CFD SIMULATION STUDY TO INVESTIGATE THE RISK FROM HYDROGEN VEHICLES IN TUNNELS

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ABSTRACT

When introducing hydrogen-fuelled vehicles, an evaluation of the potential change in risk level should be performed. It is widely accepted that outdoor accidental releases of hydrogen from single vehicles will disperse quickly, and not lead to any significant explosion hazard. The situation may be different for more confined situations such as parking garages, workshops, or tunnels. Experiments and computer modelling are both important for understanding the situation better. This paper reports a simulation study to examine what, if any, is the explosion risk associated with hydrogen vehicles in tunnels. Its aim was to further our understanding of the phenomena surrounding hydrogen releases and combustion inside road tunnels, and furthermore to demonstrate how a risk assessment methodology developed for the offshore industry could be applied to the current task. This work is contributing to the EU Sixth Framework (Network of Excellence) project HySafe, aiding the overall understanding that is also being collected from previous studies, new experiments and other modelling activities.

Releases from hydrogen cars (containing 700 bar gas tanks releasing either upwards or downwards or liquid hydrogen tanks releasing only upwards) and buses (containing 350 bar gas tanks releasing upwards) for two different tunnel layouts and a range of longitudinal ventilation conditions have been studied. The largest release modelled was 20 kg H_2 from four cylinders in a bus (via one vent) in 50 seconds, with an initial release rate around 1000 g/s. Comparisons with natural gas (CNG) fuelled vehicles have also been performed.

The study suggests that for hydrogen vehicles a typical worst-case risk assessment approach assuming the full gas inventory being mixed homogeneously at stoichiometry could lead to severe explosion loads. However, a more extensive study with more realistic release scenarios reduced the predicted hazard significantly. The flammable gas cloud sizes were still large for some of the scenarios, but if the actual reactivity of the predicted clouds is taken into account, very moderate worst-case explosion pressures are predicted. As a final step of the risk assessment approach, a probabilistic QRA study is performed in which probabilities are assigned to different scenarios, time dependent ignition modelling is applied, and equivalent stoichiometric gas clouds are used to translate reactivity of dispersed non-homogeneous clouds. The probabilistic risk assessment study is based on over 200 dispersion and explosion CFD calculations using the commercially available tool FLACS. The risk assessment suggested a maximum likely pressure level of 0.1-0.3 barg at the pressure sensors that were used in the study. Somewhat higher pressures are seen elsewhere due to reflections (e.g. under the vehicles). Several other interesting observations were found in the study. For example, the study suggests that for hydrogen releases the level of longitudinal tunnel ventilation has only a marginal impact on the predicted risk, since the momentum of the releases and buoyancy of hydrogen dominates the mixing and dilution processes.

1. MOTIVATION

Due to the increasing concerns about impending fossil fuel shortages and their effect on the environment, the possibility of using hydrogen as an energy carrier has increasingly caught interest of both public and government policy makers in recent times. There has been a large amount of work on hydrogen-fuelled vehicles, and the first serial-produced hydrogen cars can already be found on roads [1]. However, when introducing hydrogen-fuelled vehicles, an evaluation of the potential change in risk level should be performed. It is widely accepted that outdoor accidental releases of hydrogen from single vehicles will disperse quickly, and not lead to any significant explosion hazard. For more

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confined situations such as parking garages, workshops, or tunnels, the situation may be different, and an accumulated hydrogen gas cloud may pose a significant risk. The Phenomena Identification and Ranking Table (PIRT) exercise carried within the EU sponsored HySafe NoE (www.hysafe.org) highlighted a concern that hydrogen powered vehicles in the confined space of a tunnel could pose a serious hazard of fire and explosion to the tunnel and its users. In response to this, an internal project, aptly named HyTunnel, was established within HySafe to contribute to the European and global activity to establish the nature of the hazard posed by these vehicles inside tunnels and its relative severity compared to that posed by traditionally (liquid hydrocarbon internal combustion) and alternatively (e.g. LPG and CNG) powered vehicles.

Partly in support of the HyTunnel project, a simulation study to predict a quantitative explosion risk for hydrogen vehicles in tunnels has been performed for two different tunnel layouts and a number of longitudinal ventilation conditions. Comparisons with natural gas vehicles have also been carried out. However, vehicles transporting hydrogen have not been included in this study. The worst-case scenario studied was 20 kg H_2 (4 cylinders) released from one bus (from four cylinders via a single release vent) in 50 seconds, with the initial release rate around 1000 g/s. Conclusions can also be drawn from this work for the risk of hydrogen vehicles parked in enclosed parking areas. Another purpose of this work is to demonstrate calculation methods for risk, and if feasible, compare different approaches. This work focuses mainly on explosion risk, but could be extended to include risk from fire.

It must be pointed out that the results obtained in this study are based on a set of assumptions about the release parameters, tunnel geometry, vehicle characteristics, etc. These assumptions are based on existing available knowledge, previous work, and discussions with manufacturers and suppliers. The results may be different if a different set of assumptions is used.

2. SCENARIOS CONSIDERED FOR RISK STUDY

This section describes the chosen accident scenarios, including the tunnel geometries and traffic configurations. It also describes the characteristics of hydrogen vehicles, such as storage pressures, dimensions, etc. The hydrogen release scenarios have been selected based on events that, although unlikely, could nonetheless occur, and if so would release a potentially significant volume of hydrogen gas. Therefore, it is important to quantify the simulation predictions with the actual likelihood of the hydrogen release scenarios occurring, in terms of events per km tunnel travel distance or otherwise.

The current study focuses on two-lane, single bore tunnels with cross-sections of 50-60 m^2. Furthermore, it is assumed that the traffic flow is unidirectional. Longitudinal ventilation along the tunnel axis (with no ventilation as a limiting case) is considered here. This represents a common situation in tunnels, especially urban tunnels and where unidirectional traffic flow is present. It is assumed that after an incident, all the vehicles remain upright and in the direction of travel, and the spacing between all the vehicles is maintained. The tunnel walls and ceiling are assumed to be smooth with no obstructions present. Ambient conditions of 1 bar pressure and 20 °C temperature are used in this study. The H_2 release is assumed to be due to the activation of a pressure relief device (PRD), so that the entire contents of the cylinder/tank (or group of cylinders/tanks) are released to the atmosphere. The cause of the pressure relief device activating could be either thermal (e.g. as a consequence of a fire) or due to a failure or an impact. Compressed hydrogen vehicle tanks are required to have PRDs to prevent rupture during exposure to fire. If the PRD device is not present or it fails, the tank may rupture resulting in a catastrophic release likely with a hydrogen fireball [2]. PRDs can limit the amount of hydrogen that gets released if a catastrophic release should still occur. In the unlikely event that the PRD system is not able to deploy (or is insufficient), experiments [2] have indicated that catastrophic failure may occur within 6-12 minutes, which is still larger than the release times considered in this study (see Section 2.3).

