DEFLAGRATIONS OF NON-UNIFORM HYDROGEN/AIR CLOUDS IN A TUNNEL

Rattigan, W.M.[1], Lyons, K.[1], Moodie, K. [1], Fletcher, J. [1], Atkinson G.A. [1]
[1] Major Hazards Capability Group, Health and Safety Executive, Harpur Hill, Buxton, SK17 9JN, UK, wayne.rattigan@hse.gov.uk

ABSTRACT

This paper presents work undertaken by the HSE as part of the Hytunnel-CS project, a consortium investigating safety considerations for fuel cell hydrogen (FCH) vehicles in tunnels and similar confined spaces.

Hydrogen vehicles typically have a Thermally activated Pressure Release Device (TPRD) providing protection to the on-board storage of the vehicle. Upon activation, the content of the vessel is released in a blowdown. The release of this hydrogen gas poses a significant hazard of ignition. The consequences of such an ignition could also be compounded by confinement or congestion.

HSE undertook a series of experiments investigating the consequences of these events by releasing hydrogen into a tunnel and causing ignitions. A sub-section of these tests involved steel structures providing congestion in the tunnel. The mass of hydrogen released into the tunnel prior to ignition was varied by storage pressure (up to 59 MPa), release diameter, and ignition delay. The ignition delays were set based on the expected worst-case predicted by pre-simulation models. To assess the consequences, overpressure measurements were made down the tunnel walls and, for the tests with congestion, at the face and rear of the congestion structures. The flame arrival time was also measured using exposed-tip thermocouples, resulting in an estimate for flame speed down the tunnel. The measured overpressure and flame extent results are presented and compared against overpressure levels of concern.

1.0 INTRODUCTION

Hydrogen-powered vehicles are currently in service on the UK and European road networks [1] with over 56 thousand hydrogen-fuelled cars being sold worldwide by 2022 [2]. Hydrogen-powered trains have been demonstrated on the rail network in the UK [3] and the world's first 100% hydrogen operated route, in Germany, is due to be completed in early 2023 [4]. The number of hydrogen-powered vehicles will continue to grow with some predicting as many as 1 million vehicles worldwide by 2027 [5].

Due to the difference in behaviour between hydrogen and traditional fossil fuels, certain accident scenarios have different implications and potentially more severe outcomes when compounded by enclosed spaces such as tunnels. The HyTunnel-CS project [6] was created to identify and assess these scenarios [7]. The output of the project provides both theoretical and experimental insights into the identified scenarios, as well as recommendations for the safe use of hydrogen vehicles [8] and for updates to regulations, codes, and standards [9]. These insights and recommendations will enable more robust decision-making in the adoption of hydrogen vehicles.

Hydrogen fuelled vehicles are fitted with thermally activated pressure relief devices (TPRD), which prevent the onboard storage vessels from over pressurising, and bursting catastrophically, should a thermal event occur i.e., fire. One scenario identified was the release of hydrogen following TPRD activation inside a tunnel, either following an accident or in the event of a spurious activation of the TPRD. This would cause hydrogen to be released from the onboard vehicle storage tanks, at pressures up to 70 MPa, creating a non-uniform flammable hydrogen air mixture inside the tunnel, with the potential for ignition resulting in deflagration or even detonation inside the tunnel.

The objectives of the work carried out at HSE was to measure how, in the event of this type of release, the hydrogen gas would be dispersed inside a tunnel, and then to ignite the same releases and measure the resulting overpressure and flame speed. Thus, providing key information on the flammable extent, the potential for ignition and, in the event of an ignition, the hazard distances associated with the event.

The dispersion characteristics of the hydrogen were determined in two ways: by pre-trial simulations of the blow downs, carried out by NCSRD [9] and by actual blowdown releases carried out by HSE, where the concentration of hydrogen was measured at 15 locations inside the tunnel [10]. The pre-trial simulations provided key information on the likely flammable extent of any hydrogen air clouds and helped to best decide on the optimal location for the igniter when designing the release experiments. The subsequent release experiments inside the tunnel provided data to enable the ignition delays for the ignited releases to be optimized.

Experiments were planned to simulate the release from 3 types of vehicles, cars, buses, and trains, with two different train models being considered. The releases were planned with 2 different ventilation rates inside the tunnel and both with and without congestion.

In hydrogen cars the hydrogen storage tanks are underneath the vehicle and the TPRD are pointing downward. To mimic this in the experiments, the nozzle was pointing downward and close to the ground at a height of 137 mm.

For trains and buses the TPRDs for the hydrogen tanks are pointing upward, above the roof of the vehicles, and so for the corresponding experiments the nozzle was pointing vertically upward at a height of 1.54 m. It should be noted that the HSE experimental tunnel is not equivalent in size to real-world road or rain tunnels and therefore all relevant parameters, including mass of hydrogen, release height and vehicle size, are all scaled to give representative conditions. Further details of the scaling are given in paragraph 3.0.

In total, 21 ignited release experiments were carried out, providing a key insight into the ignition behaviour of non-uniform hydrogen air clouds inside a tunnel. The data generated will be used to validate numerical models.

2.0 EXPERIMENTAL SETUP

The experimental facility was created to allow for the release of hydrogen gas into a tunnel, at pressures up to 70 MPa, to measure the gas concentrations in the tunnel following a release and to then ignite the same releases and measure the resulting deflagration overpressure and flame speed. The facility comprises several component parts:

- Tunnel
- gas boosting and delivery system
- fans
- experimental control system
- igniter
- sensors
- data acquisition system

2.1 Tunnel

The facility consists of a circular steel tunnel, which is nominally 3.7 m in diameter and comprises 5 sections totalling 70 m in length. The central section is 8 m long and has a wall thickness of 55 mm. The outer sections have a wall thickness of 25 mm and together are approximately 31 m in length, each side of the central section, Figure 1a. The central section can withstand static pressures up to 3 MPa. The outer sections can withstand static pressures up to 1.4 MPa. Both the central and outer sections can withstand higher dynamic pressures of at least 3 MPa resulting from a shock or blast wave travelling along the tunnel. The sections of the tunnel were aligned and sealed to prevent any leakage of gas.

