HYDROGEN POWERED VEHICLES IN A TUNNEL INCIDENT – RISKS AND CONSEQUENCES

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DOI 10.3217/978-3-85125-996-4-45 (CC BY-NC 4.0)

ABSTRACT

The mobility sector is subject to a massive transition from fossil fuels to new energy carriers. The driving force is the reduction of greenhouse gas emissions in order to minimize the impact on global climate. Hydrogen represents a promising fuel as it can be used in combination with internal combustion engines as well as fuel cells. However, due to its physical and chemical properties it potentially poses high risks in an incident scenario. This mainly refers to its wide flammability limits as well as the common way of storage at nominal pressures of 350 bar (busses and trucks) and 700 bar (passenger cars). This paper presents the findings of the Austrian research project "HyTRA" that aimed at an evaluation of potential hazards in tunnel incident scenarios involving hydrogen powered vehicles. Five scenarios with a high potential risk have been identified and investigated related to the consequences for tunnel users and the tunnel facility. Ultimately, a comparison to incident events with conventional vehicles gives information about the consequences for the level of tunnel safety.

Keywords: hydrogen, tunnel safety, incident scenarios, consequence evaluation, risk assessment

1. INTRODUCTION

Tunnel safety represents a topic of special concern, as past tunnel incident events [1] have shown the hazard potential of such scenarios. Thus, it is inevitable to investigate new factors, which might have an impact on the safety level. The transition from fossil fuel powered vehicles to alternatively powered vehicles represent such a new factor. Battery electric vehicles have already penetrated the market and hydrogen powered vehicles (H_2 vehicles) are expected to become relevant in the future. The latter use either combustion engines or fuel cells to convert the chemically stored energy of hydrogen into kinetic energy for the vehicle. The storage system probably is the most critical part of today´s hydrogen technology. This is due to the physical and chemical properties of hydrogen, which require hydrogen to be stored liquid at very low temperatures or pressurized at a high-pressure level. The latter represents the more common way of hydrogen storage. The nominal storage pressure for busses and trucks is 350 bar. For passenger car application this value increases to 700 bar. Obviously, in an incident situation both, the mechanical energy due to high pressure as well as the chemical energy of hydrogen may cause severe harm.

Due to the importance of this topic, a variety of experimental and/or analytical and numerical investigations with respect to different hydrogen scenarios have been carried out in past research projects. This includes investigations on jet-flames, hydrogen cloud explosion as well as tank ruptures. In recent years several research projects have been funded by the European

Union [2][3][4]. These projects covered safety strategies, the evaluation of risk and the development of powerful tools, which can be used for risk assessment in future tunnel projects. Further research output was published by [5] where analytical calculations that aimed at quantifying temperatures, pressures and heat fluxes caused by incidents of vehicles powered by gaseous and liquified fuels were conducted.

However, there are still many uncertainties and the transfer of knowledge to tunnel operators, tunnel users and emergency services must be promoted. In order to reduce the uncertainties, the Austrian research project HyTRA aimed to evaluate incident scenarios with hydrogen-powered vehicles and to determine the consequences for human health and the tunnel infrastructure in the specific context of Austrian road tunnels. For this reason, extensive literature and data collection, analytical and numerical investigations as well as a detailed risk assessment have been conducted. Finally, technical and organizational measures to avoid hydrogen scenarios or to mitigate the consequences were listed and evaluated in terms of efficiency, range of influence and implementation effort. This paper provides a brief overview of the main findings of the project. The final report of the HyTRA project including detailed explanations is available via [6].

2. HYDROGEN POWERED VEHICLES

2.1. Technology Overview

H_2 vehicles operate by converting the chemically stored energy of H_2 into kinetic energy for vehicle propulsion. There are two primary types of powertrains: H_2 internal combustion engine vehicles (H_2 ICEVs) and Fuel Cell Electric Vehicles (FCEVs).

H_2 ICEVs employ internal combustion engines akin to those found in traditional gasoline-powered cars. However, instead of burning gasoline, these vehicles combust H_2 gas within the engine to generate mechanical power, propelling the vehicle forward. They serve as a transitional solution between conventional ICEVs and FCEVs, capitalizing on existing infrastructure and manufacturing capabilities.

On the other hand, FCEVs utilize H_2 by generating electricity via a chemical reaction with oxygen, powering electric motors. The powertrain of a FCEV comprises H_2 tanks for energy storage, a battery serving as an energy storage and converter, a fuel cell acting as an energy converter, several voltage converters, an electric motor, transmission and mechanical drive for the wheels. FCEVs have higher efficiencies than combustion technologies and are classified as zero-emission vehicles, emitting solely water vapor and air through the exhaust. Additionally, these vehicles offer rapid refueling times and long driving ranges. Figure 1 illustrates examples of serial vehicles on the road.

Figure 1: Selected applications of FCEVs [7][8][9][10][11][12]

H_2 ICEVs have yet to enter series production, contrasting with the availability of several models of FCEVs designed for road use. While there is notable interest in medium and heavy-duty FCEVs, the production of light-duty FCEVs, such as the Toyota Mirai 2 and the Hyundai Nexo, is already underway. By 2022, the global stock of FCEVs surged by 40% compared to 2021, surpassing 72,000 vehicles. Among these, approximately 80% are cars, while 10% trucks and nearly 10% buses. Notably, in 2022, the fuel cell truck segment experienced a rapid 60% growth rate, outpacing the expansion seen in cars and buses [13].