In this initial approach, the assumptions on incident and ignition probabilities are not based on any rigorous studies, but are based on experience from oil and gas industry, or are simply educated guesses. Future studies will likely refine these initial assumptions. The following subsections present more details on the scenarios that are considered for CFD simulations:

2.1 Tunnel Geometries

Two geometry models are proposed (see Figure 1). In both cases the length of the tunnel is assumed to be 500m, with the release location in the centre of the tunnel:

a) "Horseshoe" arched tunnel from the EC UPTUN tunnel project, i.e. 4.6m radius, with flat ground 2m below central axis (approximately 60 m^2)
b) "Rectangular tunnel", using a simple box profile, reducing the cross-section area to approximately 50 m^2.

2.2 Vehicle and Traffic Parameters

For the risk analysis study, the following H_2 powered vehicles are considered:

1. Compressed hydrogen gas (CGH_2) city bus with 40 kg H_2 stored in 8 cylinders (two sets of 4 each) – 5 kg per cylinder at a storage pressure of 350 bar. The vehicle was represented as a rectangular block (12.0 m × 2.55 m × 2.9 m) with the distance to the top of the tanks being 3.1 m.
2. Compressed hydrogen gas (CGH_2) car with 5 kg H_2 stored in 1 cylinder at a storage pressure of 700 bar. The car was represented as a simple rectangular block (5.0 m × 1.9 m × 1.5m) located 0.3 m above the ground.

And, for comparative purposes the following CNG vehicles have been considered (assuming the same geometry as the CGH_2 car and bus):

1. City bus with a storage pressure of 200 bar with a mass of 26 kg in each cylinder. It is assumed that the release occurs from a set of four cylinders with a total inventory of 104 kg.
2. Natural gas (CNG) car with a storage pressure of 200 bar and a total gas mass of 26 kg.

A dual-lane tunnel with traffic running in a single direction is assumed. Both lanes are assumed to be 100% filled by a regular pattern of buses and cars with 1.5m spacing, with 6 cars for each commercial vehicle (making 1 out of 7 vehicles a commercial vehicle). The pattern is such that there is a bus in the middle of the tunnel in one direction, and a car in the middle of the tunnel in the other direction (this way a release in the middle could be assumed either from the car or from the bus, without the need to change the geometry). The incident location is assumed to be in the centre of the tunnel. The dimensions of the cars (other than the H_2 car) are based on a typical mid-sized vehicle found on European roads. It was modelled in a simplified way as a rectangular box (size 4.2 m × 1.8 m × 1.5m) located 0.2 m above the ground. The actual shape is not expected to have too much bearing on the results. A commercial vehicle (other than the H_2 bus) was modelled as a box (15 m × 2.5 m × 3.6m) located 0.4m above the ground. It was also assumed that the new technology is more frequently installed in commercial vehicles (e.g. buses) than passenger cars, and 25% of hydrogen accidents were assumed to take place with buses (even though the number ratio is 1/7).

2.3 Release Scenarios

The release scenarios included in the study are listed below in Table 1. The frequency for failure is assumed to be constant and independent of system, i.e. same frequency for CNG & H_2. All releases are assumed to be from the centre of the tunnel, with a release height of 3 m for the bus and 1 m for the cars (upward and downward). For liquid hydrogen a release through a 20 mm nozzle is assumed (10 kg in 15 minutes). For compressed gas releases, it is assumed that the release velocity is sonic. Release profiles were calculated based on a 100 litre (700 bar) or 200 litre (200 bar or 350 bar) bottle with a 4 mm opening for hydrogen and 6 mm opening for natural gas (discharge coefficients 0.8) at a temperature of 10°C. These are presented on the right side of Figure 1. The worst-case scenario considered has a release rate 4 times higher than the shown H_2 release rate from a 350 bar tank due to simultaneous release from 4 bottles. Also, to be conservative, it is assumed that the gas tank is full when any incident occurs. The release profiles are used as a boundary condition for dispersion simulations. It must be pointed out that the durations for H_2 releases in the table below are based on the time it takes for the release rate to drop below 1 g/s. It can be seen that the release rates are significantly overpredicted if an ideal gas model is considered for high-pressure hydrogen releases. A real gas model (Noble-Abel equation of state) was therefore used in this study to obtain a more accurate estimate of the release profiles after a hydrogen release is triggered. Also, the grid was refined locally to account for the small orifice sizes for the sonic releases. The release profiles were used as boundary conditions for the dispersion modelling and a pseudo-diameter was calculated using a utility program developed along with FLACS. This is based on isentropic flow from the reservoir through the nozzle followed by a normal shock as the gas expands into the atmosphere. The LH_2 release is modelled by replacing it by a constant gaseous release (release rate 11 g/s) for 15 minutes. This is a coarse assumption, but a better representation is not expected to influence the results strongly.

A relative distribution of probability per incident is also assigned to each scenario for the purpose of carrying out quantitative risk analysis. The proposed distribution is based on an "educated guess". For each bus accident, there are 3 car accidents; and there is one LH_2 accident for each CGH_2 accident, but except for this, each of the scenarios has the same probability. The sensitivity of the results to the situation where the initial release rate from a bus for the larger inventory is limited to 234 g/s was also studied The purpose of this was to investigate what it would mean to the explosion risk if a less transient release mode were applied. It was hypothesised that this could reduce the estimated explosion risk significantly.

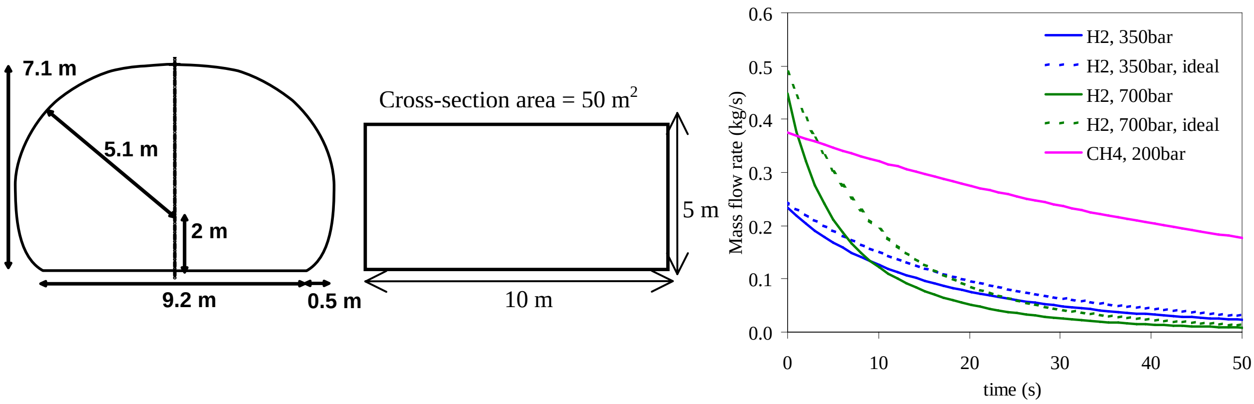

Figure 1. Schematic representation of the tunnel geometries: Horseshoe geometry (left) and rectangular geometry (middle) and associated release profiles for compressed hydrogen and natural gas releases (right); differences due to real gas effects at high pressures are shown.

