HYTUNNEL PROJECT TO INVESTIGATE THE USE OF HYDROGEN VEHICLES IN ROAD TUNNELS

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ABSTRACT

Hydrogen vehicles may emerge as a leading contender to replace today's internal combustion engine powered vehicles. A Phenomena Identification and Ranking Table exercise conducted as part of the European Network of Excellence on Hydrogen Safety (HySafe) identified the use of hydrogen vehicles in road tunnels as a topic of important concern. An internal project called HyTunnel was duly established within HySafe to review, identify and analyse the issues involved and to contribute to the wider activity to establish the true nature of the hazards posed by hydrogen vehicles in the confined space of a tunnel and their relative severity compared to those posed by vehicles powered by conventional fuels including compressed natural gas (CNG). In addition to reviewing current hydrogen vehicle designs, tunnel design practice and previous research, a programme of experiments and CFD modelling activities was performed for selected scenarios to examine the dispersion and explosion hazards potentially posed by hydrogen vehicles. Releases from compressed gaseous hydrogen (CGH_2) and liquid hydrogen (LH_2) powered vehicles have been studied under various tunnel geometries and ventilation regimes. The findings drawn from the limited work done so far indicate that under normal circumstances, hydrogen powered vehicles do not pose a significantly higher risk than those powered by petrol, diesel or CNG, but this needs to be confirmed by further research. In particular, obstructions at tunnel ceiling level have been identified as a potential hazard in respect to fast deflagration or even detonation in some circumstances, which warrants further investigation. The shape of the tunnel, tunnel ventilation and vehicle pressure relief device (PRD) operation are potentially important parameters in determining explosion risks and the appropriate mitigation measures.

1.0 INTRODUCTION

The Phenomena Identification and Ranking Table (PIRT) exercise conducted at the start of the HySafe project identified potential accidents involving hydrogen powered vehicles passing through road tunnels as a possible hazard, possibly representing an increased hazard compared to conventionally powered (hydrocarbon internal combustion) vehicles. HyTunnel, a HySafe internal project, was duly established with the primary objectives of reviewing tunnel design practice and previous research, to extend current knowledge by conducting experiments and computational fluid dynamics (CFD) modelling activities and to start developing recommendations for the safe introduction of hydrogen vehicles into tunnels.

Of most significance from the standpoint of contributing new research to the wider effort in establishing the safe use of hydrogen powered vehicles were the experimental studies involving hydrogen ignition performed at HSL in Buxton, the deflagrations and detonations performed at FZK in Karlsruhe, and, the CFD modelling studies of GexCon, the Warsaw University of Technology (WUT) and the University of Ulster (UU). These activities were conducted within the wider context of the HySafe Network of Excellence, and thus also contributed to various other HySafe work packages. While preliminary probabilistic risk analysis was applied to the use of hydrogen vehicles inside road tunnels, this is beyond the scope of this paper.

2.0 REVIEW

2.1 Tunnel design and operation

A survey of tunnel design and operational practice across Europe, together with regional and national guidance, identified suitable generic tunnel types for study within HyTunnel. These were important in particular for the CFD modelling activities described later.

Road tunnels generally fall into the following principal categories: urban or rural, naturally or mechanically (assisted) ventilated, rectangular or 'horseshoe' (arched ceiling) cross-section, and uni- or bi-directional traffic flow. Of potential significance for hydrogen (and other gaseous fuel systems such as CNG) is the ventilation regime employed to maintain an acceptable air quality, and for smoke/fire control in emergencies. Ventilation may have an important influence on whether a hazardous build-up of hydrogen occurs following the release of the fuel. Shorter tunnels (typically less than 400 m) are generally either naturally ventilated, using the flow of the traffic and atmospheric conditions to ventilate the tunnel, or are assisted by the presence of impulse (jet) fans at ceiling level to help push the contaminated air through the tunnel and out of one portal with replacement fresh air entering from the opposite portal. Longer tunnels may also be longitudinally ventilated with the assistance of impulse fans, or another arrangement such as a Saccardo nozzle. Alternatively, they may be transversely ventilated, with supply and extraction vents distributed along the tunnel. In the case of semi-transverse ventilation, supply (or alternatively exhaust) vents are distributed along the tunnel balanced by natural flow at the two portals. Information on tunnel design and ventilation can be found in various publications, e.g. [1, 2].

For the purposes of the HyTunnel CFD study, the scenarios considered the tunnel environment, the mix of vehicles involved, and the hydrogen release mechanism. The study investigated the relative importance of various physical parameters such as the variation in tunnel geometry (tunnel cross-section, gradient, obstacles), vehicle parameters (liquid or compressed gaseous hydrogen, release location and direction), and ambient and ventilation conditions. More details of the scenarios considered are given in Section 4.

