of the tank, which would in most cases be a vehicle under fire.

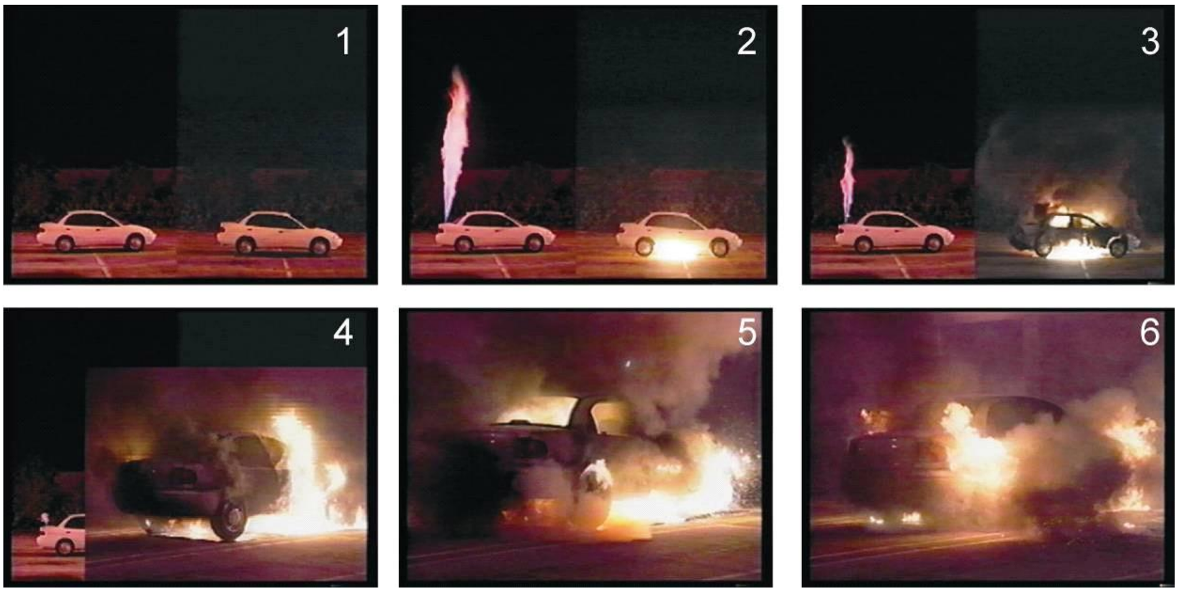

Figure 9 burning behaviour of H_2 (left side of each image) and gasoline due to leakage of fuel, at 0, 3, 60, 90 140 and 160 s after ignition, [35]

4.3. CNG AND LPG

As already mentioned above, the majority of CNG and LPG fires happen during refuelling. Fires of vehicles on the road are in most cases the consequence of vehicle fire starting from other sources than the fuel itself. Figure 10 shows an image of a CNG bus fire, which started in the vehicle and resulted in fuel release via the pressure relief valves. This released fuel caught fire and burned in a jet flame. However, incidents with severe damage of the tank might result in an uncontrolled release of the fuel and in case of LPG even in a BLEVE (Figure 11).

Figure 10 CNG-bus on fire (screenshot from a video, [36])

Figure 11 LPG-vehicle after a severe crash, [37]

Figure 12 shows a CNG bus on fire, where apparently the vehicle collided with a height restriction barrier in front of a tunnel portal causing an explosion of the tank.

Figure 12 CNG-bus on fire (screenshot from a video), [38]

5. SURVEY ON ONGOING RESEARCH AND REPORTED INCIDENTS

In Spring 2021 WG4 launched an inquiry to PIARC member states concerning information about ongoing research in the field of NEC as well as on incidents with vehicles with NEC. Unfortunately, this inquiry attracted only limited response. The following section summarizes the information gathered from the various PIARC member states.

A summary of the incidents that were received from the PIARC member states are listed in Table 3. No other response was received.