Table 1. Release scenarios considered for the risk study

Vehicle	Inventory/ Duration	Initial release rate C=const., V=variable	Orifice	Relative probability
Car LH_2	10 kg (900s)	11 g/s C	20 mm	0.375
Car CGH_2 700 bar (vent up)	5 kg (84s)	448 g/s V	Sonic	0.1875
Car CGH_2 700 bar (vent down)	5 kg (84s)	448 g/s V	Sonic	0.1875
Bus CGH_2 350 bar	5 kg (147s)	234 g/s V	Sonic	0.125
Bus CGH_2 350 bar	20 kg (147s)	936 g/s V	Sonic	0.125
Bus CNG	26 kg (255s)	375 g/s V	Sonic	0.125
Bus CNG	104 kg (255s)	1500 g/s V	Sonic	0.125
Car CNG vent up	26 kg (255s)	375 g/s V	Sonic	0.375
Car CNG vent down	26 kg (255s)	375 g/s V	Sonic	0.375

The current work studied a longitudinally ventilated (by natural or mechanical means) tunnel, in which the ventilation depended mainly on the weather and operation of background impulse fans (and to some extent on traffic whose congestion may reduce the natural ventilation, but on the other hand the traffic may increase mixing). To allow for a risk study, the following distribution of ventilation conditions was proposed (the velocities specified should be understood as an average flow velocity in the empty section of the tunnel, i.e. 2 m/s ventilation in a 50 m^2 tunnel means 100 m^3/s flow through the entrance), the frequencies assumed for initial risk study are also shown in brackets:

- 0 m/s [0.30] (Limiting case where forced and/or natural ventilation results in zero net flow)

- 2 m/s [0.30] (Typical velocity found in naturally ventilated tunnels)
- 3 m/s [0.20] (Typical value required to control the movement of heat and smoke from a vehicle fire)
- 5 m/s [0.20] (Upper level of recommended air speed for additional dilution of smoke and gases)

For the dispersion study, the main evaluation parameter is the size of the flammable gas cloud. In order to evaluate the hazard of a given gas cloud, we have developed methods used for natural gas in the oil and gas industry that aim at estimating an equivalent stoichiometric gas cloud with comparable explosion consequences. The size of the equivalent stoichiometric cloud at the time of ignition is calculated as the amount of gas in the flammable range, weighted by the concentration dependency of the flame speed and expansion. For a scenario of high confinement, or a scenario where very high flame speeds (faster than speed of sound in cold air) are expected (either large clouds or very congested situations), only expansion based weighting is used (denoted as $Q8$). For most situations lower flame speeds are expected and the conservatism can be reduced. Here a weighting of reactivity and expansion is used (denoted as $Q9$). The $Q8$ and $Q9$ equivalent volumes can be defined as $Q8 = \sum V \times E \,/\, E_{\mathrm{stoich}}$ and $Q9 = \sum V \times \mathrm{BV} \times E \,/\, (\mathrm{BV} \times E)_{\mathrm{stoich}}$. Here, V is the flammable volume, BV is the laminar burning velocity (corrected for flame wrinkling/Lewis number effects), E is volume expansion caused by burning at constant pressure in air, and the summation is over all control volumes. Thus, $Q9$ cloud is a scaling of the non-homogeneous gas cloud to a smaller stoichiometric gas cloud that is expected to give similar explosion loads as the original cloud (provided conservative shape and position of cloud, and conservative ignition point). As a practical guideline, it is recommended to choose the shape of the cloud that will give maximum travel distance from ignition to end of cloud for smaller clouds. For larger clouds, end ignition scenarios with longer flame travel should also be investigated. This concept is useful for QRA studies with many simulations, and has been found to work reasonably well for safety studies involving natural gas releases [5]. This concept has also been applied to hydrogen systems for the FZK workshop experiments [6] and has been found to give reasonably good predictions.

2.4 Ignition probability

The likelihood for ignition of releases is probably very different for CNG and H_2, since there is one order of magnitude difference in necessary spark energy at stoichiometry (the ignition energy is nonetheless very similar near the LFL). Early spontaneous ignition is frequently seen in large-scale H_2 experiments (e.g. [3]), but this is seldom reported with CNG. Dryer and co-workers [4] recently performed a comprehensive study of spontaneous ignition of high pressure hydrogen releases up to a pressure of 113 bar and found that above a certain overpressure releases of a certain size would always autoignite, if the downstream flow geometry is able to result in sufficiently fast mixing of the escaping hydrogen and shocked air in contact with it. The presence of cars with running engines may further increase the early ignition likelihood. For this reason, we may also assume a significant spontaneous ignition probability for CNG. For studies in offshore platforms with natural gas, the ignition probabilities are generally low, so there has been no need to consider detailed statistical treatment on conditionality. If ignition probability gets high, this may be needed. Three contributions were proposed:

1. Ignition from constant ignition sources (per m^3 that sees flammable gas for the first time)
2. Ignition from intermittent ignition sources (per m^3 flammable volume and second)
3. Spontaneous ignition of release (shock-waves, dust particles, charges or fire causing PRD)

Care must be taken that the total ignition probability contribution for one release scenario does not exceed one, i.e. potentially large gas clouds filling large parts of the tunnel should not contribute to risk if ignition probabilities have indicated that gas cloud will ignite much earlier. As a coarse, but realistic assumption for this study, the following ignition probabilities/intensities were proposed:

1. Constant ignition sources ~ 0.25 [10^{-4} per m^3 volume flammable first time]
2. Intermittent ignition sources ~ 0.25 [10^{-5} per m^3 flammable volume and second]
3. Spontaneous ignition = 0.5 [constant 0.1/s first 5 seconds]

More experience and accident data is needed to refine these estimates. These values imply that the approximate probability of ignition from constant ignition sources for a given incident is about 0.25, which is reached once 2500 m^3 has been exposed to flammable gas. Similarly, the assumed maximum contribution from intermittent ignition sources is filled up if 1000 m^3 of the tunnel sees flammable gas for 25 s, or 2500 m^3 for 10 s. The spontaneous ignition probability will always be 50%, but the relative weight of the other two can vary, with the maximum total contribution being 50%.

2.5 Explosion Scenarios

For calculating reference overpressures, stoichiometric gas clouds (with sizes based on meter of tunnel filled at stoichiometry) are considered to explode. The proposed cloud sizes are roughly 5 m^3 (0.1 m tunnel length), 25 m^3 (0.5 m), 50 m^3 (1 m), 125 m^3 (2.5 m), 250 m^3 (5 m), 500 m^3 (10 m) and 1000 m^3 (20 m). The smaller clouds are assumed to be rectangular boxes with aspect ratios 2:2:1. The main ignition location is at the roof exactly in the middle of the tunnel. End ignition scenarios are also simulated and represent half of the probability for the given cloud size. The main reported parameter is the maximum explosion overpressure near the tunnel ceiling. The overpressures are reported at 21 different pressure sensors placed on the central axis of the tunnel near the ceiling placed every 10 m in both directions from the centre of the tunnel. The following sensitivities are proposed (included when calculating risk):

1. Long cloud only filling upper 50% of tunnel cross-section versus cloud filling full cross-section (default); this only makes a difference for the three largest gas clouds
2. The effect of including typical pre-ignition turbulence from a jet flow.