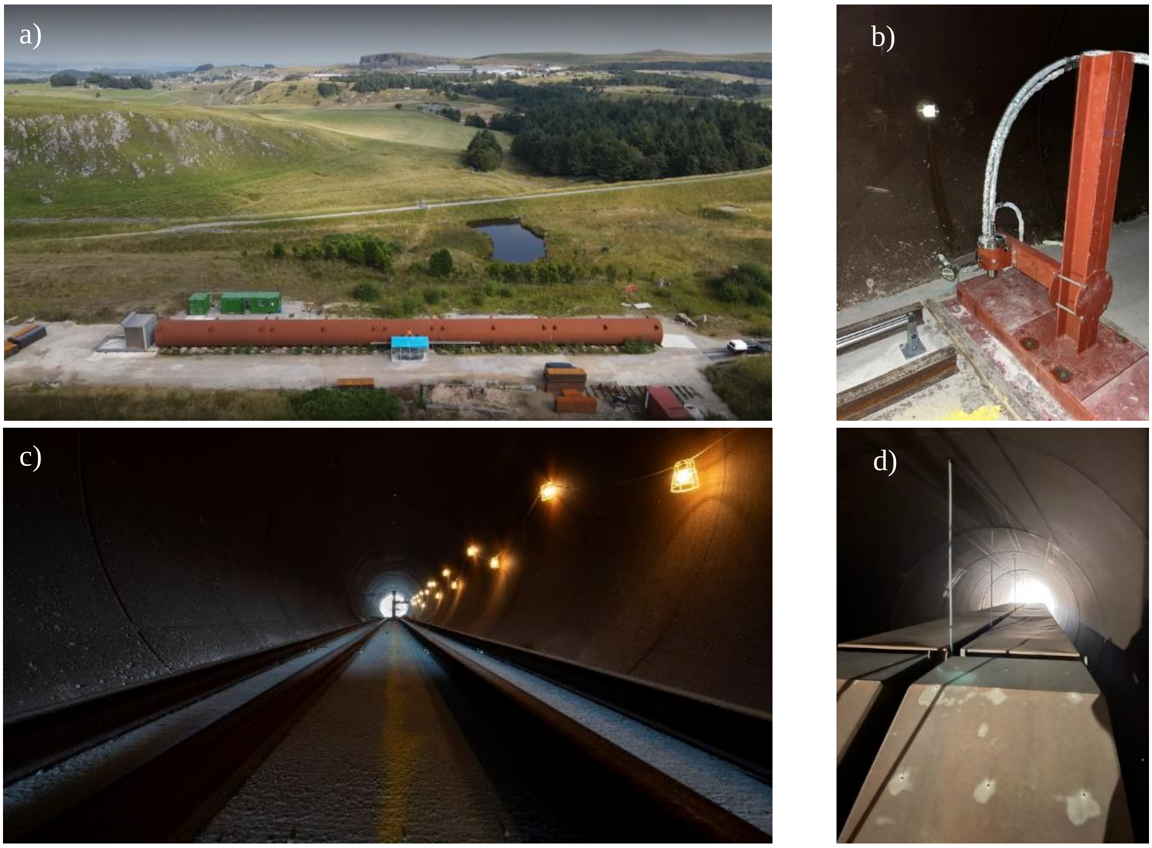

Figure 1. a) Aerial image of 70 m steel tunnel, b) discharge nozzle manifold, pointing downward, c) Inside the 3.7 m diameter tunnel showing the tracks used to secure scaled vehicles, d) scaled trains secured to tracks with thermocouple arrays also visible.

The tunnel floor was lined with concrete to a depth of 0.45 m to provide a strong and even surface for the mounting of the nozzle and for the scaled vehicles in some of the tests. A metal plate was secured directly under the vertically downwards pointing jet to act as a spreader plate for the jet during these tests and to prevent damage to the floor, Figure 1b. Steel rails were secured to the floor of the tunnel, and these were used to anchor the scaled vehicles, Figure 1c and Figure 1d.

2.2 Gas boosting and delivery system

The gas delivery rig, located externally at the centre of the tunnel takes hydrogen gas from multicylinder packs (MCP) at pressures < 17 MPa and then, in two stages, boosts the pressure to a maximum of 70 MPa. The first stage boosts the pressure up to 35 MPa using a Haskel 8AGD-30 booster pump, into a 320 L tank. The second stage boosts the pressure through a pair of twin Haskel AGD-75 booster pumps to a set of three type IV composite vessels. The second stage can be used as either a single 53 L vessel, or all three with a volume of 159 L.

A simple schematic of the set-up is shown in Figure 2.