2.2. Hydrogen Storage System

H_2 vehicles utilize H_2 as an energy carrier. H_2 is a colorless and odorless gas, possessing the lowest density among all elements and being approximately 14 times lighter than air. However, due to its low density, storage and transportation with sufficient energy density pose significant technical and economic challenges. Common methos of H_2 storage include:

- Gaseous compressed hydrogen (CGH_2) stored in pressure vessels at pressures ranging from 350 to 700 bar,
- Liquid cryogenic hydrogen (LH_2) stored at temperatures below −252.85 °C (20.3 K) in cryogenic containers,
- H_2 stored in chemical or physical compounds, primarily in or on solids or liquids, which are currently in the laboratory stage. [14]

The state-of-the-art storage technology for on-road applications is CGH_2, currently utilized in all series vehicles. In this method, H_2 is compressed to pressure levels up to 700 bar. Other storage technologies are still in a prototype phase and exhibit a low technology readiness level. Gaseous storage constitutes a closed system, enabling the storage of H_2 over extended periods without loss. Pressure vessels typically adopt a cylindrical shape for favorable stress distribution. For mobile applications, type 3 (aluminum liner wrapped in carbon fiber) and type 4 (plastic liner wrapped in carbon fiber) tanks are predominantly used due to their lightweight design, as depicted in Figure 2. Type 5 tanks (linerless, solely carbon fiber) are currently under development and not yet ready for serial application.

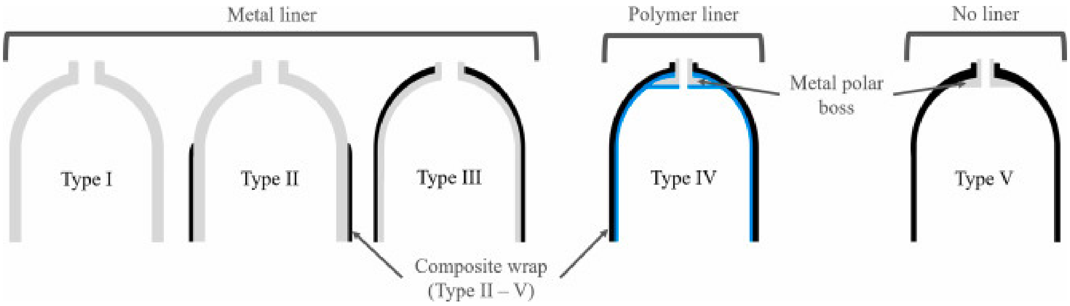

Figure 2: Types of hydrogen storage tanks for CGH2 [15]

Compared to diesel, the gravimetric energy density of H_2 is about 3 times higher with a value of 33,33 kWh/kg. To meet the usual driving range of a passenger car, a H_2 storage capacity of up to 6.5 kg is needed for passenger cars. Due to the fact, that the well-to-wheel efficiency of a FCEV is about twice of an ICEV, the total stored chemical energy in a FCEV is about 2 times lower.

Typical specification of CGH_2 storage systems for various road transport applications are defined in Table 1 and are used for the subsequent damage analysis in section 4.

Table 1: Vehicle types and tank parameters considered in the subsequent damage analysis (see section 4)

Vehicle Type	Details	Single Tank	Total Storage System
Passenger Car	3 tanks at 700 bar	52 Liter and 2,1 kg	157 Liter and 6,3 kg
Heavy duty truck	7 tanks at 350 bar	192 Liter and 4,6 kg	1342 Liter and 32,6 kg
Bus	5 tanks at 350 bar	313 Liter and 7,5 kg	1563 Liter and 37,5 kg

In a hydrogen storage system (HSS) multiple tanks can be interconnected. Alongside the tanks themselves, various components such as valves, pipework, couplings, screw fittings, and sensors are employed to monitor pressure, temperature, and tightness, as depicted in Figure 3.

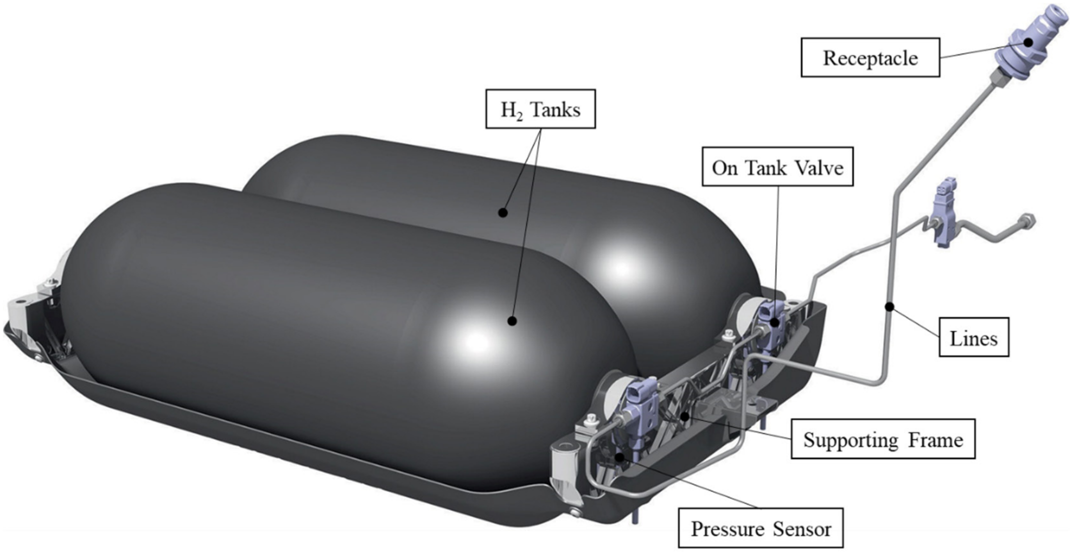

Figure 3: Automotive 700 bar compressed gaseous hydrogen storage system [16]

H_2 vehicles have additional hazards like fire and explosion hazards due the onboard stored H_2. The most critical component in terms of chemical and pressure energy is the H_2 tank. To ensure safe operation and approval for road traffic, these components must undergo design, manufacturing, testing, and maintenance in compliance with relevant codes and standards.