2.2 Previous research

Although there is extensive published literature in the areas of general ventilation and fire and smoke control for road tunnels involving petrol, diesel, or CNG powered vehicles, the information explicitly directed at hydrogen powered vehicles is relatively limited. Examples of recently published work of direct relevance to HyTunnel are summarised below. We consider here full- and reduced-scale experiments as well as computational studies (primarily CFD). The published works of Hansen and Middha [3] and Molkov, Verbecke & Makarov [4] form a direct part of the HyTunnel activity, and are discussed in Section 4.

The potential hazards associated with high pressure, non-ignited (in the initial release) hydrogen jets inside a longitudinally ventilated tunnel were explored in the EIHP studies [5] and the work of Mukai et al [6]. The findings from these studies are as follows:

- Simultaneously releasing a large mass of hydrogen, e.g. from a city bus, through multiple vents was found to be more hazardous compared to when the same mass was released through a single vent.

- While the consequence of a release from a 20 MPa natural gas system was comparable to that from a 20 MPa hydrogen system, the consequence of a similar release from a higher pressure hydrogen system was significantly more severe, in particular with respect to predicted overpressures from a subsequent explosion of the hydrogen cloud. The significant difference in the explosion hazard associated with the 20 and 35 MPa release, despite a similar energy, was attributed to the different distribution of hydrogen mass within the flammable clouds formed.

- The CFD studies highlighted that the ignition point and timing inside the dispersed hydrogen cloud significantly affects the combustion regime. Based on the predicted overpressures, typical effects could be the damaged vehicle windows or tunnel lighting units. However, the results also indicated that fast deflagrations, or potentially detonations, could be produced by the most severe hydrogen releases and ignition timing from the worst case events.

By conducting a series of hydrogen release deflagration experiments and CFD simulations inside a reduced-scale tunnel geometry, Groethe et al [7] found that:

- Tunnel ventilation reduces the hazard dramatically, and it is suggested that suitable ventilation of a tunnel can significantly reduce the chance of an explosion. However, there may be the possibility that, even in a well ventilated tunnel, a high release rate of hydrogen could produce a near homogeneous mixture at close to stoichiometric conditions, with a correspondingly increased explosion hazard.

- The complementary CFD study extended the work to examine issues such as the explosion pressure effects in the locality of obstructions.

3.0 HYTUNNEL EXPERIMENTS

Experiments were performed at HSL to examine the effect of congestion and ventilation on the explosion hazard of a flammable gas release, and at FZK to investigate the high-speed deflagrations in stratified hydrogen layers, for example, under a tunnel ceiling.

3.1 Experiments at HSL to investigate influence of congestion on explosion overpressures

Ignition experiments were performed to investigate the influence of congestion and ventilation on the over-pressure generated by igniting stoichiometric clouds of hydrogen and air in a test rig (Figure 1).

Quiescent experiments were carried out in a sealed enclosure with a congested volume (consisting of an array of pipes) of approximately 0.1% and 0.5% of the total enclosure volume filled with a stoichiometric hydrogen/air mixture. For the 0.1% congested volume experiments three different levels of congestion were used, no obstacles and pipe arrangements A and B, and for the 0.5% tests no obstacles and pipe arrangement B. Arrangement A, consisting of four rows of pipes, had a spacing of three pipe diameters between pipes, with adjacent rows orientated at right angles and the pipes staggered between every other row. Arrangement B, consisting of 3 rows of pipes, had the same orientation of pipes, but with a spacing of five pipe diameters between pipes. Experiments in the 0.5% congested volume with pipe arrangement A were abandoned as they would have given explosion overpressures high enough to damage the enclosure.

The steady-state experiments were undertaken in a ventilated enclosure. The tests covered two congestion levels (arrangements A and B), three enclosure ventilation rates (1 m/s, 2 m/s and 4 m/s) and three hydrogen leakage rates (1.5 g/s, 2.0 g/s and 4.0 g/s). In these experiments a jet of hydrogen is released into a congested volume, which is intended to be representative of a hydrogen leak into a tunnel from a pressure relief valve or damaged pipework on a vehicle.

The flow rates used in the steady-state experiments were chosen to roughly correspond to the mass flow rates that would result from scenarios identified for the HyTunnel CFD activity (see Section 4.0), but scaled to take into account that the HSL enclosure is somewhere between 1/3-scale and 1/2-scale of a real tunnel.

Figure 1 shows an enclosure made up of two modules, with approximate dimensions of 5 m by 2.5 m by 2.5 m. In the present study, six modules were combined to give a total enclosure length (internal dimension) of 14.9 m, corresponding to an enclosure volume of 93.1 m^3 in the form of a rectangular vessel. The figure also shows the cube-shape cage used for the congestion.