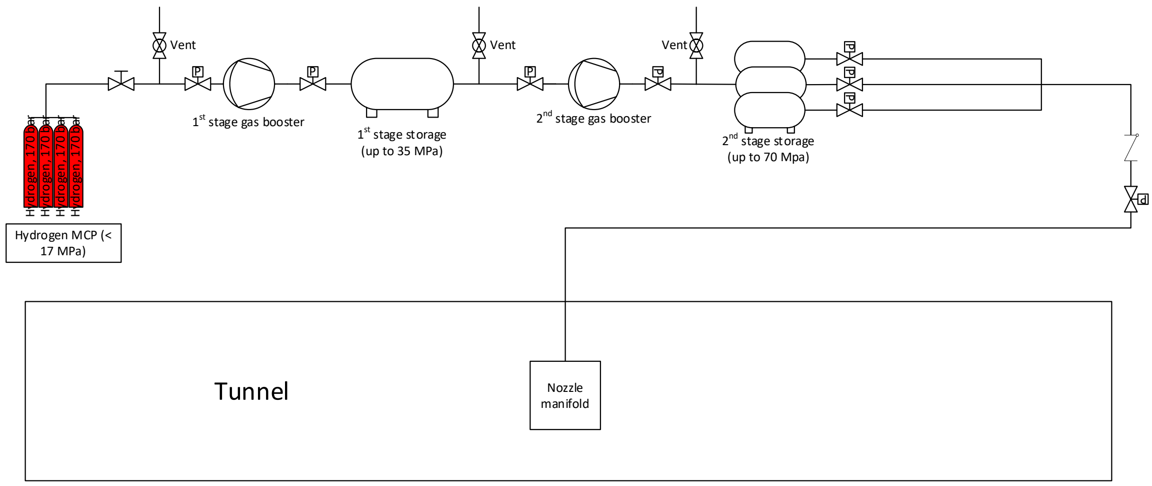

Figure 2. Simplified schematic of the hydrogen gas boosting and delivery system.

Nozzle manifold

From the gas storage system, the hydrogen could be released inside the tunnel via a configurable nozzle manifold, Figure 1b. The nozzle manifold is connected to the 2nd stage gas storage via three high-pressure flexible hydrogen hoses, which allowed the nozzle to be moved to the desired position. For simulated car releases the nozzle was pointing downward, 137 mm from the ground, and for bus and train releases it was pointing upward at a height of 1.54 m.

Table 1: Measured nozzle diameters.

Nominal Nozzle Diameter (mm)	Measured Nozzle Diameter (mm)
2.2	2.2487
4.0	4.0731
4.7	4.7662
5.7	5.7318

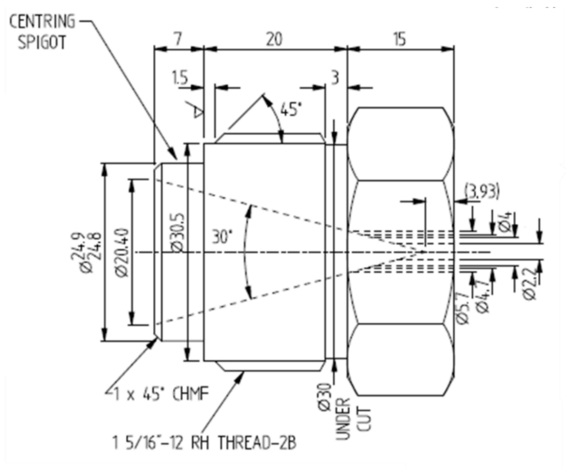

Figure 3. Dimensional drawing of the 4 available nozzles.

The manifold allowed for the interchange of nozzles to achieve the desired scaled hydrogen mass flow rates. More on the scaling of the releases to real-world scenario is explained in section 3.0. The nominal sizes of the nozzles and the actual measured hole sizes are shown in Table 1. and a dimensional drawing of the nozzles is shown in Figure 3. The nozzle sizes were chosen to give an equivalent scaled initial mass flow in the HSE experiments compared with that of release from a TPRD release in a full-scale vehicle. For example, the jet from a car cylinder at 700 bar with an orifice diameter of 1.0 mm is the equivalent of releasing 118 bar through a 2.2 mm diameter nozzle. This is because the fully expanded jets in both cases have an initial fully expanded diameter of 16.8 mm at atmospheric pressure and thereafter, they both behave in the same manner, namely as a free turbulent jet, for which the decay characteristics are well documented in the literature.

The nozzle manifold support structure is securely mounted onto the concrete layer in the tunnel via a 150 mm high steel plate. This steel plate extends beyond the release point, which means that the height of the release is based upon the distance to this steel plate rather than the concrete surface.

2.3 Fans

An array of seven Casals HCX71 T4 3-phase fans were installed at the end of the tunnel to provide ventilation and a semi-consistent wind speed. The fans could achieve volumetric flow rates up to 1.8×10^5 m^3/h, which equated to a maximum linear air flow velocity of 5.0 m/s. The fans drove air through an aluminium honeycomb hexagonal grid, which reduced the swirl from the fans and produced a ‘straightened’ air flow down the tunnel. This was measured prior to the hydrogen gas being released to provide a measure of the average air flow velocity inside the tunnel.

The fans were housed in a large, bespoke, retractable structure, mounted on wheels, and running on tracks, which allowed the structure to be pulled away from the tunnel entrance when access was required.

Figure 4. Fan array. Comprises 7 axial fans with a combined power output of 15.4 kW, capable of generating wind speeds up to 5 m/s inside the tunnel

Stable air flow velocities between around 1.2 m/s and approximately 5 m/s were achieved. However, while more stable than ambient conditions, the wind did have an impact on the wind speed inside the tunnel. Strong counter and co-flows influenced the flow regime inside the tunnel. The natural variation in the ambient wind conditions resulted in the measured air flow velocity inside the tunnel fluctuating within a range of the desired value. This range reduced as the fans speed increased, as the variation in ambient conditions was proportionally less dominant.

Scaled air flow velocities of 1.0 m/s and 2.5 m/s were chosen as basis for investigation in the HSE experiments. These equate to real-world air flow velocities of around 1.5 m/s and 3.8 m/s for road tunnels and around 1.6 m/s and 4.1 m/s for rail tunnels (see section 3.0 on scaling).

2.3 Experimental control system

Due to the potentially energetic nature of the experiments the operation of the system was done from a control room located 250 m from the tunnel.

The control system, based on a National Instruments cRIO system, allowed for the rig to be filled and discharged remotely via a series of pneumatically actuated control valves. The sequencing of the valve openings, the delay and duration of the igniter could all be set independently from the control software. The pressure and temperature of the four storage tanks, in the first and second stages, were monitored and the pressure and temperature at the discharge nozzle was also monitored. All pressure and temperature data were recorded at 200 Hz, allowing the hydrogen mass flow rate to be calculated and compared with predicted values.