Within the European Union (EU), regulations such as (EU) 2019/2144, (EU) 2021/535 and UN Regulation No 134 govern the type-approval process of H_2 vehicles and their components, focusing on safety-related functions. Here is a summary of the most crucial test procedures for tank approval [17]:

- Fire test: The tank should vent through the Thermally-activated Pressure Relief Device (TPRD) and withstand exposure to an engulfing bonfire without failure.
- Hydrostatic burst test: This test determines the burst pressure, which should be at least 2.25 times the nominal working pressure for a duration of at least three minutes.
- Ambient pressure cycling test: H_2 tanks must not leak or rupture before undergoing 11,000 fill cycles, representing a 15-year life of use.

These rigorous testing procedures ensure the reliability and safety of tanks, contributing to the overall safety of H_2 vehicles on the road.

In the event of a thermally induced rupture of the tank in a H_2 vehicle incident, there is a risk of harmful and potentially lethal overpressures in the vehicle's vicinity and along the tunnel. To mitigate this risk and prevent intolerable pressure buildup within the tank during a surrounding fire, it is imperative to equip the tank with a TPRD.

The TPRD is designed to activate thermally, typically triggered at around 110°C, and remains non-closable once activated. Upon activation, hydrogen is released through a defined opening cross-section within the TPRD, typically with a diameter ranging from 2 to 5 mm. The released H_2 flows into the environment in a controlled manner via a vent line. It is crucial that the opening of the vent line is not directed towards any ignition sources, the passenger compartment, the wheel housing, the front, the sides, or horizontally towards the floor of the vehicle [17].

Under UN Regulation R134, the functionality of the tank equipped with the TPRD must be verified through the bonfire test, as depicted in Figure 4. During this test, the tank is pressurized to the nominal working pressure (NWP) and subjected to fire exposure. Initially, the tank endures a 10-minute localized fire before progressing to an engulfing fire stage. The diameter of the TPRD is chosen so that the storage pressure drops below 10 bar before tank failure due to fire exposure. Importantly, there should be no additional release resulting from leakage (excluding release through the TPRD) that leads to a flame exceeding 0.5 m beyond the circumference of the applied flame. [17]

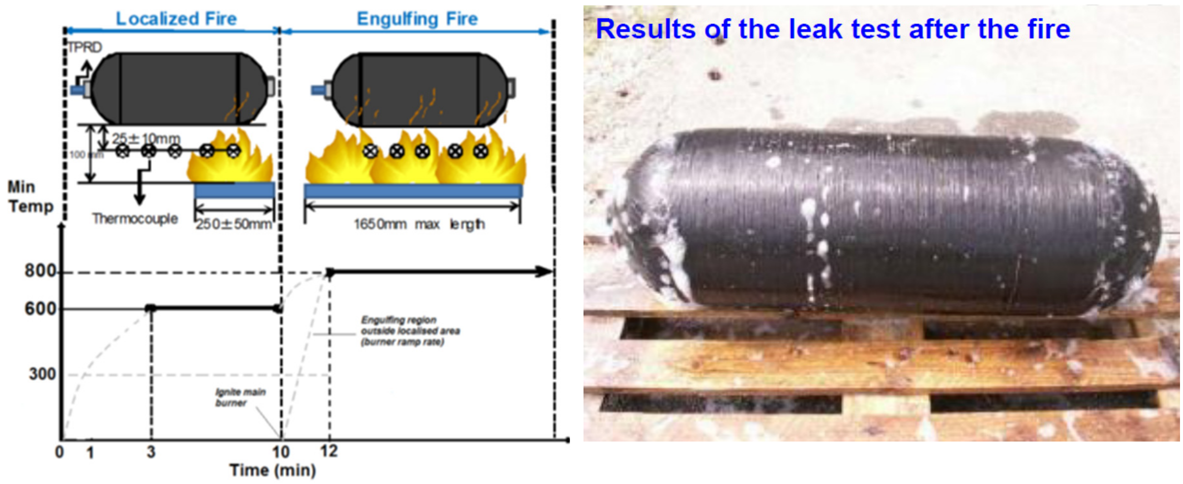

Figure 4: Bonfire test of the tank and valve in accordance with UN Regulation No 134 (left) and the tank after the test (right) [18]

In the event of a TPRD malfunction, combined with sufficient external heat, the pressure within the tank may exceed its burst pressure, potentially resulting in a tank rupture. This rupture can unleash a blast wave that propagates along the tunnel, causing severe damage to tunnel equipment and posing serious threats to human safety, potentially resulting in lethal effects. Furthermore, a tank rupture can also lead to thermal effects, manifesting in the form of a fireball, in addition to the mechanical stresses exerted.