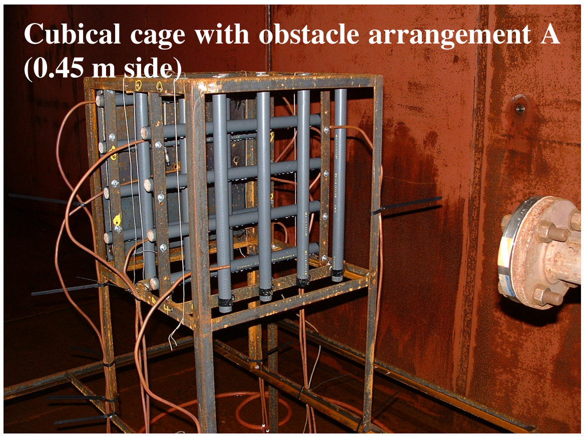

Figure 1. Experimental rig for HSL experiments

The rectangular vessel was used in two forms, firstly as a ventilated enclosure and secondly as a totally enclosed vessel. As a ventilated enclosure the ventilation rate could be varied and a critical flow orifice plate was used to create different hydrogen leakage rates into the enclosure. In the totally enclosed mode small quiescent volumes of stoichiometric hydrogen/air mixture (up to 0.55% of the enclosure volume) were created. In all of the experiments the resulting hydrogen cloud was ignited and the overpressure generated in the enclosure measured.

Ventilation of the enclosure is achieved through suction, using a variable speed fan attached to one end of the enclosure (can be seen on the left of Figure 1). The modules have pressure relief panels on the top to ensure venting, so that the enclosure is not damaged by too powerful deflagrations. An open-ended module was placed at the inlet end of the enclosure to reduce the effect of the ambient wind field. A further measure to create a homogeneous flow through the enclosure was the use of an end plate with 324 circular holes, each with a diameter of 0.05 m, for the air inlet ports. For the air outlet ports there are 16 square holes in the fan end of the enclosure. This arrangement allows air to be sucked through the enclosure.

For the measurement of the explosion overpressures generated in the enclosure, three types of pressure transducer were used. Two Kistler 4043A1 and Two Kistler 4043A2 piezo-resistive pressure transducers were fitted into the walls of the vessel. A Kistler 6031 piezo-electric pressure transducer was fitted into the wall of the congested volume cage. Some limited gas concentration measurements inside the cage were also undertaken, by the use of fixed sample probes and oxygen deficiency analysers. For all the 23 experiments (18 steady state and 5 quiescent), the pressure-time plots have been processed to give gauge pressure. Tables 1 and 2 illustrate the results obtained, showing here peak explosion overpressures.

Table 1. Results of the steady state ignition experiments: comparing peak explosion overpressures (mbar) for different obstacle arrangements

H_2 release rate	Pressure transducer locations	Air velocity (1 m/s)		Air velocity (2 m/s)		Air velocity (4 m/s)	
		Obstacle Layout A	Obstacle Layout B	Obstacle Layout A	Obstacle Layout B	Obstacle Layout A	Obstacle Layout B
1.5 g/s	Encl LH wall	28.2	16.2	13.6	8.8	12.1	6.0
	Cage wall centre	124.2	63.4	66.6	20.6	39.5	13.1
	Encl RH wall	63.5	19.6	12.6	7.5	10.5	5.0
2.0 g/s	Encl LH wall	32.4	27.5	23.2	25.7	14.1	20.9
	Cage wall centre	123.3	106.0	117.7	66.3	53.6	39.4
	Encl RH wall	55.4	46.6	39.6	46.6	14.7	25.4
4.0 g/s	Encl LH wall	48.9	48.5	37.3	48.1	26.0	28.9
	Cage wall centre	255.8	136.9	222.5	196.4	160.4	126.2
	Encl RH wall	71.2	91.7	66.0	85.8	39.2	51.2

Table 2 Results of the quiescent ignition experiments: comparing peak explosion overpressures (mbar) for different obstacle arrangements and congestion size

Pressure transducer locations	Congested volume size of 0.098 %			Congested volume size of 0.55 %	
	None	B	A	None	B
Encl LH wall	28.2	37.2	27.4	Over-range	Over-range
Encl RH wall	24.7	42.0	24.2	85.0	114.6

The main findings from the experiments were:

- In contrast to the results obtained for the quiescent tests with methane, the ignitions with hydrogen generated a non-uniform pressure field throughout the enclosure. Increasing the volume of hydrogen/air mixture increased the maximum explosion overpressure, but, unlike the results obtained with methane, increasing the level of congestion did not result in increasing explosion overpressures. An initial increase in the congestion level increased the maximum explosion overpressures, but a further increase in congestion resulted in a reduction in overpressure.

- Maximum explosion overpressures for hydrogen in the quiescent ignition tests were of the order of four times higher than the overpressures obtained for methane under identical conditions. In addition the pressure traces for hydrogen exhibited marked oscillatory behaviour in contrast to the relatively smooth traces obtained in the methane tests. Full frequency analysis of these oscillations has not been carried out, but the fundamental frequency found in the pressure-time waveform is related to the length of the chamber.