2.4 Igniter

The ignition system was based on a car spark plug and controlled from the experimental system. The ignition delay and the duration of the spark were variable. The delay was set between 0 s and 24 s depending on the desired experimental scenario and the duration of the spark was typically set to 10 s, however, it was found that, where ignitions occurred, they did so at the first spark, which was around 100 ms from the nominal ignition delay time.

The position of the igniter could be moved to match the release scenario. For bus and train scenarios, where the release was upward toward the tunnel ceiling, the igniter was located near the crown of the tunnel and 3.0 m downstream of the release point. For the downward car releases the igniter was located 1.0 m downstream of the release point and close to the ground.

2.5 Experimental Sensors

The release of hydrogen was halfway down the tunnel with the sensor arrays largely located downstream of this; one pressure transducer and one thermocouple array were located upstream of the release. All the positions of the sensors are referenced (x, y, z) to the end of the tunnel at the lowest point on the centre line. A sketch showing the co-ordinate system for the tunnel is shown in Figure 5.

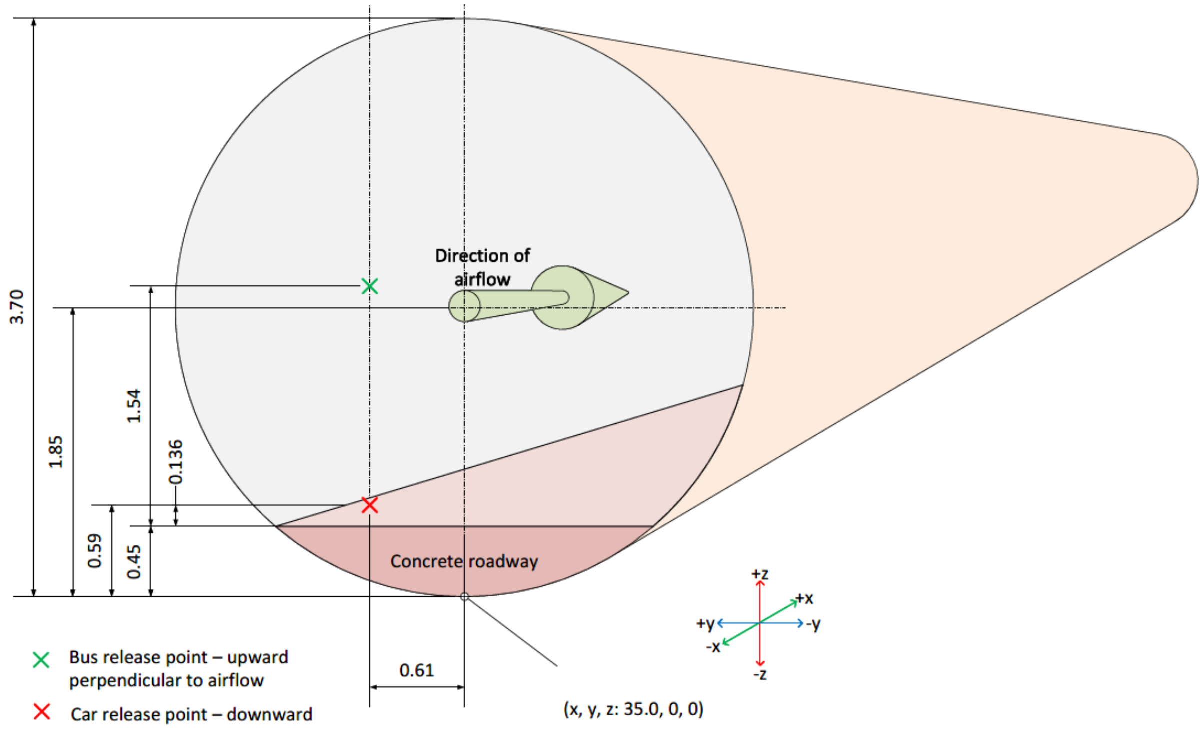

Figure 5: Cross-section sketch of the release point of the tunnel (section through the mid-point of the tunnel at x=35.0 m)

To capture any explosion events inside the tunnel it was fitted with 8 fast response pressure transducers and 45 fine-tipped (0.3 mm) type-K thermocouples. The specification of the transducers and thermocouples is shown in Table 2. It should be noted that the thermocouples were not used as temperature measurement sensors but as flame detection sensors and, although they do give an indication of the temperature, should not be treated as accurate measurements.

Table 2: Sensor accuracies.

Instrument	Sensor	Make/model	Range	Accuracy
Pressure transducer	P12, P11, P10	Kulite HKL-375M-100G	100 PSI (gauge)	± 0.5% FSO
Pressure transducer	P9, P8. P7, P5, P3	Kulite HEL-375-100A	100 PSI (abs)	± 0.5% FSO
Thermocouple	T01 to T45	Type K 0.3 mm tip	*n/a	*n/a

*n/a: the thermocouples were used as flame arrival detectors, not flame temperature sensors

The pressure transducers were mounted flush to the walls of the tunnel and captured the progression of the shock front down the tunnel. The locations of the transducers are shown in Table 3.

Table 3. Location of pressure sensors inside the tunnel

Sensor ID	Co-ordinate (m)		
	x	y	z
P12	34.0	1.85	1.85
P11	36.0	1.85	1.85
P10	37.5	1.85	1.85
P9	40.0	1.85	1.85
P8	42.5	1.85	1.85
P7	45.0	1.85	1.85
P5	50.0	1.85	1.85
P3	55.0	1.85	1.85

The 45 thermocouples were mounted on 9 vertical arrays with 5 thermocouples on each. The positioning of the thermocouples is shown in Figure 6 and the locations listed in Table 4.

The orientation and spacing of the thermocouples allowed the linear progression of the flame down the tunnel to be evaluated by measuring the time of arrival at each thermocouple station and gave an indication of the variation by height of the flame progress.