Conversely, if the TPRD functions properly and prevents tank bursting, H_2 is released with high velocities due to the high storage pressure and the small opening of the relief device. This rapid release can result in the formation of a jet flame if the released H_2 ignites. Given the low ignition energy required for H_2 (only 0.017 mJ) and the presence of an underlying fire that triggered the TPRD, ignition of the H_2 jet is highly likely. Such H_2 jet fires pose a distinct hazard, with direct contact causing severe injuries and intense pain, as the stoichiometric combustion temperature of H_2 (2130°C) far exceeds the temperatures of typical hydrocarbon fires. Additionally, H_2 flames are challenging to detect due to the lack of electromagnetic radiation in the visible spectrum.

In instances where H_2 is released unignited from the pressure relief device or any other part of the storage system, a gas cloud forms, propagating along the tunnel. With a lower flammability limit of 4 Vol.% and an upper flammability limit of 76%, there is a significant risk of such a gas cloud forming a flammable or explosive mixture within the tunnel. [19] If exposed to a sufficient ignition source, this cloud can trigger a vapor cloud explosion, further escalating the hazard.

In summary, three hazardous scenario types are associated with H_2 incidents in tunnels: tank rupture, H_2 jet flame, and H_2 vapor cloud explosion. Each presents unique risks and requires careful consideration in tunnel safety planning and mitigation strategies.

3. RISK SCENARIOS

The criticality of such events in terms of passenger safety strongly depends on the boundary conditions, and in particular the scenario timeline, under which such incidents are most likely to happen. To work out the relevant scenario boundary conditions as well as incident timelines, a simplified event-tree analysis has been applied. In this analysis an incident scenario has been defined by a set of relevant scenario parameters that contribute to the accident outcome. For the purpose of identification and analysis these parameters are categorized into three groups – accident initiators (e.g. incident type), consequence factors (e.g. type of release and time of ignition), tunnel factors (geometry, operational parameters) and vehicle factors (vehicle size, H_2 storage parameters).

To work out the relevant scenario conditions, a simplified event-tree analysis has been applied. All resulting scenarios have been assessed qualitatively with respect to their probability of occurrence and their potential consequences on tunnel users. A quantitative assessment of the probability of occurrence was not carried out as no statistical data is available on these events. Twelve scenarios are identified as relevant for tunnel safety. Five of these twelve relevant scenarios have been categorized with high priority. For comparison, a conventional scenario (gasoline vehicle) of a full vehicle fire (vehicle body and energy carrier) and a vehicle-body fire have been added, see Table 2.

Table 2: Basic scenarios for further consideration in the quantitative consequence analysis

No.	Scenario Name	Scenario description
0.1	Conventional fire	Full conventional vehicle fire (vehicle body and energy carrier)
0.2	Vehicle body only	Vehicle body only (no energy carrier)
1	H_2 tank rupture (mechanically triggered)	Collision of a H_2 vehicle with immediate tank rupture
2	Gas cloud explosion (leakage)	Unignited release of H_2 through a leakage of the tank system with delayed ignition
3	Gas cloud explosion (TPRD)	Vehicle-body fire of a H_2 vehicle with unignited H_2 release through the TPRD and delayed ignition of the H_2 cloud
4	H_2 jet-fire	H_2 release through TPRD and immediate ignition of the H_2 cloud and the vehicle body
5	H_2 tank rupture (thermally triggered)	Vehicle body fire of a H_2 vehicle and tank rupture due to a malfunction of the TPRD

4. CONSEQUENCE ANALYSIS

Aforementioned scenarios relate to three different hazards: hydrogen jet-flames, tank burst and a hydrogen cloud explosion. Each of these hazards has been investigated in detail. In a first step, an extensive literature study provided available information. In case of missing information, analytical and numerical calculations were performed to fill the gaps. In the subsequent risk assessment, the comparison to a conventional fire provided information about the potential consequences and allowed to estimate the overall risk.

4.1. Harm criteria

To analyze potential consequences to tunnel users caused by H_2 incidents harm distances, representing the minimum separation of a person from a hazard origin to avoid negative consequences, where estimated. Harm to people may be caused by high temperatures, (radiative) heat fluxes or a mechanical impact (pressure wave). In literature, different information exists about the consequence of certain temperature, heat flux or pressure levels. In HyTRA harm criteria according to Table 3 have been taken into account when defining the above-mentioned harm distances.

Table 3: Harm criteria related to high temperatures, heat fluxes and pressure impact.

Temperature	70°C	No harm
	114°C	Severe pain, exposure no longer than 5 min
	149°C	Loss of escape capability due to breathing issues
Heat flux	1.58 kW/m²	No harm
	4.73 kW/m²	Severe pain, loss of escape capability after some minutes
	35.0 kW/m²	Fatal effect after 10 sec.
Pressure	8 kPa	no harm criterion
	13.8 kPa	threshold for eardrum rupture
	103.4 kPa	threshold for lung hemorrhage

4.2. Jet-flames

In case of a thermal impact on the hydrogen tank system that would cause an impermissible pressure and lead to tank bursting, hydrogen should be released via thermally triggered safety valves (TPRD). This represents some kind of intended scenario in a fire event. The hydrogen released is most likely ignited by the frictional heat or the heat input from the fire. This leads to the formation of a hydrogen jet-flame, which for two reasons represents a hazard. On the one hand combustion temperatures above 2,000°C lead to massive burns in a direct exposure. Furthermore, the (radiative) heat flux may as well cause severe or fatal harm. Both criteria must be taken into account when determining the harm distances caused by a hydrogen jet-flame. The calculations of the flame length and the heat flux were done by HYRAM+ software [20] and an analytical tool developed in the course of HyTunnel-CS project [4] was employed. Both quantities were determined for different combinations of storage pressure and TPRD sizes. When comparing harm criteria for fatality, it turned out that the temperature criterion is decisive if an undisturbed horizontal release is assumed. Table 4 shows the comparison of harm distances for both criteria.