For quality assurance purposes overpressures obtained from the ignition of the above homogenous hydrogen clouds are compared with those resulting from ignition of realistic releases (with comparable gas cloud sizes). For the risk assessment study, the frequency for *Q*9 cloud sizes is applied. Explosion simulations with and without pre-ignition turbulence are assumed to be equally likely.

3. BRIEF DESCRIPTION OF THE SIMULATION TOOL FLACS

All the simulations for the scenarios described above have been carried out using the CFD code FLACS. FLACS is a computational fluid dynamics (CFD) code that solves the compressible Navier-Stokes equations on a 3-D Cartesian grid. The basic equations used in the FLACS model as well as the explosion experiments to develop and validate FLACS initially have been published [7,8]. Second order schemes (Kappa schemes with weighting between 2^{nd} order upwind and 2^{nd} order central difference, delimiters for some equations) are used to solve the conservation equations for mass, impulse, enthalpy, turbulence and species/combustion. A good description of geometry and the coupling of geometry to the flow, turbulence, and flame is one of the key elements in the modelling. In FLACS a “beta” flame model is applied in which the reaction zone becomes 3-5 grid cells thick. The burning velocity is primarily controlled by diffusion of reaction products. A flame library decides the laminar burning velocity as function of gas mixture, concentration with air, pressure, temperature, oxygen concentration in air and more. Initial “quasi-laminar” flame wrinkling will increase the burning velocity with distance. With increasing turbulence a turbulent burning velocity will replace the quasi-laminar. The real flame area is described properly and corrected for curvature at scales equal to and smaller than the reaction zone. More details on the burning velocity modelling within FLACS can be found in Reference [9]. All flame wrinkling at scales less than the grid size is represented by sub-grid models, which is important for flame interaction with objects smaller than the grid size. FLACS uses a standard k-ε model for turbulence. However, some modifications are implemented, the most important being a model for generation of turbulence behind sub-grid objects and turbulent wall functions [9].

Over the past few years, the focus on carrying out safety studies for hydrogen applications has increased, and the use of CFD has increased. However, the CFD tool needs to be well validated against relevant experiments. With these considerations, a strong effort has been made in the past few years to learn more about hydrogen explosions and improve FLACS in that area. We have carried out dedicated research projects involving varied small-scale experiments, combined with simulations and model improvements in order to improve the validation database for hydrogen safety predictions [10]. Simulations of many large-scale experiments from various external sources have also been carried out. This includes explosion simulations for Sandia FLAME facility [10,11], SRI Tunnel experiments [3], Fh-ICT 20 m hemispherical balloon [12], SRI confined tube [3,13], Fh-ICT lane experiments [14], McGill Detonation Tubes [15], and more. Dispersion simulations have been carried out to validate predictive capabilities for sonic jets [16] (e.g. HSL tests, INERIS experiments, and FZK tests) and subsonic jets (INERIS garage experiments [17], Swain experiments [16], GexCon low momentum release experiments [18]). Other studies have also been carried out, but are not available presently in open literature [19]. Studies presented in References [12], [17] and [18] have been carried out as a part of the benchmarking activities in the HySafe project.

The two studies that are most relevant for the current work are validation studies against the Sandia FLAME facility and the SRI Tunnel experiments as these were carried out in geometries and scales similar, albeit somewhat smaller, to those in the traffic tunnel considered here. For the Sandia FLAME facility, the geometry is a 30.5m long channel with closed or partly open ceiling (13% or 50%), and either no obstructions or repeated vertical baffles (33% blockage). In addition to being relevant for nuclear plant safety, the tests are also highly relevant for situations involving major releases in tunnels. Twenty-nine large-scale experiments were carried out and described in the data report [9], including tests with closed and partially open ceiling, with and without obstacles. Reasonable agreement in the overpressure levels between simulations and experiments was seen. The SRI Tunnel experiments were conducted in a 78.5 m long tunnel with a cross-sectional area of 3.74 m^2 (representing a traffic tunnel at about 1/5 scale). Homogeneous hydrogen-air mixtures (size 37 m^3) at different concentrations were contained in the center of the tunnel. For some tests, box-shaped obstacles were placed in the tunnel to represent model vehicles [3]. In general, the simulations were able to reproduce the measured overpressures well.

4. RESULTS AND DISCUSSION

This section presents some of the key results obtained in the study. Both dispersion and explosion simulations were carried out based on the geometrical and scenario parameters described in the previous section. First, we carried out explosion simulations assuming stoichiometric gas clouds of different sizes as described above in order to get an estimate of the reference overpressures. Based on the tunnel size and inventory, the worst-case possible stoichiometric cloud sizes were of the order 200-400 m^3 (4-8 m) except for the larger bus release scenario. For this case, the maximum possible cloud size was about 1000 m^3 (20 m). Based on this information, explosions in a range of gas cloud sizes from 5 m^3 to 1000 m^3 were simulated. The results are presented in Table 2a. The table presents overpressures for both tunnel cross-sections (rectangular and horseshoe), both fuels (hydrogen and CNG), and two different ignition positions – centre (C) and edge (E). If expected values of initial turbulence are also considered (caused by hydrogen or CNG jet), the overpressures are expected to be somewhat higher (these calculations were only performed for centre ignition). The results are presented in Table 2b.

It can be seen from this table that in general, the pressures resulting from hydrogen explosions can be very high, except for small clouds. The highest pressure seen was almost 12 barg for a 1000 m^3 gas cloud. The overpressures are significantly reduced as the gas cloud size is reduced from 1000 m^3 to 250 m^3 (factor of 4-10) but the consequences are still significant. The overpressures are much lower for CNG explosions, and the maximum overpressure observed in this case was 0.6 barg. For the largest clouds, edge ignition led to higher pressures (due to longer flame path) in most cases, but the overpressures resulting from centre ignition were generally higher for smaller clouds. However, some deviations from the general trend are seen. This is due to the placement of gas cloud with respect to the vehicles in the tunnels and the effect it has on the turbulence field. If initial turbulence is considered, the pressures go up by a factor of 2 for the case of larger clouds for hydrogen explosions, but the effect is much larger for smaller clouds. For CNG explosions, the change in overpressures caused by consideration of initial turbulence is generally much more pronounced. For the largest cloud (1000 m^3), the maximum predicted overpressure was seen to change by a factor of 4. Overall, these consequences are certainly severe and further analysis is deemed necessary in order to estimate the gas cloud size and concentration that can be realistically expected.

