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INFLUENCE OF ALTERNATIVE ENERGY CARRIERS ON TUNNEL SAFETY – A QUANTITATIVE CONSEQUENCE ANALYSIS

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ABSTRACT

The composition of road traffic is nowadays clearly dominated by petrol and diesel powered vehicles. However, one of the major goals against further climate change is the decarbonisation of road traffic by the use of vehicles with alternative energy carrier technologies. The currently most promising ones are the Li-Ion battery-powered vehicles, fuel-cell-powered vehicles and vehicles powered with internal combustion engines using hydrogen or liquefied natural gas. Although the latter do currently represent only a small share of the total traffic, it can be assumed that alternative powered vehicles will soon take on greater significance. Therefore, a deeper understanding of possible additional risks, especially in considering incidents in tunnel structures, is of greatest interest and is currently investigated in various research projects, such as [1], [2], [3]. In these projects, the focus lies only on one of the alternative energy carriers mentioned above. However, in order to obtain a thorough overview of relevant possible additional dangers as well as related consequences on the safety of tunnel users, the aim of the BASt-project FE 15.0675/2020/ERB [4] as well as of the present paper is to consider all relevant alternative powered vehicle types in order to identify possible need for adaption of the risk-analytical assessment method for road tunnels. To this aim, dangerous zones according to, for example battery fires, jet fires or vapor cloud explosions have been assessed by using numerical as well as analytical models. In the course of a detailed evacuation model, considering a large variety of agents with different velocities and respiratory volumes, the corresponding consequences of alternative energy carriers on tunnel users can be assessed. This paper will demonstrate and discuss in detail the foundation of the research project with focus on the evacuation simulation, as well as the resulting consequences analysis on tunnel users.

Keywords: Alternative energy carrier technologies, tunnel risk assessment, evacuation and consequence model, road tunnel, research project.

1. INTRODUCTION

Road traffic is currently clearly dominated by petrol and diesel-powered vehicles. The annually growing number of vehicles and increasing mileage result in a steadily increasing energy requirement. Therefore, the transport sector makes a significant contribution to greenhouse gas emissions. The decarbonization of road traffic through the establishment of climate-friendly alternatives as a substitute for petroleum-based fuels is therefore a basic requirement for achieving climate protection goals. The use of vehicles with new alternative energy carrier technologies, above all electric batteries, but also hydrogen and LNG (liquefied natural gas) are supposed to increase rapidly in the future. Moreover, as a result of the increasing urbanization the traffic is shifted to the underground.

Existing recommendations and regulations for tunnel safety, as well as methods for risk assessment however, have so far been limited exclusively to events in connection with vehicles operated by conventional energy carrier systems. In order to be able to maintain the existing level of safety in the future, the effects of events in road tunnels involving vehicles with alternative energy carriers must constantly be determined and evaluated. To this aim, the traffic composition now and in twenty years is discussed in section 2. Section 3 deals with leaks, collisions and vehicle fires in combination with alternative energy carrier technologies and the corresponding consequences on the safety of tunnel users is discussed in section 4. Results presented in section 5 can eventually be used to adapt the risk-analytical assessment method for road tunnels and to derive any necessary adjustments to the requirements for road tunnels.

2. TRAFFIC COMPOSITION – NOW AND IN 20 YEARS

In course of a thorough analysis of the existing vehicle fleet for the year 2020, a starting point for the development on the new car market could be found. The average value for the years 2016-2020 was used to quantify the found data, since due to the Covid 19 pandemic, the year 2020 alone can be assumed to not be representative in terms of new registrations. This analysis was carried out for the vehicle categories passenger cars, light trucks, heavy trucks and buses and data from the EU and worldwide studies were also applied.

All of the forecast studies that were analyzed in this regard showed that conventional energy carriers will become less important for all vehicle categories, but will nonetheless make up a large part of the vehicle fleet. The greatest change can be expected for passenger cars and buses, since a quarter of all newly registered vehicles already use energy carriers based on alternative energy sources.