Country	Year of Incident	Location	Type	Information	Fatalities /Injured
UK	2018	M25	Surface road	BEV hit a bridge abutment at speed. Fire developed slowly at first, then accelerated as the battery compartment provided energy to the fire – vehicle became fully involved and burned for another 30 minutes. Fire service arrived at 15 minutes, attempted but failed to extinguish. Eventually extinguished after 30mins. Fire re-ignited 20 minutes later, fire service still on site and re-extinguished. Road closed for 6 hours. Vehicle eventually removed to safe location to be observed.	0/1
AT	2017	Arlberg Expressway	Tunnel approach	Vehicle hit guardrail at the motorway in front of the tunnel. Fire started in the front part of the vehicle and could not be extinguished	0/0
NZ	2021	Waterview Tunnel, Auckland	Tunnel approach/portal	Electric truck (first in NZ) broke down at one of the tunnel portals. There was no fire but dealing with the truck was "more of a challenge" than usual.	0/0
NZ	2018	Arras Tunnel, Wellington	Tunnel	Hybrid vehicle started smoking in the tunnel during rush hour traffic, hence there were vehicles stopped in the tunnel. Tradesman several vehicles back took out a fire extinguisher from his vehicle and put the fire out - end of incident.	0/0
N	2021	E134	Tunnel portal	Propane-driven truck loaded with approximatly 30 tonn shreddeded car-parts startet burning in the portal of Merraskott tunnel. It is meeting traffic in the tunnel, and the truck startet burning at the entrance of the tunnel. The fire-department used around 5 hours to empty the propane-tank by controlled burning. Tunnel still closed for repairs (21.6.2021)	0/0
D	2011	A7 Elbtunnel	Tunnel	Rear end collision of three cars due to insufficient distances, emergency services were dispatched for "accident", six minutes later the operator noticed smoke development at one car on monitor and informed emergency services accordingly. Subsequently flames become visible under the car. Fire service arrived at scene eight minutes after first dispatch "accident". Fire extinguished after further seven minutes. Only then it turned out that the car was a gas fuelled vehicle. Gas tank was still intact and had caused no problems.	0/0

Table 3: reported incidents with NEC vehicles

On October 20-21 2021 a webinar organised by PIARC WG4, together with ITA-COSUF and KTP took place. The most up to date research concerning NEC as well as the roadmap for achieving carbon-neutral road transport by 2050 and the implications on NEC was discussed. A summary report of this webinar can be found in annex 8.1

6. GLOSSARY

Term	Definition
ATEX	directive for equipment working in explosive environment (Atmosphères Explosives)
BEV	Battery electric vehicle
BLEVE	Boiling liquid expanding vapour explosion
CNG	Compressed natural gas
CO	Carbon monoxide
Co	Cobalt
CO_2	Carbon dioxide
FC	Fuel cell
FCEV	Fuel cell electrical vehicle
FFFS	Fixed fire fighting systems
HEV	Hybrid electrical vehicle
HCN	Hydrogen cyanide
HCl	Hydrogen chloride
HF	Hydrogen fluoride
HGV	Heavy goods vehicle
HC	Hydrocarbons
HRR	Heat release rate
H_2	Hydrogen
ICE	Internal combustion engine
Li	Lithium
LNG	Liquified natural gas
LMP	Lithium metal polymer

LPG	Liquified petroleum gas
Mn	Manganese
NEC	New energy carriers
PC	Passenger car
PH_3	Phosphine
PHEV	Plug in hybrid vehicles
SOC	Status of charge (battery)
THR	Total heat release
TPRD	Thermal pressure relief device

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8. APPENDIX

8.1. COMMON PIARC-ITA_COSUF-KTP WEBINAR ON NEW ENERGY CARRIERS IN ROAD TUNNELS

Authors: Ben van den Horn (ITA COSUF) and Peter Juijn (Peter Juijn Teksten)

On the 20-21 October 2021, an international meeting was held for the second time on new energy carriers for road transport, such as battery electric vehicles, vehicles propelled by natural gas and hydrogen, and the negative consequences these new energy carriers can have for underground infrastructure. Due to the covid-19 pandemic, the conference was completely digital. Like the first congress in February 2019, it was organized by PIARC, ITA-COSUF and KPT. The various presentations show that knowledge about the risks of the new energy carriers has increased significantly in the past two years and that various solutions have been identified to manage these risks.