Table 2a. Summary of overpressures as a function of gas cloud size for stoichiometric explosion calculation in the two tunnel geometries for centre and end ignition (quiescent scenarios)

Ignited gas cloud volume * Overpressures (barg)		5 m^3	25 m^3	50 m^3	125 m^3	250 m^3		500 m^3		1000 m^3	
						Long	2:2:1	Long	2:2:1	Long	2:2:1
H_2 incident	**C**	0.05	0.11	0.17	0.29	0.50	1.01	1.29	3.22	2.66	6.52
Horseshoe	**E**	0.03	0.07	0.11	0.19	0.52	0.38	0.77	2.96	4.28	9.97
CNG incident	**C**	0.01	0.01	0.01	0.02	0.05	0.05	0.14	0.09	0.54	0.41
Horseshoe	**E**	0.005	0.01	0.01	0.02	0.04	0.03	0.08	0.06	0.37	0.40
H_2 incident	**C**	0.05	0.11	0.19	0.37	2.45	1.59	2.90	3.28	9.46	5.57
Rectangular	**E**	0.03	0.08	0.11	0.74	3.48	2.08	4.28	4.79	7.99	11.71
CNG incident	**C**	0.005	0.01	0.02	0.03	0.06	0.05	0.21	0.14	0.67	0.60
Rectangular	**E**	0.005	0.01	0.01	0.03	0.04	0.04	0.08	0.12	0.39	0.41

* 1 m^3 stoichiometric H_2 cloud contains 0.024 kg H_2 and 1 m^3 stoichiometric CNG cloud contains about 0.067 kg CNG

Table 2b. Summary of overpressures as a function of gas cloud size for stoichiometric explosion calculation in the two tunnel geometries for centre ignition (initial turbulence included)

Ignited gas cloud volume * Overpressures (barg)		5 m^3	25 m^3	50 m^3	125 m^3	250 m^3		500 m^3		1000 m^3	
						Long	2:2:1	Long	2:2:1	Long	2:2:1
H_2 incident Horseshoe	**C**	0.10	0.26	0.47	1.22	2.60	2.96	3.79	8.28	10.60	9.52
CNG incident Horseshoe	**C**	0.01	0.06	0.13	0.29	0.47	0.60	0.64	1.05	0.86	1.82
H_2 incident Rectangular	**C**	0.08	0.34	0.56	1.40	2.86	3.51	8.85	6.13	8.77	12.90
CNG incident Rectangular	**C**	0.01	0.07	0.13	0.30	0.51	0.59	0.72	1.14	0.82	2.26

* 1 m^3 stoichiometric H_2 cloud contains 0.024 kg H_2 and 1 m^3 stoichiometric CNG cloud contains about 0.067 kg CNG

For that purpose, the release and subsequent dispersion from various hydrogen (or natural gas) release incidents were modelled. The actual calculated cloud sizes are presented in Table 3. It can be seen from this table that a LH_2 release generally results in very small clouds in both tunnel geometries. The releases from a car powered by CGH_2 (as well as the CGH_2 bus with small release inventory) result in a larger accumulation of combustible fuel, and the flammable cloud sizes are found to be of the order of 200-300 m^3. Quite significant gas clouds (1500-2500 m^3) are seen for the scenario involving CGH_2 release from 4 cylinders on a bus. As a comparison, compressed CNG vehicles were also considered. In general, gas clouds resulting from CNG releases were found to be mostly insignificant compared to those obtained from CGH_2 releases, except for the larger bus release in a rectangular tunnel. There seems to be a lesser hazard associated with horseshoe shape, due to the fact that there is 50% longer distance from PRD to the ceiling, which allows further dilution prior to impingement, and also less momentum for the jet to get recirculated back towards the floor.

In general, these accumulated gas clouds were quite lean. Table 3 also presents the equivalent stoichiometric gas cloud sizes for the same scenarios and for all cases (calculated using the methodology described briefly in Section 2.3), the equivalent stoichiometric gas clouds were found to be insignificant, indicating that the accumulated fuel does not present a very large danger. Even for the hydrogen incidents involving gas release from 4 cylinders in a bus, the equivalent stoichiometric gas cloud was only about 25-30 m^3. The largest equivalent stoichiometric gas cloud was found for a CNG bus incident in a rectangular tunnel. The CNG study showed that a reduction of tunnel cross-section and an increase in the release rate could result in a significant increase of the hazard. In general, the results indicate that the overpressures obtained from explosion calculations described above are likely far too conservative, and much smaller overpressures can be expected than those obtained from the large gas clouds (see Tables 2a and 2b). Therefore, the high pressures that are reported in these tables seem unrealistic.

Table 3. Summary of maximum flammable gas cloud sizes for all vehicle/inventory scenarios considered in the study in the two tunnel geometries

Vehicle/Release Characteristics	Inventory (kg)	Maximum flammable gas cloud size m^3 (& kg)		Maximum equivalent stoichiometric flammable gas cloud size m^3 (& kg)	
		Horseshoe tunnel	Rectangular tunnel	Horseshoe tunnel	Rectangular tunnel
Car LH_2	10 kg	1.4 (0.007)	1.8 (0.009)	0.02 (0.003)	0.02 (0.004)
Car CGH_2 700 bar (vent up)	5 kg	281 (1.14)	273 (1.21)	4.42 (0.07)	4.31 (0.09)
Car CGH_2 700 bar (vent down)	5 kg	268 (1.33)	308 (1.39)	17.75 (0.29)	8.77 (0.18)
Bus CGH_2 350 bar	5 kg	213 (0.89)	190 (0.81)	2.16 (0.04)	1.94 (0.04)
Bus CGH_2 350 bar	20 kg	1795 (7.46)	3037 (13.97)	27.46 (0.45)	24.67 (0.49)
Bus CNG 200 bar	26 kg	3.4 (0.15)	4.6 (0.19)	1.15 (0.08)	1.18 (0.08)
Bus CNG 200 bar	104 kg	45 (2.01)	647 (26.0)	13.47 (0.90)	113.48 (7.60)
Car CNG 200 bar (vent up)	26 kg	2.1 (0.10)	3.4 (0.15)	0.85 (0.06)	1.03 (0.07)
Car CNG 200 bar (vent down)	26 kg	17 (0.78)	15 (0.65)	6.31 (0.42)	5.25 (0.35)

The expected overpressures based on the equivalent stoichiometric gas clouds resulting from the various release scenarios are presented in Table 4. The maximum expected overpressures in this case are 0.1-0.3 barg (based on Tables 2a and 2b). Although this value is somewhat lower than first expected, it is likely to be realistic as FLACS has been validated extensively, and has been found to predict pressure loads well in cases involving both dispersion and explosion, such as the FZK workshop experiments [20]. The results obtained from many other explosion and dispersion scenarios presented have been found to correlate well with available experiments (for both H_2 and CNG).