Table 4: Harm distances (fatal consequences) caused by a hydrogen jet-flame. [6]

Hydrogen storage system	Temperature (> 149 °C)	Heat flux (> 35 kW/m²)
350 bar / 2.25 mm TPRD	20.2 m	7 m
350 bar / 5.00 mm TPRD	34.3 m	15 m
700 bar / 2.25 mm TPRD	28.3 m	9 m
700 bar /5.00 mm TPRD	43.9 m	18 m

4.3. Tank burst

In case of an unacceptable mechanical impact due to a collision or a malfunction of the TPRD in a thermal event, a tank burst may occur. Such a scenario leads to a disruptive pressure wave propagating throughout the tunnel and causing severe harm to people. Because of the severity of this scenario, it was deeply investigated in the HyTunnel-CS project. Figure 5 shows the decay of overpressure in a tunnel for distances of 0 m to 1,500 m from the point of tank rupture [7]. Moreover, harm distances according to criteria defined in Table 3 are added in red.

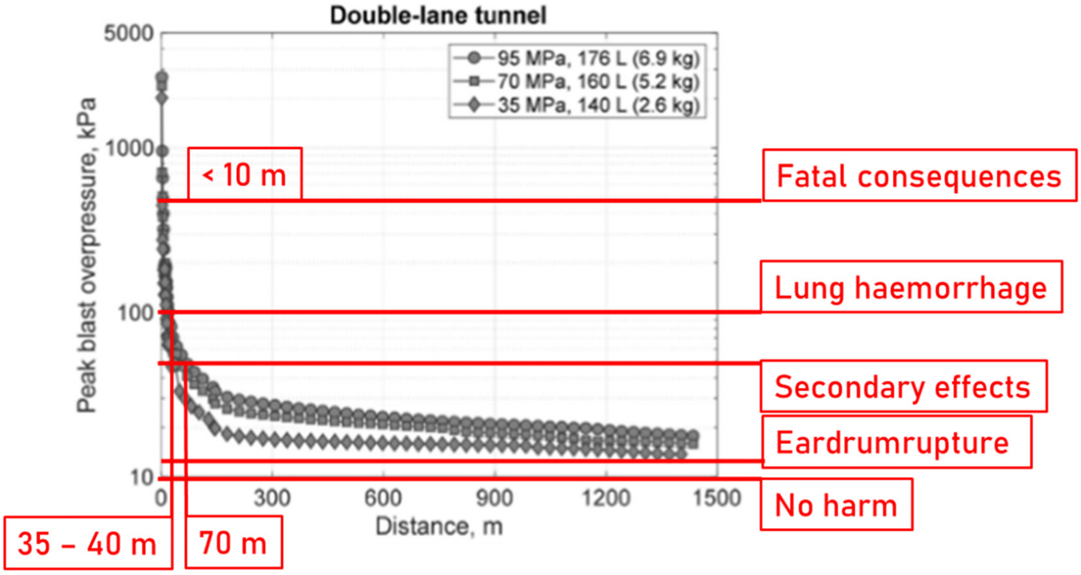

Figure 5: Peak overpressure as a consequence of a hydrogen tank rupture and harm distances on basis of harm criteria according to Table 3. [4]

4.4. Hydrogen cloud explosion

Although hydrogen is characterized by a very low activation energy, it cannot be ruled out that hydrogen will also be released unignited. In such a case it is most likely that, due to strong buoyancy forces, hydrogen will accumulate beneath the tunnel ceiling and form a hydrogen cloud. Within a range of 4 - 76 Vol.% hydrogen in the air, one can speak of a flammable cloud. This flammable cloud moves driven by the tunnel air flow and will ignite when getting in contact with an ignition source. A small electric impulse (fans) or a hot surface (non-LED bulbs) is sufficient to ignite the hydrogen cloud. However, due to the movement of the hydrogen cloud, the point of ignition is not necessarily identical to the release point. Hence, the definition of harm distances is quite complex.

The more effective way to investigate the hydrogen cloud scenario, is to put the focus on the hydrogen cloud formation and to determine whether critical hydrogen concentrations are reached under realistic tunnel operation conditions. For this reason, a series of numerical investigations were conducted. These simulations mainly covered the release from a passenger car at different tunnel air speeds (no ventilation, 1 m/s and 2 m/s according to the Austrian guideline RVS 09.02.31 [21]). Traffic induced airflow characterized by a transient air speed profile was also taken into account in another simulation run. In addition, one single simulation considered the release from a hydrogen driven bus. This simulation aimed at determining maximum hydrogen concentrations in a tunnel, as the entire hydrogen inventory was released in a short period of time.

Figure 6 illustrates the hydrogen cloud formation at different longitudinal air speeds. Apparently, there is a strong impact of the longitudinal air flow on the extension of the hydrogen cloud. An air speed of 2 m/s significantly reduced the hydrogen concentration at the ceiling and led to concentrations below the lower flammability limit apart from the direct vicinity of the release point.