Table 1 shows the relevance of the energy carrier types for each of the four vehicle types for the years 2020, 2030 as well as for the year 2040 and thus summarizes the forecasts identified in a clear form. Basically, it is difficult to reliably predict the vehicle mix to be expected. Many influencing factors, in particular leaps in technological development and political decisions, influence the assertiveness of the individual technologies and the forecasts presented show a currently valid trend rather than a reliable forecast.

Table 1: Relevance of energy carrier types to vehicle types for 2020, 2030 and 2040[1]

	Cars			**Light HGV**			**Heavy HGV**			**Bus**		
	2020	**2030**	**2040**	**2020**	**2030**	**2040**	**2020**	**2030**	**2040**	**2020**	**2030**	**2040**
Conventional	high	high	medium	high	high	high	high	high	high	high	high	high
Hybrid[2]	high	medium	medium	low	medium	medium	low	medium	low	high	medium	high
BEV	medium	high	high	low	medium	medium	low	low	low	medium	high	high
CNG	low	low	low	low	low	low	low	low	low	low	low	medium
LNG	low	low	low	low	low	low	low	low	medium	low	low	medium
LPG	low	low	low	low	low	low	low	low	low	low	low	low
FCEV	low	low	medium	low	low	medium	low	low	medium	low	low	medium
H_2	low	low	low	low	low	low	low	low	medium	low	low	medium

[1] Conventional: Gasoline, Diesel, BEV: battery electric vehicle, CNG: compressed natural gas, LNG: liquified natural gas, LPG: liquified petroleum gas, FCEV: fuel cell electric vehicle,
[2] Note, that the carrier "Hybrid" includes all different types of hybrid vehicles

3. IDENTIFICATION OF ADDITIONAL RISKS DUE TO ALTERNATIVE ENERGY CARRIERS

Based on traffic mix forecast for the year 2040 presented in Table 1, possible tunnel events involving battery-powered electric vehicles, fuel cell-powered vehicles and vehicles with internal combustion engines (CGH2, LNG), were investigated risk-analytical. This was done in constructing as a first step simplified exemplary hazard trees according to accidents involving vehicles with the mentioned alternative energy carriers. Each of the energy carriers exhibit special physical properties that are directly related to the type of storage and may result in differentiated types of risk when involved in an accident.

As an example, Figure 1 shows the schematic representation of a hazard tree according to the battery electric engine and it will now be used to discuss the different hazard-tree branching-points in a bit more detail. For each of the alternative energy carrier types mentioned above, four different vehicle types (car, light truck, heavy truck, bus) have been considered according to their respective relevance shown in Table 1. The splitting in four vehicle types is of main importance since not every new energy carrier system is suitable for every vehicle type. For example, due to the high weight of the battery a battery-powered heavy transporter is not an alternative to a heavy truck that runs on a conventional energy source. Furthermore, the energy storage devices of different vehicle types may be of different sizes and most often are placed in different positions and thus may lead to differentiated danger zones or hazards. The next branching points in the hazard tree relate to the type of event. Is the event under consideration a fire incident – a hot incident – or a purely mechanical one – a cold incident. Is the built-in safety device functional or damaged respectively not functional. The branching point concerning the object of hazard does in addition to the risk of tunnel users also consider the risk of third-party rescue teams as well as the risk for the tunnel infrastructure. However, the focus lies on the last branching point, the potential hazard types - such as heat, toxic gases, acid, electricity, overpressure, the effects of a rapidly expanding flame front (fireball) and cryogenic burns.