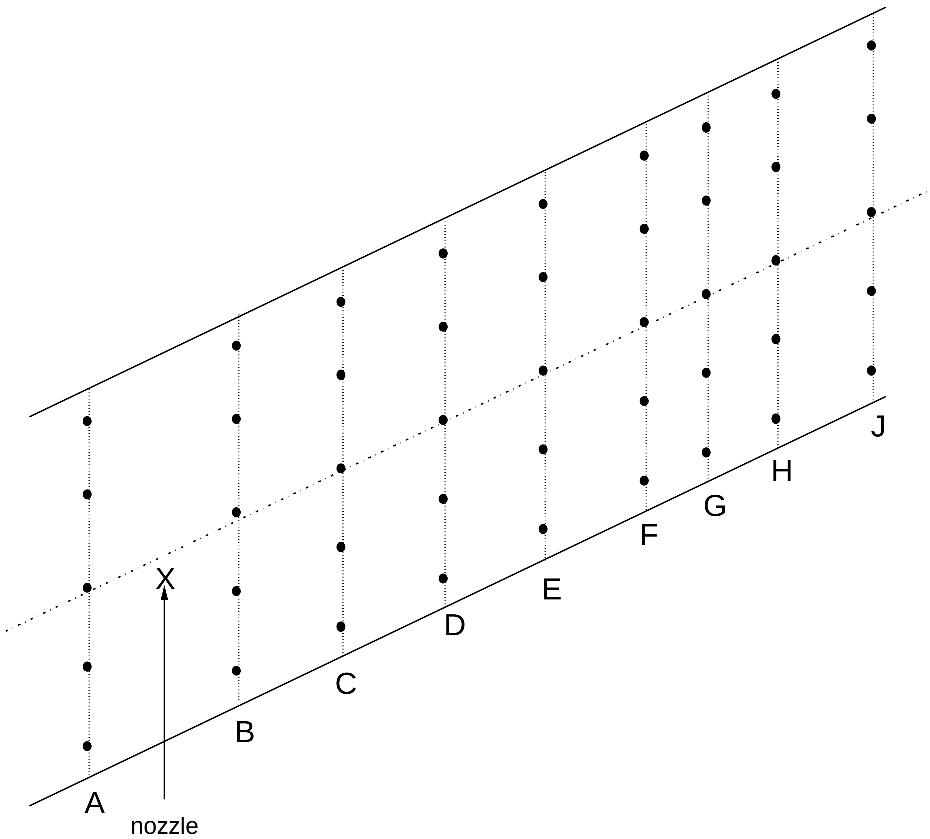

Figure 6. 3-D representation of thermocouple flame sensor locations relative to release point

Table 4. Location of thermocouple sensor arrays inside tunnel. The release point is at 35.0, 0.61, 1.99 for buses and trains, and 35.0, 0.61, 0.54 for cars.

Array	Sensor ID	Co-ordinate (m)		
		x	y	z
A	T05, T04, T03, T02, T01	34.0	0.0	3.25, 2.75, 2.15, 1.65, 0.95
B	T10, T09, T08, T07, T06	37.5	0.0	3.25, 2.75, 2.15, 1.65, 0.95
C	T15, T14, T13, T12, T11	40.0	0.0	3.25, 2.75, 2.15, 1.65, 0.95
D	T20, T19, T18, T17, T16	42.5	0.0	3.25, 2.75, 2.15, 1.65, 0.95
E	T25, T24, T23, T22, T21	45.0	0.0	3.25, 2.75, 2.15, 1.65, 0.95
F	T30, T29, T28, T27, T26	50.0	0.0	3.25, 2.75, 2.15, 1.65, 0.95
G	T35, T34, T33, T32, T31	55.0	0.0	3.25, 2.75, 2.15, 1.65, 0.95
H	T40, T39, T38, T37, T36	60.0	0.0	3.25, 2.75, 2.15, 1.65, 0.95
J	T45, T44, T43, T42, T41	65.0	0.0	3.25, 2.75, 2.15, 1.65, 0.95

2.5 Scaled Vehicles

To understand the influence of congestion on the developed overpressure within the tunnel, experiments were planned where scaled vehicles would be located downwind of the hydrogen release point. In total, 6 experiments were undertaken, simulating the release from bus and train respectively. The dimensions and layout, referenced to the mid-line of the tunnel, are shown in Figure 7. below. An image of the installed vehicles in the HSE tunnel is shown in Figure 1d.

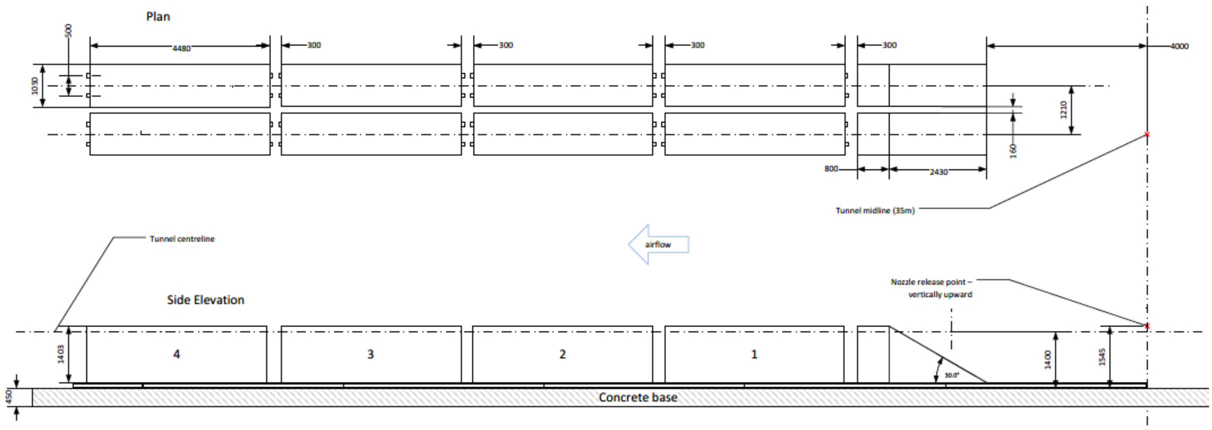

Figure 7. Layout and dimensions of scaled vehicles in HSE 70 m tunnel (distance from mid-line of tunnel (x = 35.0) are indicated).