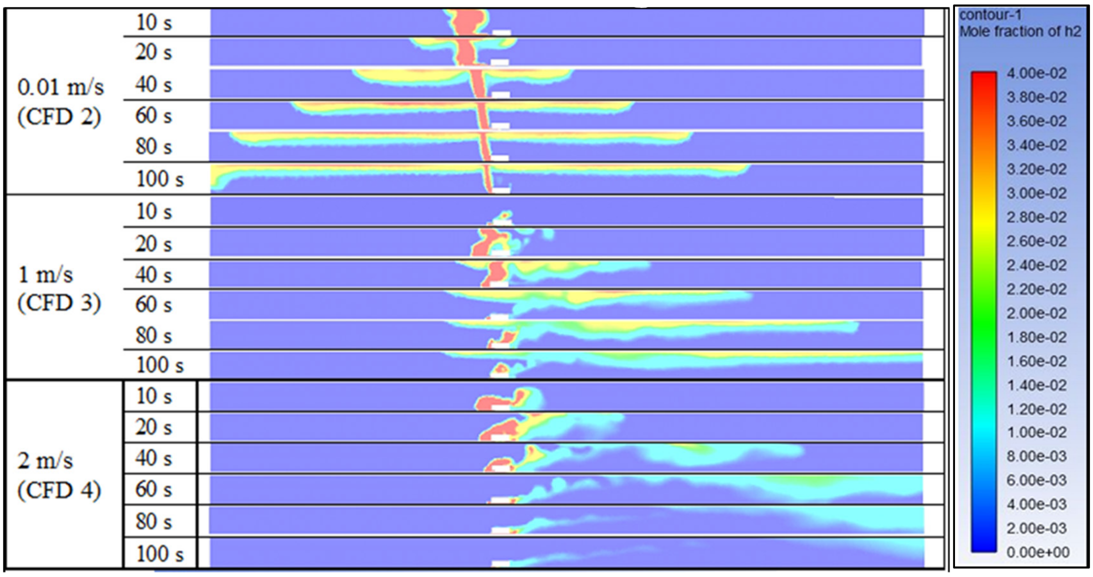

Figure 6: Impact of longitudinal airflow on hydrogen cloud formation after an unignited release. [6]

4.5. Consequence assessment

In the next step the models and findings from the consequence analysis were combined with an evacuation model usually used in quantitative tunnel risk assessments according to the Austrian tunnel risk assessment methodology TuRisMo [22]. The results demonstrated that the consideration of the evacuation procedure is essential for estimating the overall risk, as the impact of time is even more relevant than in conventional tunnel fire scenarios. Several parameters, as time of TPRD activation, TPRD orientation or the number of involved hydrogen tanks, important for the assessment, are either related to large uncertainties or were needed to be estimated based on expert judgment, as precise data for these parameters does simply not exist. The account for this uncertainty in some of the input parameters related to hydrogen scenarios, the quantitative consequence assessment of hydrogen scenarios was performed with varying scenario parameters and the most optimistic (Optimistic approach) and most conservative result (Conservative approach) for each hydrogen scenario, stemming from these parameter variations, are presented in Figure 7 (passenger cars) and Figure 8 in order to show the potential bandwidth of possible results. Figure 7 (passenger cars) and Figure 8 (buses) depict the number of fatalities for conventional fire scenarios (no bandwidth since scenario parameters are generally better known due to decades of experience with such events), in comparison to consequences for the quantitatively investigated hydrogen scenarios S1, S4 and S5 from Table 2.

Scenarios S2 and S3 (hydrogen cloud explosion) are not included in the comparison, as their potential consequences where not assessed quantitatively.

The results demonstrate the propagation of the uncertainty in the input parameters to the consequence outcome, showing potentially significantly larger consequences for hydrogen scenarios compared to conventional fire scenarios in unidirectional well-ventilated tunnels. This result must, however, be interpreted with great care. The potentially significantly larger consequences do not necessarily refer to an increased risk for hydrogen vehicles. First, because the results refer only to consequences, while incident probabilities (the second dimension of risk) where not quantified and are indeed likely to be significantly smaller for specific hydrogen scenarios than for conventional fires. If this is the case, potentially larger consequences could be relativized by smaller probabilities for hydrogen scenarios.

Second, as experience from real world incidents is missing, the exact development of hydrogen scenarios is uncertain (even more uncertain than for conventional fire scenarios). To account for this uncertainty, scenario parameters such as time of TPRD activation or the number of involved hydrogen tanks have been varied and the smallest and largest consequence numbers resulting from all the variations are presented for each hydrogen scenario (Optimistic approach vs. Conservative approach for S1, S4 and S5). Larger values for consequence numbers in Figure 7 (passenger cars) and Figure 8 (buses) must therefore be seen as upper boundaries of very broad consequence intervals, which are due to combinations of conservative assumptions (like early TPRD activation or unfavorable TPRD orientation) to reflect parameter uncertainties and model limitations, and are unlikely to manifest in reality.

However, what these large upper boundaries for consequence intervals are qualified to demonstrate is that without actual knowledge and experience from real world operation of hydrogen vehicles inside road tunnels or alternatively, extensive additional experimental investigations under realistic tunnel operation conditions, catastrophic tunnel incidents, even though potentially extremely unlikely, cannot be excluded with certainty, as proper measures to mitigate consequences are presently not available. Despite the potentially larger consequences of hydrogen scenarios compared to conventional fire scenarios and the broad bandwidth of potential consequences of hydrogen scenarios, the results indicate that accidental scenarios involving buses are much more critical than incidents involving only passenger cars. This is true for conventional cars but seems to amplify for hydrogen vehicles as more persons (i.e. all bus passengers) are located in close vicinity to the hydrogen tank.