- In the steady state ignition tests the maximum explosion overpressures increased with increasing leakage rate and decreased with increasing ventilation rate. Explosion overpressures were similar in magnitude to those obtained in the quiescent tests and were also non-uniform throughout the enclosure.

- The trend in maximum explosion overpressure with the level of congestion depended on the leakage rate of hydrogen. At the lowest leakage rate the more congested configuration gave the highest explosion overpressures, while for the highest leakage rate the less congested configuration, except at the lowest ventilation rate, gave the highest explosion overpressures.

- Hydrogen concentration measurements have been made within the congested volume under the same conditions as the steady state ignition tests. These measurements have shown the expected trend, i.e., increasing the hydrogen leakage rate increases the hydrogen concentration, while increasing the ventilation rate reduces the hydrogen concentration. Increasing the level of congestion also increases the hydrogen concentration.

The above findings of the HSL experiments have the following implications to the safety of hydrogen powered vehicles in tunnels:

- Significant levels of overpressure can be generated in confined or semi-confined spaces, by the ignition of a hydrogen-air mixture filling only a small fraction, of the order of a few percent, of the space. These could be high enough to cause damage to tunnel services, e.g. ventilation ducting.

- For larger percentage fills of hydrogen-air mixture, the possibility of deflagration to detonation transition (DDT) cannot be ruled out.

- Hydrogen explosions are more prone to produce an oscillatory pressure-time profile than hydrocarbon explosions, which may have implications for the response of structures subjected to a hydrogen explosion.

3.2 Experiments at FZK to investigate deflagration and detonation in hydrogen ceiling layers [8]

Nine preliminary experiments and ten main experiments were performed to examine high-speed deflagrations in stratified hydrogen layers, for example, under a tunnel ceiling. The experiments were used to obtain the critical conditions defining the possibility of the self-sustained detonation in flat mixture layers.

The preliminary experiments were performed in a small-scale facility having the dimensions of 1.5 m x 0.5 m x 0.4 m (L x W x H). The first two preliminary experiments were conducted without any channel obstructions while in the later experiments an acceleration section, consisting of a large number of thin metal grids piled up in longitudinal direction, was installed close to the ignition end of the channel. The first two preliminary experiments without hydrogen were performed to check the experimental procedure and the triggering of the data acquisition system. In all these experiments, a commercially available spark plug was used to ignite the mixtures.

The main experiments were performed in a wide large rectangular chamber having the dimensions of 5.7 m x 1.6 m x 0.6 m, using layer heights of 0.15 m, 0.3 m and 0.6 m and hydrogen concentrations in the range of 15% to 25% by volume. Figure 2 shows the main experimental facility used, where the rectangular channel was opened from below. The main experiments were performed either in the unobstructed channel or with the channel equipped with an acceleration section and further obstacles with an effective blockage ratio equal to 60%. Both series of experiments included variations of the hydrogen concentration in hydrogen-air mixtures, whereas only in the main experiments was the hydrogen layer thickness also varied. A high frequency spark generator was used to ignite the mixture inside the large scale facility. The hydrogen concentration was kept uniform, with the level of non-uniformity being to within 1% by volume.

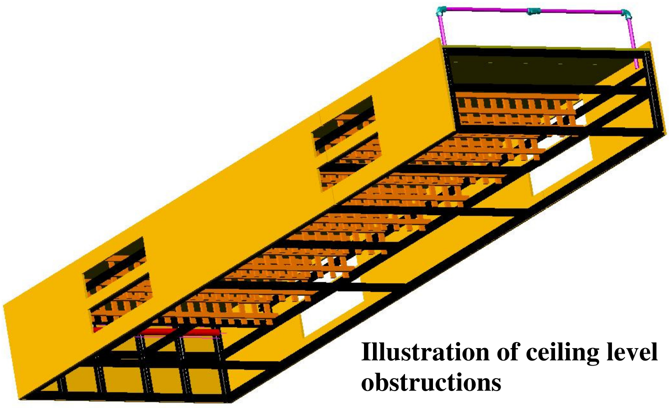

Figure 2. Experimental rig for FZK experiments

The experiments were equipped with pressure transducers (main experiments only), ion probes, light sensors, and high-speed photography. The sequence of frames obtained from high-speed photography was processed using 'background-oriented schlieren' method with the aim to provide visualization assistance of the flame propagation process.

All experiments in the unobstructed channel led to slow flame propagation regimes, with a maximum flame velocity of approximately 33 m/s. In the experiments with the obstructed channel three different combustion regimes could be distinguished according to the records of the sensors installed in the facility. The results are summarised in Table 3.

Two fields in the matrix above (shown italicised) could not be covered by experiments since the facility was destroyed during the experiment with a layer height of 0.3 m and a hydrogen concentration of 25%. Nonetheless, following the trend observed during the experiments one can assume that for a layer height of 0.6 m and a hydrogen concentration of 20% a fast deflagration and for a layer height of 0.6 m and a hydrogen concentration of 25% a detonation would have occurred.