The installed congestion gave a blockage ratio of 29% across the cross-section of the tunnel.

3.0 SCALING

Since the HSE tunnel is smaller compared to a typical road or rail tunnel, scaling has been used to allow for extrapolation of the results. The scaling used is an existing method [12] and discussed in detail previously [13], [11]. This section shows a summary of the method to enable an application to the results.

The main objective of the scaling is to enable a similar hydrogen concentration at the normalised height of the HSE tunnel, which will be applicable to real-world tunnels. This is achieved by scaling the hydrogen mass and mass flow rates of real scenarios by a factor based on the relative diameters of the HSE tunnel to a real tunnel. Based on this scaling and practical constraints (hydrogen cylinder volume availability), the initial conditions for the experiments were selected. These factors will be applied to the measured concentrations to describe the real scenario modelled.

The scaling factors are derived as follows:

- Scaling factor (H) for tunnel diameter is D/D_{HSE}
- Scaling factor for mass of hydrogen stored is H^3
- Scaling factor for the mass flow rate is $H^{5/2}$.
- Scaling factor for the discharge time is: $H^{1/2}$.
- Scaling factor for the airflow in the tunnel is: $H^{1/2}$.

Table 5. Scaling factors for mass, mass flow rate, discharge time and airflow velocity.

Scenario	SF	SF (mass)	SF (mass flow rate)	SF (discharge time)	SF (airflow)
Car	2.275	11.775	7.806	1.508	1.508
Bus	2.275	11.775	7.806	1.508	1.508
Train 1	2.665	18.927	11.594	1.632	1.632
Train 2	2.665	18.927	11.594	1.632	1.632

4.0 RESULTS

Overall, 21 successful release experiments were carried out in the HSE facility with attempted ignition. Seven of these were simulated car releases, 7 were bus releases and 7 were train releases.

The achieved test matrix and the experimental variables: nozzle diameter; ignition delay; hydrogen volume and pressure; congestion; wind speed; and ignition outcome, are all summarised in Table 6.

Table 6. Experimental test matrix and test variables.

Test No.	Nozzle diameter (mm)	Ignition delay (s)	Vol. (l)	Nominal pressure (MPa)	Congestion	Wind speed (m/s)	Ignition (Y/ N)
13	2.2	20	53	11.8	None	1.1 to 1.6	N
14	2.2	10	53	11.8	None	1.1 to 1.6	N
15	2.2	0	53	11.8	None	0.9 to 1.8	N
17	2.2	10	53	11.8	None	0.8 to 1.4	N
18	2.2	0	53	11.8	None	0.8 to 1.6	N
19	2.2	0	53	11.8	None	0.7 to 1.8	N
20	2.2	0	53	11.8	None	0.7 to 1.8	N
21	4.0	12	159	32.0	None	0.9 to 1.5	Y
22	4.0	12	159	32.0	None	2.3 to 2.6	N
23	4.0	15	159	32.0	None	1.1 to 1.6	Y
24	4.0	15	159	32.0	None	2.2 to 2.5	N
25	4.7	12	159	58.0	None	1.0 to 1.6	Y
40	4.0	20	159	32.0	Yes	Natural	Y
42	4.0	20	159	32.0	Yes	Natural	Y
43	4.0	24	159	32.0	Yes	Natural	Y
44	4.7	4	159	58.0	Yes	Natural	Y
45	4.7	6	159	58.0	Yes	Natural	Y
46	4.7	8	159	58.0	Yes	Natural	Y
55	4.7	3	159	58.0	No	Natural	Y

Test No.	Nozzle diameter (mm)	Ignition delay (s)	Vol. (l)	Nominal pressure (MPa)	Congestion	Wind speed (m/s)	Ignition (Y/ N)
56	4.7	5	159	58.0	No	Natural	Y
57	4.7	10	159	58.0	No	Natural	Y

4.1 Car Releases

Typical storage pressures inside cars are up to 70 MPa, with storage volumes varying between 115 litres and 156 litres in two cylinders, each fitted with a TPRD pointing downward and behind the vehicle. An average size of 135 litres (equivalent to 5.4 kg hydrogen) was used as the basis for the HSE experiments.

The accident scenario suggested that both TPRDs could activate simultaneously releasing the entire hydrogen inventory. To simulate this release experimentally a nominal hydrogen pressure of 11.8 MPa, volume 53 litres, was released through a 2.2 mm nozzle.

Tunnel ventilation rates were set at both the low and higher values, 1.0 and 2.5 m/s, and the ignition delay was varied from 20 s to 0 s. Ultimately, the final three tests, 18 to 20, were carried out with the igniter firing constantly for a duration of 60 s with a delay of 0 s; the ventilation rate was also set to its lowest.

It was not possible to initiate an ignition in any of the 7 tests undertaken. The planned tests with congestion, to demonstrate the effect of turbulence on explosion intensity, were not undertaken as they became redundant without an ignition being possible.

4.2 Bus Releases

Typical storage pressures inside buses are up to 35 MPa. The eight storage tanks are located on the roof of the vehicle with each having a volume between 200 litres and 220 litres and each fitted with a TPRD. An average size of 210 litres (equivalent to 4.97 kg hydrogen) was used as the basis for the HSE experiments.

To simulate this release experimentally a nominal hydrogen pressure of 32.0 MPa, volume 153 litres, was released through a 4.0 mm nozzle.