The situation for bus passengers is in particular critical in case of fast incident development, as is the case for an immediate tank rupture following a collision (S1 – optimistic approach and conservative approach) and a jet fire with an early TPRD activation, (S4 – conservative approach). In these situations, the hydrogen scenario (explosion or jet fire) is triggered before bus evacuation, which takes significantly longer than evacuation of a passenger car, has been completed successfully.

For a thermally triggered tank rupture (S5) the number of involved tanks and thus the severity of the explosion is an important factor. Under conservative assumptions, where all hydrogen tanks are supposed to rupture and burst simultaneously, the large amount of hydrogen stored on a bus leads to a further extending fatality zone (zone where the fatality overpressure threshold is exceeded), extending to areas to which bus passengers have managed to egress between start of the evacuation and detonation of the tanks, leading to more than 60 fatalities in the considered scenarios.

In particular the last two consequence number results mentioned before – S4 conservative approach and S5 conservative approach, demonstrate the conservativity of the assumptions leading to the upper boundaries of the resulting hydrogen consequence number intervals. In case of early TPRD activation (S4 conservative approach) TPRD activation was assumed at the time a gas temperature of 110° was reached, neglecting the time needed to actually heat the TPRD to the activation temperature. In case all tanks are involved in the thermally triggered tank rupture (S5 conservative approach) all hydrogen tanks are assumed to rupture simultaneously without any time delay. The time delay, which is in fact likely to occur in reality as not all of the tanks will rupture exactly at the same instant, would lead to a less enhancing superposition of the resulting pressure waves from the individual tanks and thus to lower consequences. In this regard, the upper boundaries of the presented consequence number intervals for hydrogen scenarios must again be but into perspective and interpreted with care.

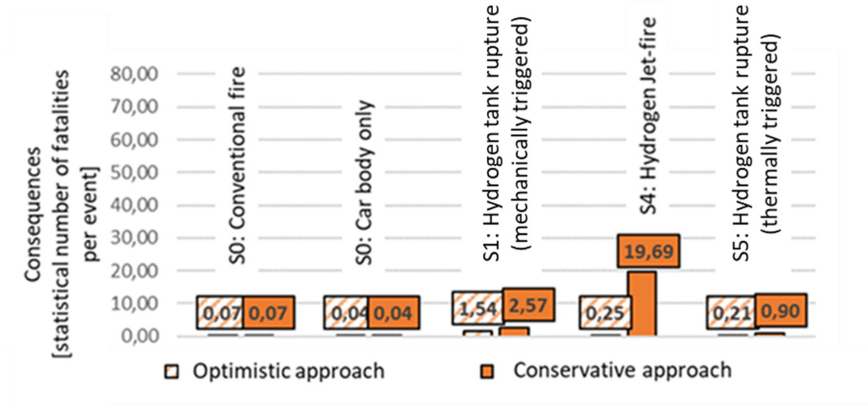

Figure 7: Comparison of risk for different incident scenarios of passenger cars. [6]

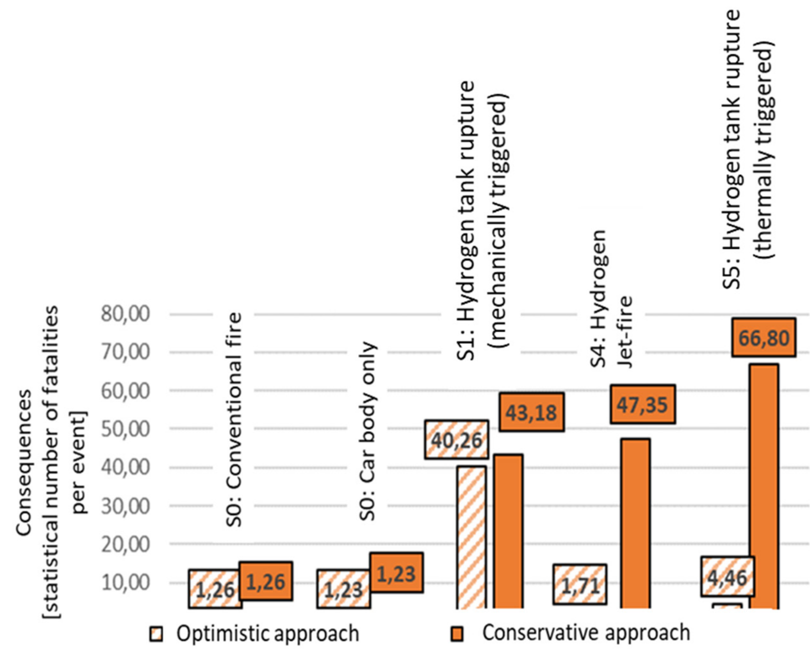

Figure 8: Comparison of risk for different incident scenarios of passenger buses. [6]

5. PREVENTIVE AND MITIGATION MEASURES

As indicated by Figure 8 H_2 vehicles pose new risks in a tunnel incident situation. In particular, explosion scenarios may lead to a disruptive pressure wave that cause severe harm to humans. Thus, measures to prevent such scenarios or to mitigate their consequences are potentially needed in the future. In HyTRA a list of technical and organizational measures has been developed. In addition, measures were prioritized on basis of their range of influence, effectiveness and required effort for implementation. In the present paper only measures with high priority are explained in more detail.