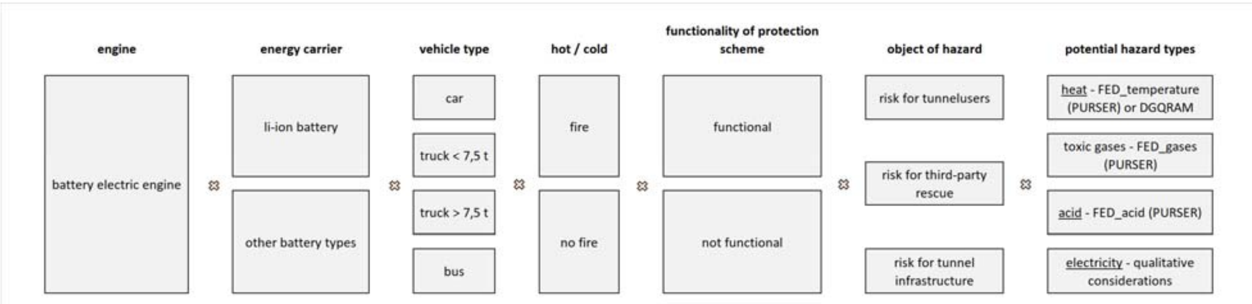

Figure 1: Battery electric engine hazard tree – schematic representation

4. RISK ANALYSIS

Based on the very general hazard trees presented in chapter 3 in combination with available experience reports and expert assessments event trees were developed. The latter contain a manageable number of relevant hazard scenarios. Depending on the type of scenario, numerical methods such as numerical flow models, analytical models or already existing models have been used. Necessary adaptations have been made to identify the influence of vehicles with alternative energy carriers on the hazard extent in the tunnel structure in order to estimate the potential extent of damage with regard to people in the tunnel.

4.1. Determination of frequencies

Initially, it should be noted that the proportion of alternatively powered vehicles is too small to derive frequencies based on statistical methods, so that estimates of the probability of occurrence for each hazard scenario can currently only be made on the basis of qualitative assessments. However, this may change in the future and therefore the possibility for considering adapted data has been provided.

Wherever possible, frequencies from the general road tunnel risk analysis in accordance with the adapted BASt-booklet B66 [5] have been used in quantifying the event tree branches described above – for example in the collision and fire frequencies, or in the distribution of fire sizes for truck fires. Where there have been no corresponding frequencies available, estimates have been made by the experts involved in the project by taking into account the findings and assumptions from similar research projects.

4.2. Damage extent modeling of alternative energy carriers

Li-Ion battery fire

In the case of Li-ion battery fires, analogous to fires in conventional vehicles, three main hazards with regard to personal safety were considered. These refer to the danger of heat, restricted visibility (smoke gases) and the danger of inhaling toxic substances. As a result, the model fire curves defined in the research project BRAFA [1] and the associated pollutants released were used as the basis for the three-dimensional CFD simulations.

Hydrogen VCE

In case of an accident involving a hydrogen-powered vehicle, the hydrogen tank can rupture due to the mechanical impact or due to thermal stress (in case the safety device on the tank is not working) and a vapor cloud explosion (VCE) may occur. When modeling the VCE, two different hazards were considered: the hazard of a fast expanding fireball and the overpressure hazard. The hazard area corresponding to the fireball was estimated with an experimentally founded relationship between the diameter of the fireball and the mass involved [6]. To estimate the overpressure hazard area, the generally valid relationship between overpressure and distance from the origin of the detonation corresponding to hydrogen tank explosions was used [7].

Hydrogen jet fire

If a hydrogen-powered vehicle catches fire and the temperature at the safety valve reaches the threshold value, hydrogen is released. Due to the already existing fire, the released hydrogen is immediately ignited and consequently leads to a jet fire. The corresponding risk area was estimated for all considered vehicle types by using model results that were experimentally verified in [8]. In particular, the different number of tanks, the different tank volumes, the possible different storage pressures and possible different blow-out directions were explicitly taken into account.

LNG BLEVE

The overpressure of an exploding LNG tank in the tunnel was modeled with the well-established TNT equivalence model (similar to the OECD/PIARC DG-QRAM model [9]).The existing mass of LNG in the tank is converted into an equivalent mass of TNT. From numerous experiments relating to the damage caused by TNT explosions, the damage respectively the hazard area of the LNG BLEVE (Boiling Liquid Expanding Vapor Explosion) was estimated.