Figure 13: Title page of the Webinar on NEC in road transport

The webinar was spread over two afternoons. The first day started with opening words by Eric Premat, Max Wietek and Ben van den Horn, representatives of PIARC, ITA-COSUF and KPT respectively, in which they introduced the organizing parties. They also briefly looked back at the first conference in 2019 and discussed the importance of research in a European context into new energy carriers in relation to underground infrastructure. The starting point is that the arrival of new energy carriers (NEC) is inevitable in view of the negative consequences of the use of fossil fuels by road traffic and the climate objectives. An important question is whether the risks associated with the use of new energy carriers require adaptation of safety guidelines for underground infrastructure and, for example, different working methods for tunnel operators and emergency services. The full presentations are available at the ITA COSUF webpage [39].

Felix Haberl from Volvo Powertrain explained how Volvo wants to achieve that all vehicles produced are completely 'fossil-free' by 2040. For passenger cars and light commercial vehicles, which are used, for example, for urban and regional transport, Volvo is looking for the solution in battery technology. For heavy vehicles and vehicles that have to cover large distances, the emphasis is on fuel cells that produce electricity with green hydrogen. Volvo also assumes that a small part of the vehicles will still have a combustion engine with, for example, green gas as a fuel or other renewable energy carriers.

Safe hydrogen vehicles

Dimitri Makarov from the University of Ulster presented the preliminary results of the Hytunnel-CS research project. This project investigates how to ensure that hydrogen-powered vehicles and hydrogen tankers can make safe use of underground infrastructure. This requires that the risks posed by hydrogen vehicles can be adequately controlled. This concerns the following risks: the occurrence of a burning gas cloud, an exploding gas cloud, jet flames if hydrogen escapes through the expansion valve (the thermal pressure release device, TPRD) and ignites, and a bursting gas tank (tank rupture) while there is a fire causing a huge explosion can occur.

To control these kinds of risks, the researchers are looking at design parameters for pipes and TPRDs, among other things, that prevent the formation of jet flames and gas clouds. They also look at design parameters like the diameter of TPRDs and the direction in which the overpressure is released to prevent the formation of a gas cloud under ceilings, and to avoid temperatures higher than 300° Celsius in pipes of mechanical ventilation systems in parking garages. They also look at tank designs that are explosion-proof.

One of the results of the study is that tunnel ventilation in the same direction as the escaping hydrogen gas can significantly reduce the size of the gas cloud. Furthermore, the angle of inclination of a tunnel appears to have hardly any effect on the size of the gas cloud. In parking garages, mechanical ventilation has little effect on the maximum size of the gas cloud with optimized TPRDs. Another outcome is that the combustible layer of hydrogen gas remains smallest when the gas leaves the TPRD at an angle of 45°. Furthermore, TPRDs with a diameter of 0.5 and 0.75 millimeters do not create gas clouds under the ceiling of parking garages. An exception is if the released gas hits an obstacle, such as the wall of a garage. Then a larger combustible gas cloud can form. Yet another outcome is that TPRDs with a small diameter hardly lead to a higher heat release rate (HRR) in a jet fire.

Model calculations and field tests show that a bursting hydrogen tank can lead to an enormous pressure wave. The loss of pressure then creates a so-called BLEVE, a boiling liquid expanding vapor explosion. Such powerful explosions are highly undesirable. Special design of pressure tanks can prevent this kind of explosion. For example, the researchers have conducted tests with TPRD-less plastic tanks with a coating that melts at higher temperatures. This makes the tank wall porous and allows the gas to escape gradually. Fire tests with these tanks show that there are no pressure waves, flames or fireballs. Data from the Hytunnel research project is available at https://zenodo.org/communities/hytunnelcs.

Underground car parks

Max Lakkonen of the German Institut für angewandte Brandschutzforschung (IFAB) stressed that the application of new energy carriers not only affects tunnels, but also other underground infrastructure, such as car parks, bus depots and underground stations and transport systems. In his presentation, he discussed underground parking garages. These usually have multiple parking levels and can hold a large number of cars, ensuring a high energy density. According to Lakkonen, the existing rules and regulations do not match with the new risks of NEC vehicles. For example, the fire and smoke behavior of battery electric vehicles is different from that of traditional cars and fires with these types of cars also require different fire fighting methods. That is why he argues for a different design approach, performance-based design, in which performance requirements are central. This approach is always project specific, is based on risk analysis and during the design phase takes into account all important aspects such as fire curves of NEC vehicles, ventilation design, evacuation strategy, asset protection, fire fighting techniques and the safety of emergency services.