Table 4. Summary of maximum overpressures based on a) the entire flammable gas cloud at stoichiometric concentration and b) the equivalent stoichiometric gas cloud size for all vehicle/inventory scenarios considered in the study

Vehicle/Release Characteristics	Inventory (kg)	Maximum pressure for max. equivalent cloud *Q*9 Quiescent / Pre-ignition turb.	
		Maximum *Q*9 equivalent volume (m^3)	Maximum overpressure (barg)
Car LH_2	10 kg	0.02	< 0.05 / 0.1
Car CGH_2 700 bar (vent up)	5 kg	4.42	0.05 / 0.10
Car CGH_2 700 bar (vent down)	5 kg	17.8	0.11 / 0.34
Bus CGH_2 350 bar	5 kg	2.16	0.05 / 0.10
Bus CGH_2 350 bar	20 kg	27.5	0.11 / 0.34
Bus CNG 200 bar	26 kg	1.18	0.01 / 0.01
Bus CNG 200 bar	104 kg	113	0.03 / 0.30
Car CNG 200 bar (vent up)	26 kg	1.03	0.01 / 0.01
Car CNG 200 bar (vent down)	26 kg	6.31	0.01 / 0.07

In order to ensure that the above results do not underestimate the consequences and to evaluate the uncertainty in the equivalent stoichiometric gas cloud formulation, we carried out sensitivity studies by igniting the (likely) most dangerous release scenario (large H_2 release from a bus) inside the jet (two different ignition positions) at different times after the beginning of the release. Contour plots of the gas cloud concentration between 15 and 40% hydrogen at two different times (5 s and 15 s after beginning of release) are shown in Figure 2. Even for this case, the gas cloud concentration is significant only near the jet axis. The gas cloud extent with concentration above 4% (LFL) is presented in the middle part of the same figure.

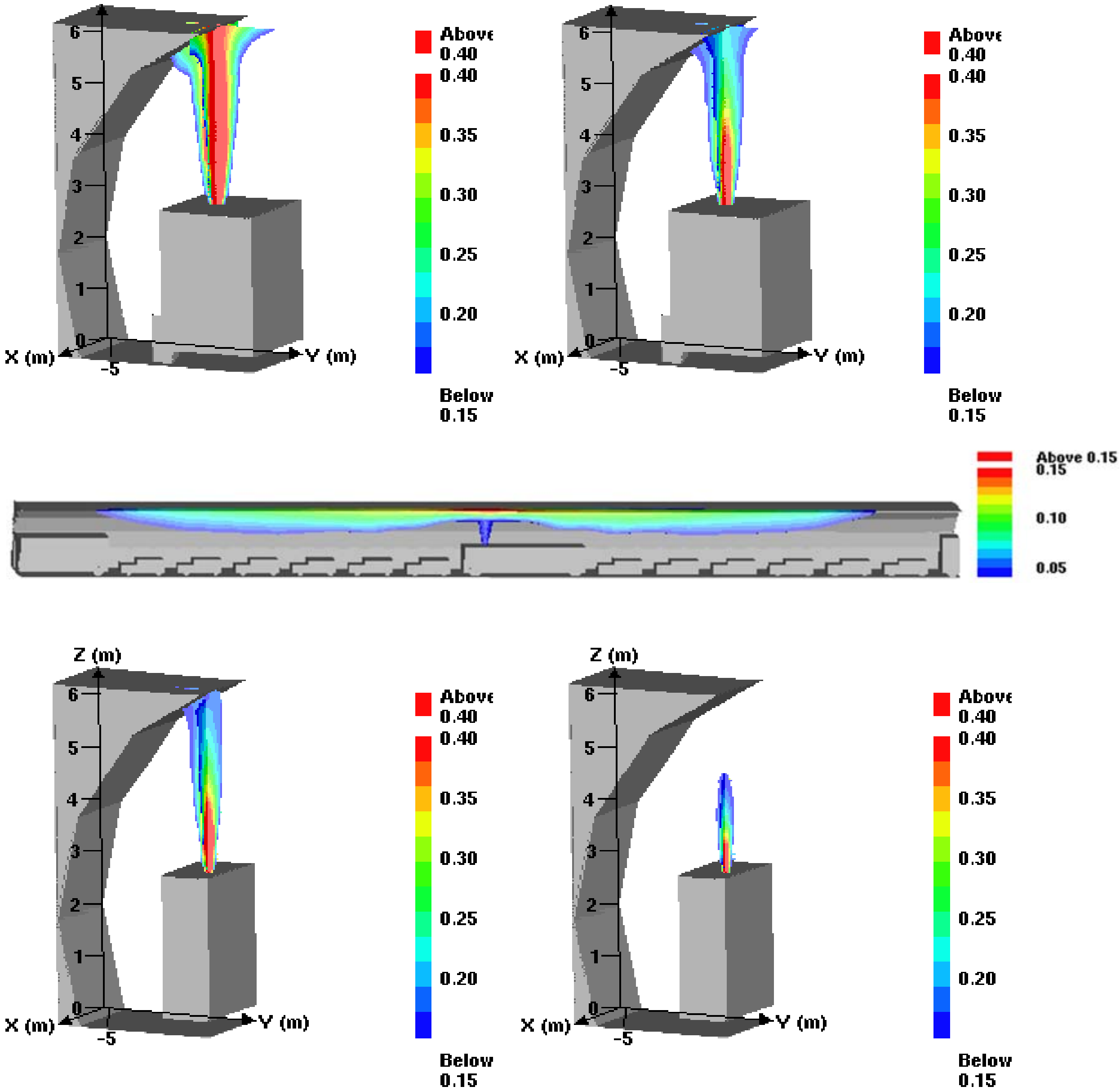

Figure 2. Hydrogen concentration contours for two different times (5 and 15 s after beginning of release) for two different release scenarios: 20 kg (top) and 5 kg (bottom) bus incident. The gas cloud extent for concentrations above 4 % (LFL) for the 20 kg bus release is shown in the middle.

It can be seen that the flammable hydrogen cloud is quite large, but most of this gas is fairly dilute and expected to lead to minimal overpressures when ignited. For comparison, similar plots for the smaller bus release are also shown. It can be seen that the gas cloud with significant concentrations resulting from this scenario is even smaller. The worst-case cloud was further ignited within the jet at a position 2.8 m (near the ceiling) from the release location on the jet axis. The flame development as a function of time is also seen in Figure 3. The resulting pressure traces at sensors close to the ignition location are presented in Figure 4. Maximum overpressures of around 0.25 barg are seen on the pressure sensors. Local pressures will exceed 0.25 barg due to reflections on and under vehicles. Thus, the values of overpressures obtained using the equivalent stoichiometric gas cloud concept can be expected to be reasonable for all cases.

The effect of ventilation is illustrated next for the "worst-case" 4 cylinder release from a hydrogen bus. If no ventilation is present, the maximum flammable gas cloud size was found to be 1800 m^3 (with maximum $Q9$ = 27 m^3). With 2 m/s ventilation velocity, the maximum flammable gas cloud size was reduced to 1500 m^3. However, the maximum equivalent stoichiometric gas cloud size increased slightly to 30 m^3. For the case of 5 m/s ventilation velocity, the respective values of flammable gas cloud size and $Q9$ were 1000 and 25 m^3. Thus, the ventilation did not have any significant impact on equivalent stoichiometric gas cloud sizes. It can be concluded that ventilation is only important if more significant volumes of reactive clouds are seen. With the high momentum releases considered here, the momentum from jet dominates the dilution process. However, there is a possibility that lower momentum and "trapping" of gas cloud can lead to more dangerous results. The very significant buoyancy certainly precludes the "trapping" process, but more investigation is required.