Preliminary assessments gave a value for the critical layer thickness for a DDT event in the range of 7 - 20 detonation cell widths. With the results obtained from the experiments in the facility described, this value can be identified in the closer range from 7.5 to 15 times the detonation cell width.

The results of the full scale FZK experiments have highlighted the potential hazard posed by the explosion of hydrogen-air mixture in a tunnel. The results have indicated that DDT is, in principle, possible in the confined space of a tunnel. Consequently, ceiling design and mitigation measures may be important.

It was noted that the obstructions in the tunnel ceiling could add some turbulence to flame propagation and make explosions more severe.

Table 3. Summary of the experimental results in the obstructed experimental facilities

		Small scale	Large scale		
		Layer height [m]	Layer height [m]		
		0.40	0.15	0.30	0.60
$c(H_2)$ [Vol.-%]	15	slow deflagration	slow deflagration	slow deflagration	fast deflagration
	20	fast deflagration	fast deflagration	fast deflagration	*(fast deflagration)*
	25	detonation	decaying detonation	detonation	*(detonation)*

4.0 HYTUNNEL CFD STUDIES

The aim of the computer modelling activity was to complement the above experiments and to better understand the consequences of accidents inside road tunnels resulting in the release of hydrogen from vehicles. Using CFD, two aspects of the problem were addressed: Firstly, the dispersion of the released hydrogen within the tunnel, as a result of the activation of a PRD, and secondly the result of an explosion involving the dispersed hydrogen. Other aspects of the problem, arguably as important as those investigated, have not been addressed in the HyTunnel CFD activity. These include, for example, the consequence of an ignited high pressure jet of hydrogen, which may promote fire spread between vehicles as the jet flame propagates along the tunnel.

Simulations were conducted for an arched and a rectangular cross-section tunnel, and these are the focus of this paper. Some simulations were also conducted for an urban underpass or bridge with exposed structural beams under the ceiling to provide obstructions that might influence the dispersion and explosion characteristics of a hydrogen release. These indicated that that the ceiling obstructions (beams) caused an increase of approximately five times in a subsequent explosion overpressure.

4.1 Dispersion and explosion calculations by GexCon [3]

Dispersion and explosion simulations using the standard k-ε, Reynolds-averaged Navier-Stokes (RANS) CFD model FLACS were carried out for a two-lane, single bore tunnel with both rectangular and arched (horseshoe) cross-sections and an area approximately 50 m^2 and 60 m^2 respectively. It was assumed that the traffic flow was unidirectional. Longitudinal ventilation with different imposed upstream velocities was considered (with zero velocity representing natural ventilation in the absence of wind or 'piston' effects being a limiting case). The tunnel walls and ceiling were taken as smooth with no obstructions. The hydrogen release was assumed to be due to the activation of a PRD, so that the entire contents of the cylinder/tank (or group of cylinders/tanks) are released to the atmosphere. To be conservative, it was assumed that the hydrogen tank is full when the incident occurs. The length of the modelled tunnel was 500m, with the release location in the centre of the tunnel. Three hydrogen powered vehicles were considered in the simulated accident scenarios:

- Compressed hydrogen gas (CGH_2) city bus. The description was taken from the work of the EIHP-2 project, i.e. a representative city bus with roof mounted compressed gas fuel tanks housing a total 40 kg of hydrogen in 8 cylinders (in two sets of four cylinders), with 5 kg per cylinder at a storage pressure of 350 bar. The length and width of the bus were 12.0 m and

2.55 m respectively and its height 2.9 m, with the distance to the top of the tanks being 3.1 m. The vehicle was approximated in the CFD modelling as a rectangular block of dimensions 12.0 m by 2.55 m by 2.9 m.

- CGH_2 (fuel cell) car. An inventory of 5 kg hydrogen is stored in one cylinder at a pressure of 700 bar. The car was approximated as a simple rectangular block (5.0 m x 1.9 m x 1.5m) located 0.3 m above the ground.

- Liquid hydrogen (LH_2) internal combustion engine car. An inventory of 10 kg of liquid hydrogen was assumed.

For comparative purposes the following compressed natural gas (CNG) vehicles have been considered (assuming the same geometry as the hydrogen car and bus):

- City bus where 104 kg of natural gas stored at a pressure of 200 bar is released. It was assumed that the release occurs from a set of four cylinders, each with 26 kg natural gas.

- Car where 26 kg of natural gas stored at a pressure of 200 bar is released.

Both lanes were taken to be 100% filled by a regular pattern of buses and cars, spaced 1.5m apart, with 6 cars for each commercial vehicle. The incident location was assumed to be in the centre of the tunnel for both the car and bus release scenarios, as shown in Figure3.