Full scale fire tests

The presentation by Patrik Fößleitner of the Austrian Forschungsgesellschaft für Verbrennungskraftmaschinen und Thermodynamik (FVT) focused on fire tests with batteries. As part of the research project Brandauswirkungen von Fahrzeugen mit alternativen Antriebssystemen (BRAFA), full-scale fire tests were conducted with battery cells, battery modules, a full battery and electric and traditional cars. During each test, gas and temperature measurements were taken and the distribution of heavy metals was examined. In addition, two alternative firefighting techniques have been tested, a large fire blanket that can be pulled over a burning car and an extinguisher lance. The tests show that the heat release rate (HRR) of battery vehicles largely corresponds to that of cars with a combustion engine, only the peak in the HRR is higher at 10 MW. Furthermore, a battery fire produces considerably higher emissions of the toxic HF. The fire blanket appears to work moderately: it is difficult to pull it over a burning vehicle and it only works in the first phase of a fire. Then the blanket will limit the development of smoke. The results of the extinguishing lance are better, although this lance is difficult to operate. For example, the pointed lance must be driven through the wall of a battery so that water can be sprayed into the battery. That is not easy. If the lance with its spray head is in the battery, the fire can be extinguished quickly.

Gas tanks

Haukur Ingason of the Research institute of Sweden (RI.SE) discussed fire tests conducted in 2019 and 2021 with fuel tanks for hydrogen and natural gas. In 2019, eight gas tanks for natural gas were heated over a fire at a pressure of 50 to 170 bar. Four of the tanks were made of steel and four of a composite material. The tests looked at the functioning of the TPRD, the pressure build-up, the size of the jet flames and the heat released. Additional tests were conducted in 2021 with two hydrogen tanks with a pressure of approximately 400 bar and five natural gas tanks with a pressure of 150 to 180 bar, which included the effect of cooling the tanks with water. These latest tests show, among other things, that TPRDs can be effectively cooled with water without endangering the safety of tanks. Due to the cooling, the TPRD stays closed for longer, making more time available for evacuating people. In practice, this means that quick action by the fire service can reduce the risks. It also appears that the heat from hydrogen and natural gas jet flames is relatively cold, so that the heat radiation a few meters from the flames is limited. Another result is that hydrogen tanks that become porous when heated can prevent bursting, thus avoiding a life-threatening BLEVE. In addition to the fire tests, it was also examined whether the pressure of a hydrogen tank can be released more quickly by, for example, having a firefighter shoot a hole in the tank with a rifle. There was no fire in the shooting experiment.

Transition road transport

Remy Berger from the European Cluster for Mobility Solutions (CARA) talked about the necessary transition of road transport against the background of, among other things, the EU's target to reduce CO_2 emissions from passenger cars by 55% by 2030 compared to 1991. In 2021 the standard for CO2 emissions according to the so-called WLTC test 118 grams of CO_2 per kilometer and in 2030 this should be another 37.5% lower. To achieve this reduction, there are various options for light cars, such as battery electric vehicles, cars with fuel cells and hybrid cars. Electric propulsion with batteries can also be a solution for heavier vehicles, especially for local and regional transport. There are two solutions for large distances and, for example, heavy freight traffic: electric propulsion in combination with systems that can charge the batteries while driving (such as overhead wires or charging strips in the road surface) and electric vehicles with a hydrogen tank and a fuel cell. In the further future, liquid hydrogen and systems with metal hydrides may be an option. Furthermore, traditional combustion engines in combination with biofuels, natural gas, LPG and hydrogen are a possibility. What the traffic park will look like in 2030 and the years beyond depends strongly on economic growth and environmental legislation. Berger showed four scenarios for 2040 and compared them with the situation in 2019. The decrease in diesel vehicles and the increase in battery electric vehicles were particularly striking.