A probabilistic risk assessment study is undertaken next. Table 5 presents the "exposure times" provided no ignition for a given cloud size (total flammable volume) for a hydrogen incident in both tunnel geometries. For comparison, the values for a CNG incident in the horseshoe tunnel are also presented. It can be seen that for both the geometries, very small clouds are seen for the most part. For each incident, it can be seen that for a horseshoe tunnel, a 1000 m^3 gas cloud is only seen for 3.5 s (for the assumed probabilities). This duration is about half a minute for a rectangular tunnel. The clouds obtained for the CNG incident are even smaller, and the maximum gas cloud size was only about 125 m^3, which was present only for a short time (much larger gas cloud was seen for a rectangular tunnel for a 4 cylinder bus release as presented in Table 4 but the values presented in this table are for the horseshoe geometry only).

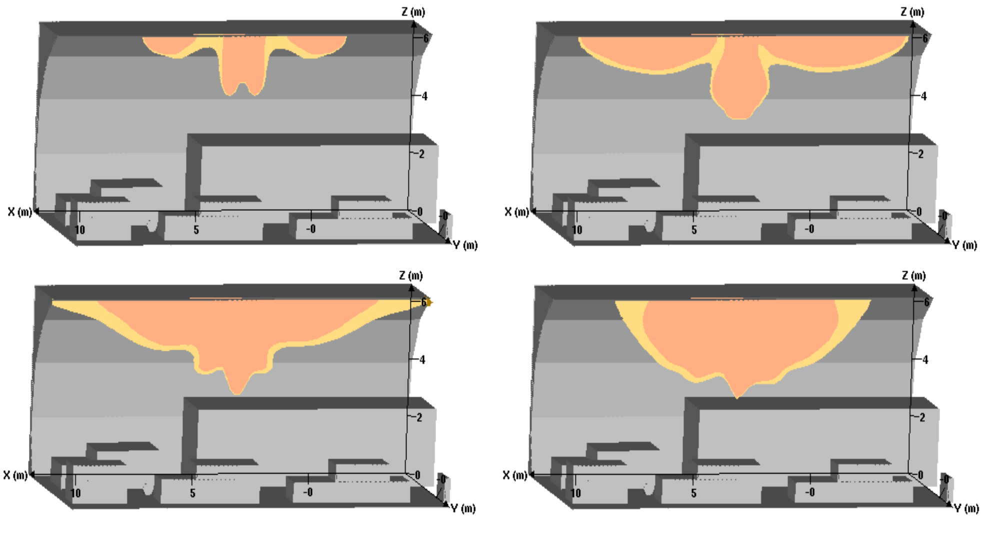

Figure 3. Flame development for the large H_2 bus release upon early ignition within the jet near the ceiling

The estimated probabilities for ignited gas clouds of different sizes (in terms of the equivalent gas cloud $Q9$) in both tunnel geometries are presented in Table 6. As described above, no equivalent gas clouds larger than 25-30 m^3 are present for hydrogen (or natural gas in horseshoe tunnel). Therefore, the ignition probabilities are zero for cloud size larger than 25 m^3. For natural gas releases in a rectangular tunnel, the worst-case cloud is expected to be larger, but not above 125 m^3. Limited pressure loads are thus expected to be seen.

Based on the above two tables, the frequency of exceedence curves of a given pressure load for a hydrogen (or CNG) incident can be estimated. To include the effects of jet-induced turbulence simulations with pre-ignition turbulence were also included. The results are presented in Figure 5. The frequency (or likelihood) per incident for a certain pressure load for a hydrogen incident for both tunnel geometries are presented. It can be seen that the maximum expected overpressures are of the order of 0.35 barg (cloud assuming pre-ignition turbulence), but the estimated likelihood to ignite a cloud with that size and severity is estimated to 5%. From the study it is found that typically, pressure loads around 0.1-0.2 barg can be expected for a hydrogen incident. If the initial release rate for the large bus release is limited to maximum 234 g/s, a sensitivity study showed that the likelihood of obtaining pressure loads higher than 0.1 barg is significantly reduced. For a CNG incident, the expected pressure loads are generally of the order 0.01 barg.

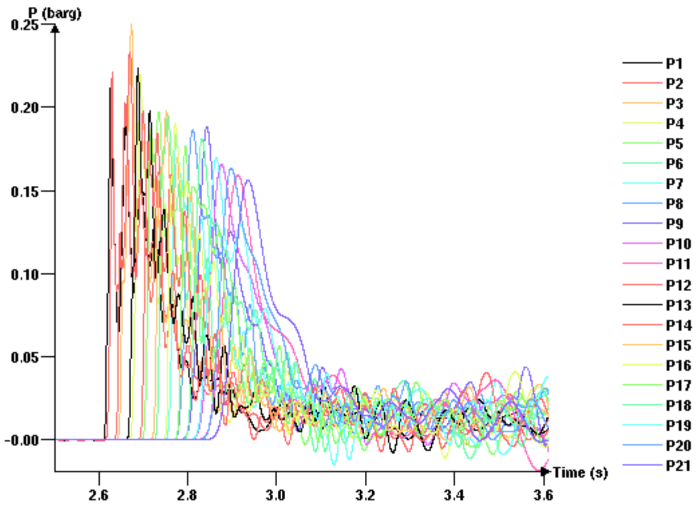

Figure 4. Overpressures resulting from the worst-case ignition inside jet for the larger bus release

Table 5. Summary of "exposure times" for a given flammable cloud size for a hydrogen incident in both tunnel geometries. The values for a CNG incident in the horseshoe tunnel are also presented.

Cloud size* Exposure time	5 m^3	25 m^3	50 m^3	125 m^3	250 m^3	500 m^3	1000 m^3
H_2 incident Horseshoe	454s	117s	34s	38s	52s	0.8s	3.5s
H_2 incident Rectangular	402s	115s	14s	42s	3.0s	0.97s	34s
CNG incident Horseshoe	462s	23s	2.5s	0.05s	0s	0s	0s

* Cloud size class used for horseshoe shape is 20% higher than cloud size indicated

Table 6. Ignition probability as a function of equivalent stoichiometric gas cloud size for a H_2 incident in both tunnel geometries. The values for a CNG incident in the horseshoe tunnel are also included.

Ignited gas cloud sizes Frequency /incident	5 m^3	25 m^3	50 m^3	125 m^3	250 m^3	500 m^3	1000 m^3
H_2 incident Horseshoe	0.45	0.18	0	0	0	0	0
CNG incident Horseshoe	0.42	0.08	0	0	0	0	0
H_2 incident Rectangular	0.52	0.15	0	0	0	0	0

We also studied the sensitivity of the results for cases involving only low ventilation velocities (0 and 2 m/s) and involving only high ventilation velocities (3 and 5 m/s). The results are also presented in Figure 5. It can be seen from this figure as well that the effect of ventilation is small. For the scenarios described above involving ignition within the jet, the maximum overpressures for both geometries and all different ignition times were found to be of the order of 0.11-0.25 barg, and hence were not significantly different from those obtained by the ignition of quiescent stoichiometric clouds of the appropriate size. This is indicated in the Figure 5 above by a black arrow. Since the likelihood of ignition for a flammable gas cloud larger than 125 m^3 is found to be negligible for both H_2 and CNG incidents, it is recommended to include more explosion classes below that size in order to obtain smoother exceedence curves.