4.3. Evacuation model

The applied, elaborate and in general terms defined evacuation model is now discussed in a nutshell. Instead of repeating the evacuation simulation for statistical reasons with a changed arrangement of so called agents along the tunnel, at each position in the tunnel, the number of persons is decomposed into 18 different agent types. This number results from assuming three age categories for both genders, i.e. six agents. Further on, for each of the six agents, three evacuation speeds are assumed – leading to 18 different agent types. Moreover, at each position in the tunnel, for each of the 18 agent types, five starting times are considered. It can be assumed, that agents going by car or by truck as well as the first part of bus passengers are able to start their respective evacuation process without any delay. The evacuation start time according to the second part of bus passengers is assumed to be shifted via 10 seconds, the third part via 20 seconds and the fourth via 30 seconds. In addition, 3% of the persons (sum of passenger car occupants, HGV occupants and Bus occupants) are assumed to stay in their vehicle and are not evacuating due to limitations in mobility or because they behave incorrect.

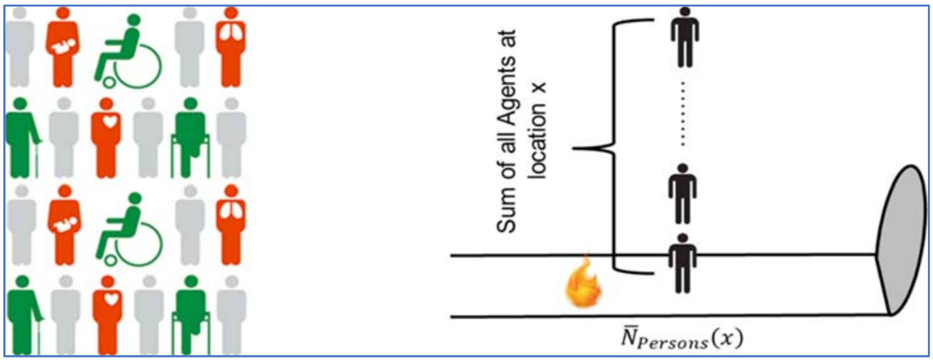

Figure 2: Evacuation model: Agent configuration

4.4. Survivability model

Each agent starts its individual evacuation process from its respective starting location into the direction of the next emergency exit. However, it is assumed that the agents do never evacuate across the fire. In this case they are assumed to decide to take the longer, but safer, way to the emergency exit in opposite direction.

For every evacuation point *x* in the tunnel, success or failure is calculated for each of the different agent types. This is done for all the distinct mentioned dangers according to the different energy carriers – conventional fire, Li-Ion battery fire, hydrogen VCE, hydrogen jet fire and LNG BLEVE. In case of conventional fires as well as for battery fires, the FED / FIC[3] approach according to Purser and McAllister [10] is used, i.e. inhaled toxic fire products are summed up for each agent along its individual evacuation path and if one of the values exceeds the respective fatality threshold before the emergency exit or the tunnel portal is reached, the agent is considered as incapacitated. As to identify the fatality zones of the jet fire scenarios or the explosion scenarios, various different danger zones, depending on the size as well as the position of the tanks, were calculated. If in course of the evacuation process, an agent happens to be within one of the danger zones, the agent is considered as incapacitated.

5. EVALUATION AND INTERPRETATION OF RISKS

In order to be able to evaluate and identify possible additional risks due to alternatively powered vehicles in the tunnel, a suitable hypothetical comparison tunnel (one-way traffic tunnel without

[3] FED: Fractional Effective Dose; FIC: Fractional Irritant Concentration

traffic congestion) based on the results of the BASt-research project FE 15.0663/2019/ERB [11] was chosen. On the basis of this tunnel, a relative assessment approach was pursued, in which different safety levels were compared through a relative comparison of different vehicle fleet constellations. By using a relative evaluation approach, the influence of imprecision on the evaluation result can be minimized and accordingly even the smallest safety-related changes can be made visible.