Battery fires

Ola Willstrand from RI.SE presented research into fires involving battery vehicles. These fires can be caused by a problem in the 12/24-volt system, by a problem in the propulsion system or by frictional heat somewhere in the vehicle. It is extremely rare for a fire to start in the battery. Furthermore, the risks of a battery vehicle are no greater than those of vehicles with a combustion engine, just different. The heat production and HRR are comparable to those of traditional cars. When a battery vehicle fires, more toxic substances are released. In particular, the amount of HF released is significantly greater, but this does not lead to much more serious risks. For example, the HF concentration is no problem for firefighters with gas masks. Furthermore, soot from battery fires contains relatively many fluorine particles and (heavy) metals. The fire tests also involved injecting water into a burning battery. This appears to work well: the fire goes out fairly quickly and the temperature does not rise as high.

Additional risks

Christophe Willman of the French Center d'Études des Tunnels (CETU) discussed the additional risks that new energy carriers can cause in tunnels. In addition to the risks of traditional vehicles, fire and accidents in tunnels, these include jet fire, gas cloud explosions and gas tank bursts in vehicles with gas and hydrogen tanks and thermal runaways in electric vehicles with Li-ion batteries. These risks can arise from a failure in the NEC vehicle itself or can be initiated by another vehicle. To estimate the magnitude of the various risks, the researchers studied the results of CETU studies and studies by other knowledge parties. Fire with a natural gas bus does not create an extra risk, unless the bus has a TPRD that horizontally releases the overpressure and blows this gas flow against the tunnel wall. The chance of a gas cloud explosion due to a collision with a natural gas bus is also extremely small, as is the chance of a natural gas tank bursting open. In addition, in the event of a fire involving a natural gas can, approximately 8 to 20 minutes elapse before a tank bursts open. In most cases, this is more than enough to evacuate all bus passengers and occupants of surrounding cars.

With hydrogen vehicles, jet fire is only an extra risk if the vehicle is standing against the tunnel wall and the TPRD blows the released gas against that wall. The chance of a gas cloud explosion is smaller with a hydrogen bus than with a natural gas bus and the chance of the tank bursting open is about the same as with a natural gas bus. With buses running on LPG, a tank rupture is a considerable extra risk because much more energy is released with LPG than with hydrogen and natural gas. The risks of a fire due to thermal runaway in battery vehicles are more or less the same as in a traditional vehicle fire.

Practical tests Li-ion batteries and Firefighting Techniques

Frank Leismann of the German Studiengesellschaft für Unterirdische Verkehrsanlagene (STUVA) talked about the research project Safety of Urban Underground Structures due to the Use of New Energy Carriers (SUVEREN), which ran from July 2017 to the end of 2020. An important part of this large project were field tests and CFD (computational fluid dynamics) simulations. During the practical tests, fire tests were carried out with Li-ion batteries and natural gas tanks, various fire-fighting techniques were tested and battery fires in underground parking garages were examined. The large-scale fire tests with batteries show that without intervention, the fire moves from cell to cell and eventually, after more than an hour, reaches the entire battery. The way the battery is installed in the car determines the spread of the fire. It also appears that the fire load depends on the type of battery and the type of cells. Other results are that early detection of a battery fire is difficult, that the released gases are combustible, but ignition does not take place quickly and that thermal runaway continues through the exothermic process, even when no fire is visible.

In the second series of tests, detection sensors and fire-fighting techniques were tested. The abatement techniques involved extinguishing techniques with water, such as sprinklers, low- and high-pressure mist, foam and the extinguishing agent F500, and techniques with gases such as aerosols, nitrogen, CO_2 and the extinguishing agent Novec. All techniques appear to work and can prevent the spread of a battery fire to other cells. Furthermore, the tests show that gas-based techniques lead to higher temperatures than water-based and that water in batteries does not cause electrical problems.

To properly anticipate fire with electric vehicles in underground parking garages, performance-based design is required. This requires, among other things, a reliable fire load of the current vehicle fleet, including electric cars. According to the researchers, it is good for the fire curve to assume a rapid development of fires, a heat release rate of approximately 7 MW during five minutes and a total burning time of approximately 45 minutes. Tests have already been carried out to get a good picture of the effects of a fire in parking garages. The results of this will be announced at the next STUVA conference.