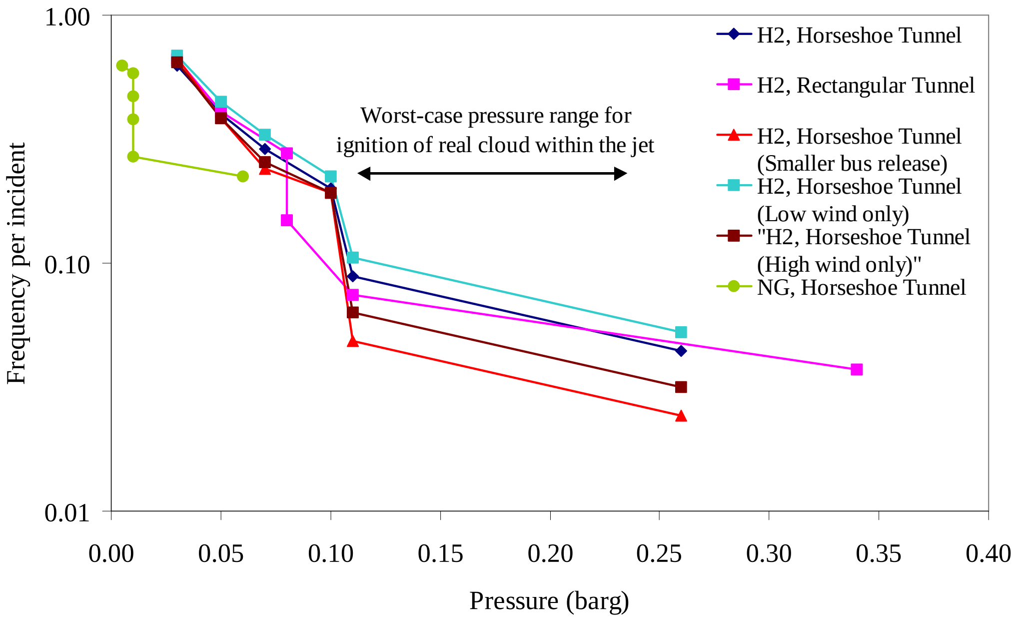

Figure 5. Frequency of exceedance curves for a hydrogen (and CNG) incident in the tunnel geometry.

Thus, the hazards arising from the use of hydrogen vehicles in a tunnel has been estimated. The worst-case screening approach indicated the potential for very high overpressures. However, by performing a dispersion study those values were found to be far too conservative, and the explosion loads found when igniting the dispersed clouds were not too significant. In the end, a probabilistic study has been carried out which suggests that the hydrogen vehicles do not present a very significant explosion risk in a tunnel, and can be used in a safe manner. It can be concluded that larger and “taller” tunnels are even safer, as horseshoe tunnel was found to present a smaller danger in terms of the flammable cloud concentrations than a rectangular tunnel due to possibility of larger mixing and hence dilution.

5. FINAL COMMENTS AND CONCLUSIONS

This paper presents a CFD modelling study to help understand the risk posed by hydrogen vehicles in road tunnels, It involved two different tunnel geometries, and several release scenarios, representative of the actual hydrogen vehicles that are expected on European roads in forthcoming years. The worst-case screening study involving tunnels filled with stoichiometric hydrogen air gas clouds of different possible sizes revealed very high overpressures. But a more realistic “worst-case” analysis involving a dispersion study to estimate the actual gas clouds that would result from a hydrogen release, and their subsequent ignition, reduced the estimated worst-case pressures by 2 orders of magnitude. A probabilistic study reduced the expected risk even further. The maximum possible pressure load predicted by the simulations was about 0.1-0.3 barg, which represents a limited human fatality risk. These values are expected to be reasonable as the consequence tool FLACS has been extensively validated against experiments at comparable scales and scenarios as those studied in the paper. This validation includes dispersion and explosion tests for both hydrogen and natural gas, in many cases through blind predictions, and thus the results can be expected to be reasonable. For comparison, eardrum rupture data show 10% rupture for peak pressures of about 0.25 barg, and explosion tests in the US indicate that almost all humans (99%) will survive blast pressures of 2 barg [21]. However, secondary blast effects (projectiles, etc.) may lead to injuries (or even death) at much lower pressures. Further, the pressure sensors were placed on the ceiling for all simulations. It is expected that local overpressures due to reflections from the sidewalls and/or the vehicles are somewhat higher than those reported.

Finally, the results obtained must be put into perspective. The conclusions are based on a set of assumptions, namely the release scenarios, tunnel geometries, vehicle dimensions, etc. The scenarios were chosen based on the typical process specifications of hydrogen vehicles, previous hydrogen safety activities within the EU, and experiences of HySafe project partners. The scenario choices could be refined further. However, that is not expected to have too much bearing on the results, except if much higher release inventories are considered. In the study it has been assumed that the tunnel ceiling is smooth and that there are no obstructions near the ceiling. If the ceiling design is such that gas can be trapped and the momentum of impinging releases significantly reduced, this could reduce the mixing and change the conclusions. The presence of significant congestion elements (light armatures or fans) near the ceiling could also add some turbulence to flame propagation and make explosions slightly more severe. This awaits further study. The study also assumed that the new technology is more frequently installed in commercial vehicles (e.g. buses) initially, and 25% of hydrogen incidents were assumed to take place with buses (even though the number ratio is 1/7). Also, to be conservative, the hydrogen tank has also been assumed to be full when an incident occurs. The results are obtained based on a set of assumptions about incident/ignition probabilities that may need further examination based on experience, accident data, and experimental studies. The results are also based on the applicability of the equivalent stoichiometric gas cloud concept to hydrogen systems. This approach has been found to work reasonably well for many different risk assessment studies within GexCon and elsewhere for natural gas systems. It has also been found to work well for the simulations of workshop experiments carried out at FZK. Further, we have also tested the applicability by igniting a realistic, inhomogeneous gas cloud with jet turbulence at different ignition positions to obtain the maximum pressure loads. The resulting values have been found to agree reasonably well with those obtained using the *Q*9 approach. Nonetheless, there are some uncertainties associated with the approach, but the results are not expected to be significantly different. Although direct ignition simulations of gas clouds resulting from hydrogen releases can be carried out, the *Q*9 concept is quite useful in reducing computational requirements for risk assessment purposes.

Interesting observations were found in the study. The findings reported here will contribute to the wider hazard assessment being conducted within the HySafe NoE. It should also be stressed that the results of this CFD study are only one part of this process. Experiments are being conducted at FZK in Germany and HSL in the UK to support the modelling work. Additional dispersion and combustion simulations will also be performed by HySafe partners before final conclusions are available from that project.

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