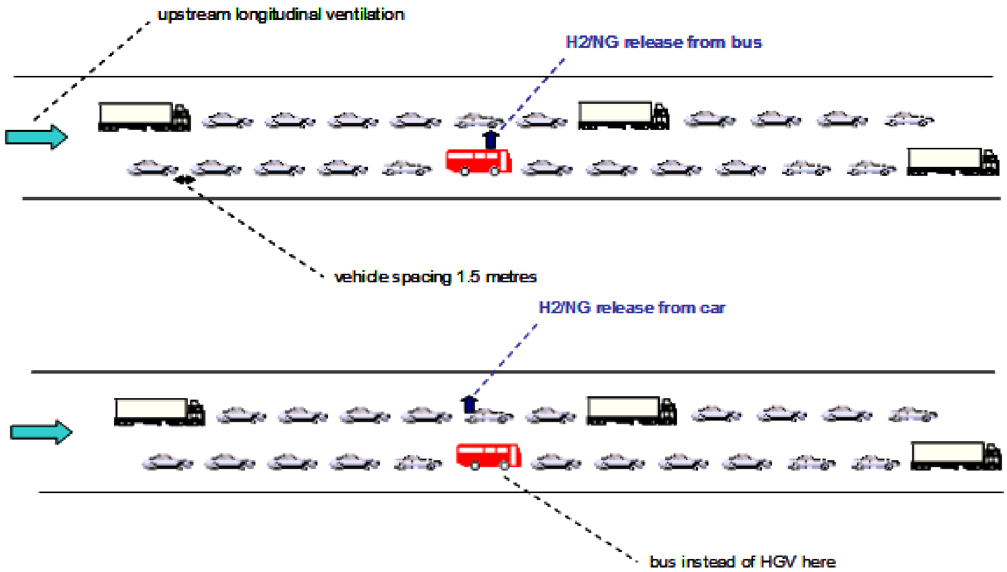

Figure 3. Traffic arrangements for GexCon simulations (schematic diagram)

For the liquid hydrogen a release through a 20 mm nozzle was assumed (10 kg in 15 minutes). For compressed gas releases, it was assumed that the release velocity was sonic. Release profiles were calculated for 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 coefficient 0.8). The release profiles were used as a boundary condition for dispersion simulations. Note that the durations for the hydrogen releases were based on the time it takes for the release rate to drop below 1 g/s.

Upstream longitudinal ventilation rates between 0 m/s and 5 m/s were investigated. Note that 3 m/s represents a typical value required to control the movement of heat and smoke from a vehicle fire inside a tunnel, i.e. eliminate the presence of back-layering so that the fire products are all forced in the direction of air flow, allowing egress in the opposite direction and easy access for the emergency services. Figure 4 illustrates the graphical output from the CFD simulations, showing hydrogen concentration contours for the 20 kg (bus) release for the case of no forced ventilation.

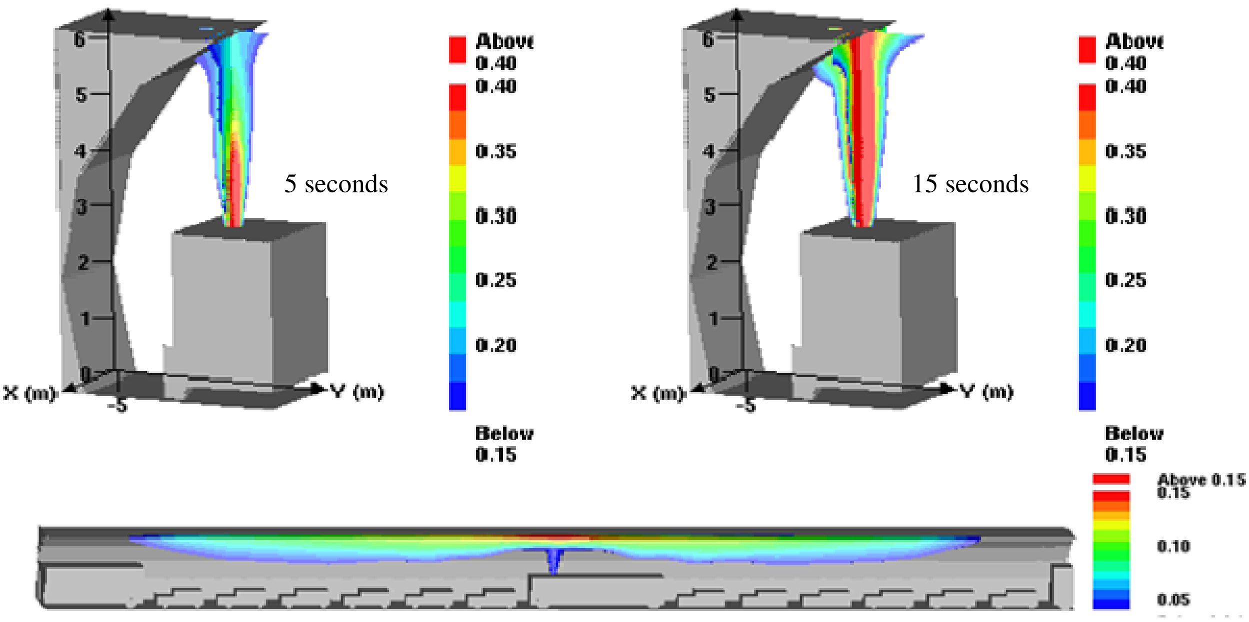

Figure 4. Hydrogen concentration contours for 20 kg (bus) release scenario (GexCon); The gas cloud extent for concentrations above 4 % (LFL) for the 20 kg bus release is shown in the middle.