In summary, Leismann states that battery fires are serious and difficult to extinguish, but are not significantly more dangerous than fires with traditional vehicles. This means that no additional facilities are required in tunnels equipped in accordance with current guidelines. Battery fires can be problematic for other underground infrastructure such as underground parking garages.

Toxic substances

Oliver Heger of the Austrian ILF Consulting Engineers discussed the quantitative consequences of battery fires in tunnels. Based on analyzes of the BRAFA project (see presentation Patrik Fößleitner, day 1), the conclusion is that battery fires lead to higher temperatures and higher emissions of CO, HF and NOx, but all remain below the risk limits and are therefore acceptable. The question is whether this applies in every tunnel. To determine this, a generally applicable model has been developed, with generalized fire curves, heat release rates and emissions of toxic substances. Based on this model, the researchers conclude that battery fires in tunnels certainly pose a risk due to the higher temperatures and emissions of toxic substances, but that the overall risk of these types of fires is no different from traditional vehicles on fire. Heger did note that this outcome is based on a relatively small number of fire tests. He therefore called on parties to provide data from their fire tests so that the research results can be better validated.

Future scenarios fleet

Holger Heinfellner of the Austrian Umwelt Bundesamt presented the research project 'Carbon-neutral Road Transport 2050', which was carried out by members of the European Road Transport Research Advisory Council (ERTRAC). These researchers have analyzed a number of scenarios for CO_2-neutral road transport in 2050. They looked at different propulsion technologies and fleet compositions and what effects each mix has on energy consumption. Two important concepts were applied in the analysis, tank to wheel and well to wheel. The first concerns the amount of energy required to drive the car and the second concerns the amount of energy required to produce one MW of 'generation energy', such as electricity, biofuel or hydrogen.

The three scenarios studied are highly electrified (battery vehicles and plug-in hybrid vehicles and heavy transport with 'mobile charging' systems), highly electrified including hydrogen (battery vehicles and vehicles with fuel cells) and hybrid (battery vehicles, plug-in hybrid vehicles and vehicles with a combustion and electric motor). In addition, four fuel scenarios were examined: biofuels, mixed fuels (bio and e-fuels), e-fuels (electricity) and limited fossil, based on the assumption that each scenario is CO_2-neutral, for example because fossil fuel is combined with underground CO_2. storage. Two scenarios for improving energy efficiency (optimistic and pessimistic) and two scenarios for electricity production in 2050 (fully sustainable and 1.5 Tech) were also used for the calculations. Assuming significant energy savings in 2050, the vehicle fleet will require 2050 between 730 to 1,900 TWh of energy (tank to wheel). Converted to well-to-wheel, depending on the various scenarios, this leads to an energy consumption of 900 to 6,000 TWh.

Based on these results, the researchers conclude that CO_2-neutral road transport will be possible in 2050 with various techniques, but will require radical changes. In addition, the energy efficiency increases with a larger share of electric vehicles. Furthermore, sustainable energy production is crucial to achieve CO_2-neutral transport. Another outcome is that hydrogen will be needed for heavy transport and long-distance transport.