In order to objectively compare the potential risk of the individual energy carriers, the determined risk values for each vehicle type and each energy carrier technology have been compared, whereby it has been assumed in each case that the vehicle type is operated to 100% with the respective energy carrier technology. Representative for all vehicle types, the results according to all three, most promising alternative engines according to cars are shown in Figure 3 and the results show that in comparison to the conventional engine, there can no relevant increase in the overall risk be identified. Fire and explosion risks are not relevant for the selected comparison tunnel in absolute terms since the major part of the risk is due to mechanical incidents – collisions without fire development or explosion. This is due to the tunnel being a unidirectional tunnel with longitudinal ventilation at critical velocity as well as due to the fact that mechanical incidents do statistically occur ten times more often than fire incidents. However, in considering the pure fire and explosion risks there is a significant increase in risk from gas-powered vehicles visible. This increase in fire risk is mainly due to the additional jet-fire scenarios taken into account in considering the fuel-cell engine.

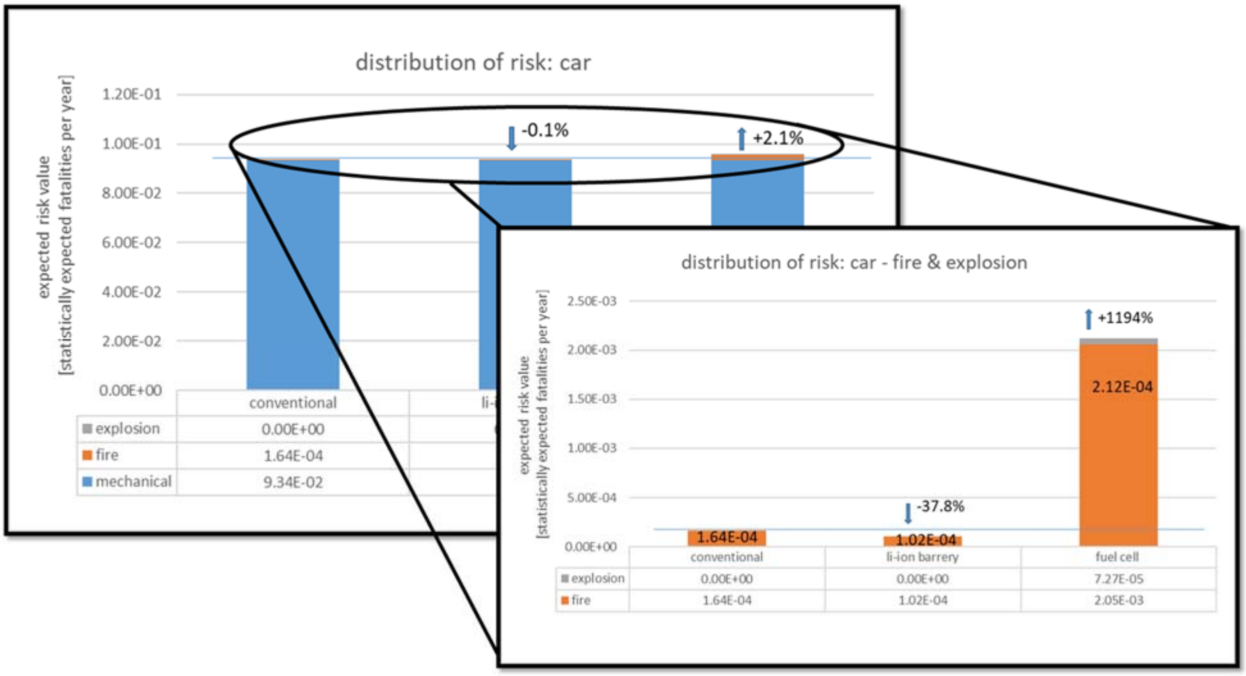

Figure 3: Comparison of total risk respectively fire and explosion risk according to the three alternative energy carriers that will most probably be used for cars in future. 100% share for each propulsion technology for each vehicle type, here the car, is assumed

In calculating the risks according to the predicted share of the respective energy carries in the total traffic, the results presented in Figure 4 show that no increase in the overall risk for the traffic forecast compared to 100% conventional engines can be derived. As has already been mentioned before, fire and explosion risks are not relevant for the considered tunnel in absolute terms, but can increase significantly for changed shares of vehicles powered by alternative energy carriers in the tunnel. The extent to which the increase in the risk according to fire and explosion is relevant under other conditions or to what extent the overall risk increases with changed conditions - especially for tunnels with a relevant proportion of traffic jams - is still to be clarified.