The initial tests, 21 to 24, were undertaken without congestion and with 2 tunnel ventilation rates. The 2 tests where the higher ventilation rate of around 2.5 m/s was utilized did not produce ignition for either ignition delay, 12 s or 15 s.

The experimental plan was to carry out the same tests, where ignition occurred, but with congestion. However, it should be noted at this point that the planned tests could not be carried out due to damage to the test facility. This damage occurred when undertaking the largest release without congestion, simulating a train release scenario. The overpressure generated was sufficient to shunt the fan assembly 8 m away from the tunnel, despite being secured to the tracks. The fans were significantly damaged and were not repairable within the timeline of the project.

Therefore, all the following tests with congestion, bus and train scenarios, were carried out with natural ventilation. The natural wind speed inside the tunnel was measured prior to the test releases.

The repeat tests undertaken, test 40 and 42, with an ignition delay of 20 s showed good reproducibility. The measured overpressures at the nearest downstream pressure transducer from the release point (P11) were 10.51 kPa and 10.23 kPa respectively. The overpressures 19 m downstream at the last pressure transducer (P3), were 7.29 kPa and 4.93 kPa respectively.

The test where the ignition delay was 24 s, test 43, produced an overpressure of 34.13 kPa at P11 and 30.87 kPa at P3.

Comparing the congested tests with the uncongested tests is difficult owing to the variation in test conditions, primarily the absence of the fans to provide ventilation in the latter tests but also the difference in ignition delay.

4.3 Train Release

Typical storage pressures inside trains are up to 35 MPa. Two different train models were considered.

The first model (Train 1) is a two-carriage unit with each carriage having 24 cylinders of 175 litres volume, which is equivalent to 4.1 kg hydrogen per cylinder. There are 2 TPRDs per cylinder, which vent upward at roof height.

The second model (Train 2) has a total of 72 cylinders split between the lead and trail carriages. Each cylinder has a volume of 245 litres, which is equivalent to 5.8 kg of hydrogen per cylinder. There are 2 TPRDs per cylinder, which vent upward at roof height.

The dispersion behaviour of hydrogen for both the train 1 and train 2 scenarios were demonstrated in the earlier trials carried out at HSE. However, only the train 2 scenario was demonstrated in the ignited trials, in large part due to the damage caused to the experimental facility. To simulate the train 2 scenario experimentally a nominal hydrogen pressure of 58 MPa, volume 153 litres, was released through a 4.7 mm nozzle.

There was a total of 7 tests carried out on train release scenarios. The first test without congestion and with a low ventilation rate of around 1.0 m/s led to the damage to the facility and shall be discussed first. The remaining 6 tests were all carried out with natural ventilation, 3 tests with congestion and 3 without.

The single test carried out with forced ventilation of 1.0 m/s was one of four planned tests, which were intended to explore the variation in ignitability, explosion overpressure and flame speed by testing under 2 different ventilation rates, 1.0 and 2.5 m/s, and with 2 ignition delays. However, the first test, test 25, resulted in a significantly larger overpressure than planned.

The test was undertaken with the lowest ventilation rate of 1.0 m/s and with a 12 s ignition delay. The peak overpressure at P11, the closest downstream transducer to the release point, was 34.3 kPa and at the furthest measured point, which was P3 at 55.0 m, the pressure remained relatively high at 32.7 kPa. This indicates that the fan structure was hit by a shock front greater than 30 kPa. This was sufficient to move the fan structure more than 8 m, despite being anchored to the rails, and to snap the 7 heavy duty electrical cables powering the fans.

All the remaining tests were carried out with natural ventilation. The three tests with congestion were carried out with ignition delays of 4, 6 and 8 s. These values were chosen to limit the extent of the flammable hydrogen air cloud at the time of ignition and hence the explosion severity, although the potential for damage was limited once the fan structure had been removed. The tests resulted in peak overpressures at P11 of 19.7, 38.0 and 75.9 kPa respectively.