8.2. ONGOING RESEARCH ON NEC IN THE NETHERLANDS

Known research initiatives in-country with regards the safety of alternatively fuelled vehicles (battery electric; Hydrogen; Gas)	**link/additional info**	Ongoing or Complete (and date of completion
Dutch Incident management guide	http://webshop.incidentmanagement.nl/wp-content/uploads/woocommerce_uploads/2016/01/REVI-JUNI-201	In Dutch, completed update 2019
Literature survey hydrogen in parking garages, by the Dutch Fire	https://www.ifv.nl/kennisplein/Documents/20210209-IFV-Hydrogen-cars-in-parking-garages.pdf	In English, Complete Feb 2021
Literature survey hydrogen in building, by the Dutch Fire research	https://www.ifv.nl/kennisplein/Documents/20201014-IFV-Safety-aspects-relating-to-the-use-of-hydrogen-in-	In English, Complete Okt 2020
Use of Immersing container, by the Dutch Fire research Institute	https://www.ifv.nl/kennisplein/Documents/20210224-IFV-Onderzoek-dompelcontainers.pdf	In Dutch, complete Feb 2021
Incident protocol Salvage companies	https://www.incidentmanagement.nl/Portals/0/Protocol%20Elektrische%20Voertuigen%202019%20-%202022	In Dutch, May 2021
Dashboard on incidents with alternatively propulsed vehicles, by the Dutcl	https://kerncijfers.ifv.nl/mosaic/kerncijfers-veiligheidsregio-s/incidenten-met-alternatief-aangedreven-voert	In Dutch, on air since May 2021
A draft amendment on the Dutch Building regulations on newly built	https://www.internetconsultatie.nl/verzamelwijzigingbbl2021	ongoing consultation In Dutch, June 2021
Electric and hydrogen cars in parking garages (English annex)	https://www.rijksoverheid.nl/binaries/rijksoverheid/documenten/rapporten/2020/02/06/risicos-in-	in Dutch, partly in English, complete 2020
Safety and electric passenger cars, CE-Delft	https://ce.nl/wp-content/uploads/2020/11/CE_Delft_200180_Safety_and_electric_passenger_cars_Def.pdf	In English, Complete Nov 2020
Incident methods, KPT	https://www.kennisplatformtunnelveiligheid.nl/bijeenkomsten/incidentdetectie-methodieken-europese-tun	
Dutch Hydrogen Safety Innovation Programme, Work Package 4	At the start of 2020, the Netherlands launched the four-year Hydrogen Safety Innovation Programme, which is a public-private partnership between the national government, network operators, emergency services, knowledge institutes and companies. The programme identifies safety issues in the area of hydrogen and proposes policies and agreements that allow these issues to be adequately addressed. The Safety Programme focuses on the national level but aims to implement international developments. The work concentrates around six working packages: WP1: harmonization of the permitting process for HRS by developing guidelines WP2: risk and incident management WP3: legal aspects, including the finding of white spots WP4: safety risks inventory for production, storage, transport and hydrogen use WP5: HAZID-studies on the use of hydrogen in public spaces WP6: International knowledge and lessons learnt More about WP4: safety risks inventory for production, storage, transport and hydrogen use Hydrogen is a well-known gas with which there is a lot of experience, especially in the chemical industry. The transition from natural gas to hydrogen as an energy carrier and its use by the general public requires acceptance of hydrogen as a safe substance under all possible (daily) conditions. To this end, it is necessary to make an inventory of all possible safety risks to which the general public may be exposed and to take appropriate measures. Within this theme, all possible safety aspects and risks are identified throughout the chain, from the point of production to the moment of use, and which measures must be taken to ensure that hydrogen can be implemented safely. Also risks arising from deliberate damage (vandalism/terrorism/etc.) of hydrogen facilities is considered Objective: The objective is twofold. Firstly, an overview of all possible safety risks associated with the production, storage, transport and use of hydrogen is made. Secondly, which measures are necessary to enable the introduction of hydrogen as a safe and reliable energy carrier on a large scale and thereby increase public acceptance. Research question: What are the safety aspects in the production, storage, transport and use of hydrogen	ongoing, 2020-2024

Safety working group of the Dutch intergovernmental charter on Zero Emission Buses	In The Dutch intergovernmental charter on Zero Emission buses it is agreed that all public buses are zero emission in 2030. As of 2025 all new public buses are ZE. Safety has been identified as one of five priority areas within this charter, therefore a working group on safety has been launched in 2021. Key focus of this working group is to provide an overview of all safety issues related to the deployment and use of ZE buses.	ongoing in 2021
Research on the impact of risks with hygrogen busses on the quantification of the risk. If necessary expanding the model of QRA-tunnels with scenarios with hydrogen releases		ongoing in 2021
ITF workshop standards for low and zero emission electric heavy duty vehicles: workshop presentations	https://www.itf-oecd.org/mapping-standards-low-and-zero-emission-electric-heavy-duty-vehicles-expert-wor	In English, Complete Feb 2021
ITF workshop standards for low and zero emission electric heavy duty vehicles: report	https://www.itf-oecd.org/sites/default/files/docs/regulations-standards-clean-trucks-buses_0.pdf	In English, Complete Sep 2021

World Road Association (PIARC)

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