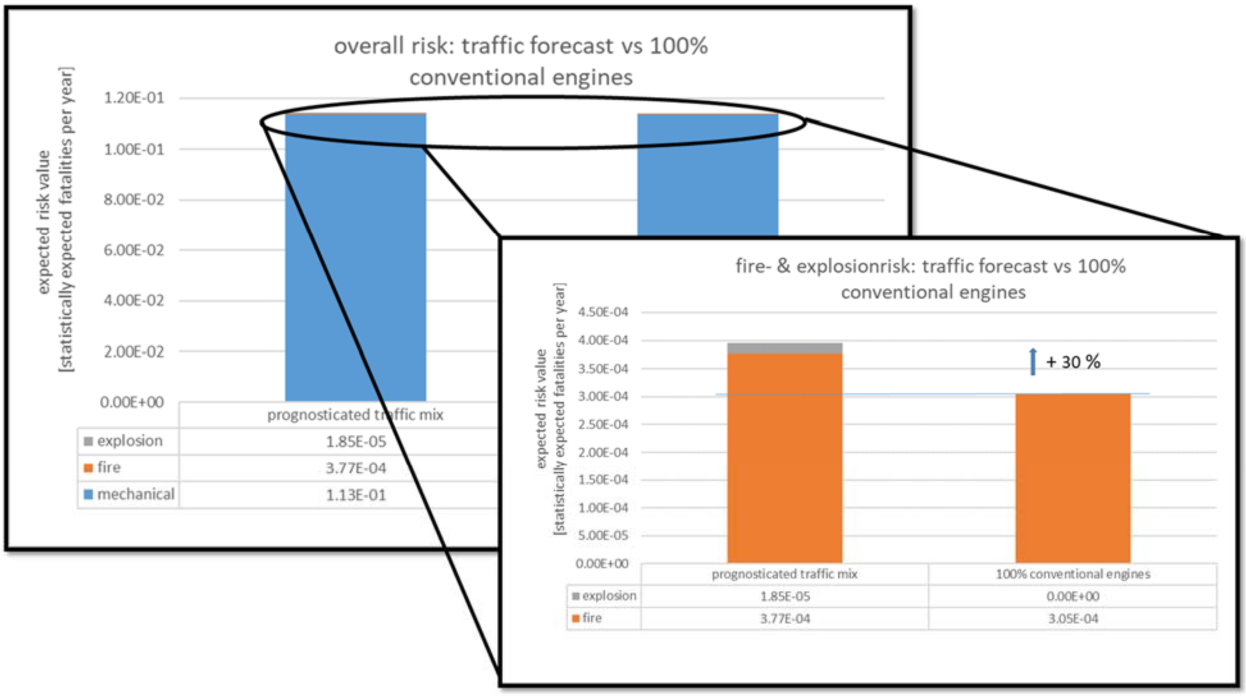

Figure 4: Comparison of the total risk as well as the fire and explosion risks according to the traffic forecast 2040 and for 100% conventional engines

6. SUMMARY AND CONCLUSION

The current paper outlines a thorough risk assessment procedure how to identify possible additional risks due to alternatively powered vehicles in tunnel structures. Based on the research efforts, it can be concluded that, according to the current state of knowledge, battery-powered vehicles do not cause a significantly higher fire risk than conventional vehicles. According to gas-powered vehicles, the risk assessment showed that the overall risk remained almost the same as for conventional powered vehicles; however, a significant increase in the risk regarding to fire and explosion scenarios could be identified. Even if the jet-fire, the VCE or the BLEVE incident are extremely unlikely from today's perspective, the same statement applies to them as to large fire events, namely that they may not be relevant in the overall risk context, however, they will rouse socially a lot of attention and have therefore to explicitly taken into account. Therefore, the development of the vehicle share of these energy sources should be regularly reviewed in order to be able to take precautions here accordingly at an early stage.

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