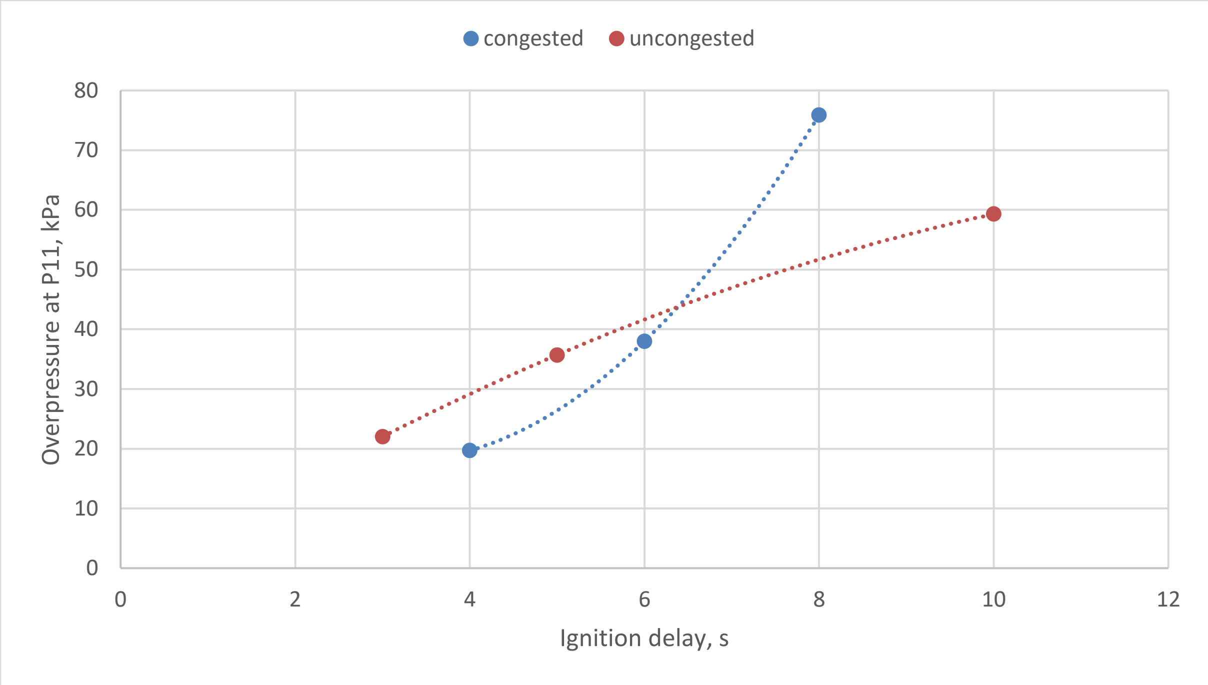

Figure 8. Comparison of the generated overpressure for releases of hydrogen at different ignition delay times and with and without congestion.

The tests without congestion had slightly broader range of ignition delays of 3, 5 and 10 s. The peak pressures generated at P11 for these tests were 22.0, 35.7 and 59. 3 kPa respectively. The results of both the congested and uncongested tests are plotted in Figure 8.

The overpressures generated are linked to the ignition delay, longer ignition delays leading to inevitably larger hydrogen air clouds, which, when ignited lead to larger overpressures. There is some evidence to suggest the presence of congestion influences the generated overpressure. However, this is only evident for the longer ignition delay of 8 s and further research would be needed to evaluate and quantify this.

Although the lack of control of tunnel ventilation is unfortunate the consistency of the results suggests that the gas concentrations in the turbulent parts of the cloud capable of supporting high flame speeds may be dominated by the momentum of the release and consequently relatively insensitive to the slow flow in the tunnel. This is not expected to continue for very long ignition delays where the cloud is mixed with the tunnel flow and flame acceleration is associated with turbulence driven by combustion – rather than the source.

4.0 CONCLUSIONS

For all car release scenarios and although a flammable extent of hydrogen air cloud is predicted, we were unable to cause an ignition at either the low or high ventilation rates.

Where ignition did occur, for the bus and train scenarios, the pressure within the tunnel decayed at a relatively moderate rate. This would indicate that the hazard distances associated with any such an event in a real-world tunnel would be relatively large.

The ignition behaviour has shown a subtle interplay between the total mass of hydrogen discharged before ignition and hence the ignition delay, the distribution of hydrogen along the tunnel at the time of ignition and the likely role of vehicles (congestion) in promoting combustion once ignited.

The data generated during this project is freely available on the Zenodo [14] open access data repository. The data, along with the supporting scaling and dimensional detail of the HSE experimental facility, will enable the development and validation of numerical simulations and engineering models which can be applied to real-world full-scale rail and road tunnels.

ACKNOWLEDGEMENTS

This project has received funding from the Fuel Cells and Hydrogen 2 Joint Undertaking (now Clean Hydrogen Partnership) under Grant Agreement No. 826193. The contents, including any opinions and/or conclusions expressed, are those of the authors alone and do not necessarily reflect HSE policy.

REFERENCES

1. Element Energy Ltd, “London: a capital for hydrogen and fuel cell technologies”, Hydrogen London, 2016.
2. Hydrogen Central Hydrogen Industry News & Market Intelligence. *How many Hydrogen Passenger Vehicles Have Been Sold So Far? Over 56 Thousand*. Available from: https://hydrogen-central.com/how-many-hydrogen-passenger-vehicles-have-been-sold-far-over-56-thousand/ (accessed March 2023)
3. C. Calvert, J. Allan, P. Amor, S. Hillmansen, C. Roberts, and P. Weston, “Concept development and testing of the UK’s first hydrogen-hybrid train (HydroFLEX)”, *Rail. Eng. Sci.*, vol. 29, pp. 248-257, 2021.
4. World premiere: 14 Coradia iLint to start passenger service on first 100% hydrogen operated route, Alstom. Available from: https://www.alstom.com/press-releases-news/2022/8/world-premiere-14-coradia-ilint-start-passenger-service-first-100 (accessed March 2023)
5. Hydrogen vehicles in service to exceed 1 million globally by 2027, as alternatives to battery electric vehicles needed. Available from: https://www.juniperresearch.com/pressreleases/hydrogen-vehicles-in-service-to-exceed-1m?ch=whitepaper%20hydrogen%20vehicles%202027 (accessed March 2023)
6. HyTunnel, “About HyTunnel-CS”, hytunnel.net. https://hytunnel.net/?page_id=31 (accessed Mar. 2023)
7. M. Pursell, M. Garcia, V. Molkov, T Van Esbroeck, and K. Vågsæther, “Report on selection and prioritisation of scenarios”, HyTunnel-CS, Rep. D1.3, 2019.
8. J.L. Saw *et al.* “Recommendations for inherently safer use of hydrogen vehicles in underground traffic systems”, HyTunnel-CS, Rep. D6.9, 2022.
9. J. van den Berg *et al.* “Recommendations for RCS”, HyTunnel-CS, Rep. D6.10, 2022.
10. S. Gianissi *et al*. “Final report on analytical, numerical and experimental studies on hydrogen dispersion in tunnels, including innovative prevention and mitigation strategies”, HyTunnel-CS Rep. D2.3, 2022.
11. W. Rattigan *et al.* "Results of the deferred experimental programme and associated activities", HyTunnel-CS, Rep. D4.4, 2022.
12. Hall, D. J. and S. Walker (1997). "Scaling rules for reduced-scale field releases of hydrogen fluoride." Journal of Hazardous Materials 54(1): 89-111.
13. W. Rattigan *et al.* “Detailed research programme on explosion in underground transportation systems”, Rep. D4.1 2019.
14. HyTunnel CS | Zenodo https://zenodo.org/communities/hytunnelcs/?page=1&size=20 (last accessed March 2023)