Identification of hydrogen powered vehicles

The identification of a hydrogen powered vehicle in order to be aware of the potential risk is essential in an emergency situation. Different concepts exist that enable the identification.

These range, for instance, from visual elements on the car body to allow for video detection, a monitoring at the portals using transmitters and receiver (e.g. GO box) to a dedicated vehicle-infrastructure communication. However, it is very important to keep the identification simple, as in an emergency situation, emergency services have to decide quickly on the intervention strategy. Today, legal requirements hinder the implementation of a monitoring system due to privacy rules. Thus, there is the urgent need of starting the process of implementation that starts with the adaption of laws.

Early detection of congestion and primary events (e.g. fire)

Results of HyTRA show the time (to evacuate) being one of the key elements in the emergency response. For this reason, it is essential to enable an early detection of emergency events or events that may trigger a tunnel incident. These include heat detection wires to detect thermal events such as a tunnel fire, and systems (e.g. automatic video detection or acoustic detection – "AKUT" [23]) to detect congestion. While the latter aims to prevent an immediate tank burst due to a massive mechanical impact, the early detection of thermal events extends the time available for evacuation and intervention.

TPRD orientation towards the road surface (passenger cars) or the ceiling (busses and trucks), optimization of TPRD size or self-venting tanks

Hydrogen jet-flames are characterized by high temperatures. An exposure leads to severe harm to people that may result in the loss of escape capability. The hydrogen release through a TPRD most likely results in a hydrogen jet-flame characterized by a certain length, which dependents on the storage pressure as well as the TPRD size. In order to keep flame lengths short and decrease the possibility of an exposure, a rapid reduction of momentum should be aspired. This can be realized by the optimization of the release orientation, which should be towards (angle of 45°) the road surface (passenger cars) or the ceiling (busses and trucks).

Furthermore, the TPRD size needs to be optimized as two opposing requirements have to be met. On the one hand, the TPRD diameter has to be large enough to prevent from thermally triggered, unacceptable storage pressures. On the other side, smaller TPRDs reduce the hydrogen flame length due to a limited outlet momentum.

A new tank technology hast been described by Molkov V. et al. [24] which does not require any TPRD. Instead, the gas-tight wall of the tank becomes permeable when exposed to high temperatures, allowing H_2 to escape around the circumference of the tank. This prevents dangerous flashbacks or other pressure peaks. This new technology can massively increase the safety of H_2 vehicles. However, this technology is still at the research stage.

General measures that increase traffic safety

General measures to increase traffic safety lower the risk of incidents involving hydrogen powered vehicles. One among a variety of measures are speed limits. The efficiency of speed limits is significantly increased if mechanisms to enforce the speed limit are in place. As an example, Section control has proven to be very effective in encouraging drivers to reduce their driving speed. In addition, distance control is effective as well, as sufficient time for action is available if a sufficient distance to the car in front is kept.

It is worth noting that some low priority measures may need to be upgraded to the high priority category in the future as the number of H_2 vehicles on European roads might increase.

6. SUMMARY AND CONCLUSION

The presented study aimed at a detailed analysis of hydrogen incident scenarios. Such scenarios pose additional risk in a tunnel incident. In an event-tree analysis, five hydrogen related scenarios could be identified to be characterized by a potential high risk. This included:

- Collision of a hydrogen powered vehicle with massive mechanical impact
- Accidental hydrogen release with delayed ignition
- Thermally triggered activation of TPRD with delayed ignition of hydrogen
- Thermally triggered activation of TPRD with immediate ignition of hydrogen
- Malfunction of TPRD in a thermal event

Three different hazards can be associated with these scenarios. These include a hydrogen jet-flame, a tank rupture and a hydrogen cloud explosion. In an extensive literature study as well as analytical and numerical calculations, harm distances were determined based on harm criteria taken from literature. The applied criteria accounted for the impact of high temperatures, heat fluxes as well a mechanical impact due to a pressure wave. Subsequently, the obtained harm distances were taken into account in a detailed consequence assessment that was part of an overall semi-quantitative risk assessment. A quantitative comparison of conventional vehicle fires and hydrogen incidents provided information about the statistical number of fatalities per event. It was observed that boundary conditions such as the activation time of TPRD, TPRD orientation, or the number of involved hydrogen tanks have a significant impact on the accident consequences. Compared to a conventional passenger vehicle fire in a tunnel, the number of fatalities are around 3 (optimistic) to 280 (conservative) times higher. For a bus, the number of fatalities compared to a conventional fire is approximately 1.4 to 53 times higher. However, as the probability of occurrence has not been taken into account, no assumption regarding the overall risk can be made. Even though such accidents are very unlikely to happen these days due to the low penetration rate of hydrogen vehicles, significant consequences in case of hazardous hydrogen scenarios cannot be excluded with certainty unless more knowledge from real-world tunnel incidents or experiments under realistic tunnel operation conditions are available.

Ultimately, measures to prevent hydrogen scenarios and to mitigate their consequences were listed and prioritized on basis of criteria that refer to the range of influence, effectiveness and implementation effort. Measures with highest priority are:

- Identification of H_2 vehicles in an emergency event
- Early incident detection (fires and congestions)
- Optimized TPRD and/or tank design
- Measure which generally increase the traffic safety level

Acknowledgments

The HyTRA project was funded by the Austrian Research Promotion Agency FFG. Financial resources were provided by the Austrian Federal Ministry for Climate action, Environment, Energy, Mobility, Innovation and Technology as well as by ASFINAG.

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