In view of the limited space available here, given below are only the most important findings from the Hytunnel research (for more details see the previous ICHS paper [3] and the HyTunnel final report [9]):

- The LH_2 car release generally resulted in very small predicted gas clouds in both tunnel geometries. The compressed gas releases from the (fuel cell) car and the CGH_2 bus with the smaller release inventory resulted in a much larger accumulation of combustible fuel, with the flammable cloud sizes in the order of 200-300 m^3 in volume. Quite significant gas clouds (1500-2500 m^3) are seen for the scenario involving hydrogen released from 4 cylinders on a CGH_2 bus. However, the average concentration for these clouds was found to be fairly dilute, which meant that the associated explosion risk was not severe (see the last comment below).In general, the natural gas clouds resulting from releases from the CNG vehicles were found to be mostly small compared to those obtained from the CGH_2 vehicles, except for the large bus release in a rectangular tunnel.

- A lesser hazard (smaller flammable cloud) seemed to be associated with the arched (horseshoe) tunnel cross-section. It is suggested that this is due to the fact that there is 50% greater distance from the PRD vent to the ceiling, which allows more dilution prior to impingement and reduces the momentum of the impinging jet.

- While the predicted flammable gas cloud sizes were large for some scenarios modelled, if the actual reactivity of the predicted clouds is taken into account then only very moderate explosion overpressures resulted, in the region 0.1-0.3 barg.

- The sensitivity of the results for cases involving only low ventilation velocities (0 and 2 m/s) and involving only higher ventilation velocities (3 and 5 m/s) was studied. It was found that the effect of ventilation was small, which is in contrast to some other authors including WUT (see below).

4.2 Dispersion calculations by WUT

WUT investigated selected scenarios from the set described above using the FLUENT CFD code in RANS mode. Figure 5 illustrates a typical output from the CFD simulations. While the details of the work are beyond the scope of this paper, the main findings are summarised below:

In contrast to the GexCon work, it is suggested that the introduction of even a low level of ventilation (1 m/s) causes a significant reduction in the flammable cloud size and its associated hazard. The introduction of a minimum ventilation level of 3 m/s has been identified as a suggested requirement for hydrogen vehicles to be safely accommodated in road tunnels.

Results indicated that the arched (horseshoe) section was safer than the rectangular one as it allows for faster dispersion of the released hydrogen, which is in accordance with the GexCon's findings.

The simulations indicated that the compressed gas hydrogen releases were safer than those from liquid hydrogen vehicles, which is in contrast to the GexCon's findings. Clearly this requires further investigation, including physical experiments.

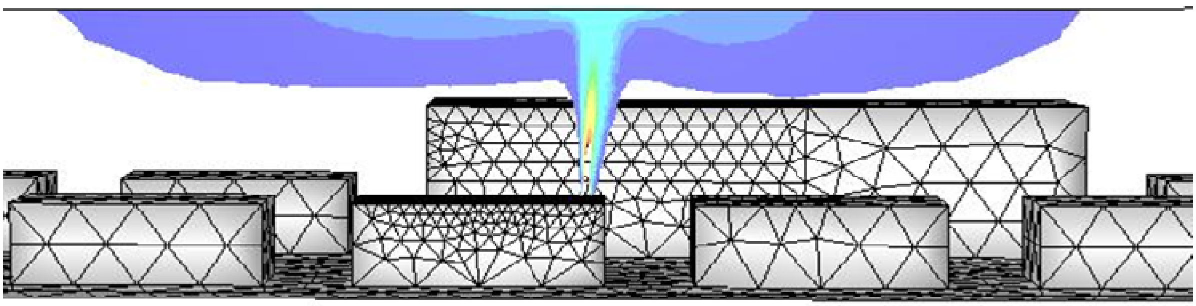

Figure 5. Hydrogen-air flammable cloud for the rectangular tunnel with no forced ventilation for CGH_2 release (700 bar) from a car – at time 84 s (cross-section through the release location and the longitudinal axis of the tunnel)

4.3 Dispersion and explosion calculations by UU [4]

The UU study compared their results on hydrogen releases from a bus using both a RANS and Large Eddy Simulation (LES) CFD modelling with those generated previously under the EIHP-2 project (where a RANS model had been employed). The bus was located at the tunnel midpoint, 100 m from each portal and centrally in one lane of a two lane, bi-directional tunnel. An investigation of the 'blow down' scenario of 5 kg of hydrogen released at an initial cylinder pressure of 350 bar through a 6 mm PRD vent was conducted.

It is suggested that the explosion overpressures may be larger than previously reported. It is also suggested that the smaller PRD vent diameters may help reduce the consequential explosion hazard. For further details see the published paper [4].

5.0 CLOSING REMARKS AND RECOMMENDATIONS

The experimental and CFD modelling work conducted within HyTunnel, together with a review of other published work, has provided a better understanding of the potential hazards associated with hydrogen vehicles in road tunnels. However, as illustrated by the conflicting findings from various elements of the work, the analysis of hydrogen vehicles in road tunnels is a complex task. Further investigation is clearly warranted before firm recommendations can be made. Nonetheless, the main findings from HyTunnel make an important contribution to the effort, and indicate provisionally that hydrogen powered vehicles can be operated safely in tunnels provided attention is given to various issues.

Some of the main findings are as follows. (1) Obstructions in the tunnel, particularly at ceiling level, have been identified as potentially increasing the risk of fast deflagration or even detonation in some circumstances. The design of tunnels in this respect requires consideration. (2) The increased ceiling height associated with arched cross-section tunnels has been identified as reducing the hazard associated with the release of hydrogen, due to increased dilution of the hydrogen stream and a reduction in momentum of the impinging jet. (3) Various research activities conducted within HyTunnel and elsewhere have suggested that imposing a minimum rate of ventilation inside road tunnels will mitigate the risk of explosions occurring following the release of hydrogen. However, the evidence is not conclusive, and further research is recommended. (4) The potential hazard associated with an extended, ignited hydrogen jet following activation of one or more PRDs has been raised. Further analysis of the risk, and how to best locate and operate the PRD(s) should be investigated further.

The ignition of a hydrogen-air mixture, filling only a few percent of the confined space of the tunnel, can generate significant overpressures that could be high enough to cause damage to tunnel services, e.g. ventilation ducting. For larger volumetric mixtures of hydrogen-air, the possibility of DDT cannot be ruled out. Hydrogen explosions are more prone to produce an oscillatory pressure-time profile than hydrocarbon explosions, which may have implications for the response of structures.

The HyTunnel work indicates that in new tunnels it may be preferably to allow a minimum distance to the ceiling to more safely disperse any released hydrogen gas. Reducing congestion at the ceiling (lighting etc) may also be important in reducing explosion hazards. In existing tunnels it may be prudent to impose a minimum ventilation rate to reduce the size of any flammable gas clouds.

7.0 REFERENCES

1. National Fire Protection Association, NFPA 502 (2008 ed.) – Standard for Road Tunnels, Bridges, and other Limited Access Highways.
2. World Road Association (PIARC) (1999). *Fire and smoke control in road tunnels*. World Road Association, Paris, France.
3. Hansen, O.R. and Middha, P., CFD simulation study to investigate the risk from hydrogen vehicles in tunnels, *Proc. 2nd Int. Conf Hydrogen Safety*, 11-13 September 2007, San Sabastian.
4. Molkov, V., Verbecke, F. and Makarov, D., LES of hydrogen-air deflagrations in a 78.5-m tunnel, *Combustion Science and Technology*, **180**, pp. 796-808, 2008.
5. Venetsanos, A.G., Baraldi, D., Adams, P., Heggem, P.S. and Wilkening, H., CFD modelling of hydrogen release, dispersion and combustion for automotive scenarios, *Journal of Loss Prevention in the Process Industries*, **21**, 2008, pp. 162–184.
6. Mukai, S., Suzuki, J., Mitsuishi, H, Oyakawa, K. and Watanabe, S., CFD Simulation on Diffusion of Leaked Hydrogen Caused by Vehicle Accident in Tunnels, *Proc. 1st Int. Conf Hydrogen Safety*, 8-10 September 2005, Pisa.
7. Groethe, M. Merilo, E., Colton, J., Chiba, S., Sato, Y. and Iwabuchi, H., Large-Scale Hydrogen Deflagrations and Detonations, *Proc. 1st Int. Conf Hydrogen Safety*, 8-10 September 2005, Pisa.
8. Friedrich, A., Grune, J., Jordan, T., Kotchourko, A. and Kotchourko, N., Experimental Study of Hydrogen-Air Deflagrations in Flat Layer, *Proc. 2nd Int. Conf Hydrogen Safety*, 11-13 September 2007, San Sabastian.
9. Kumar, S. , Miles, S.D., Adams, P., Kotchourko, A., Prichard, D., Hedley, D., Middha, P., Molkov, V., Vaerbecke, F., Teodorczyk, A., Angebo, A., and Zenner, M., HyTunnel Final Report, HySafe Deliverable 111, 2009.