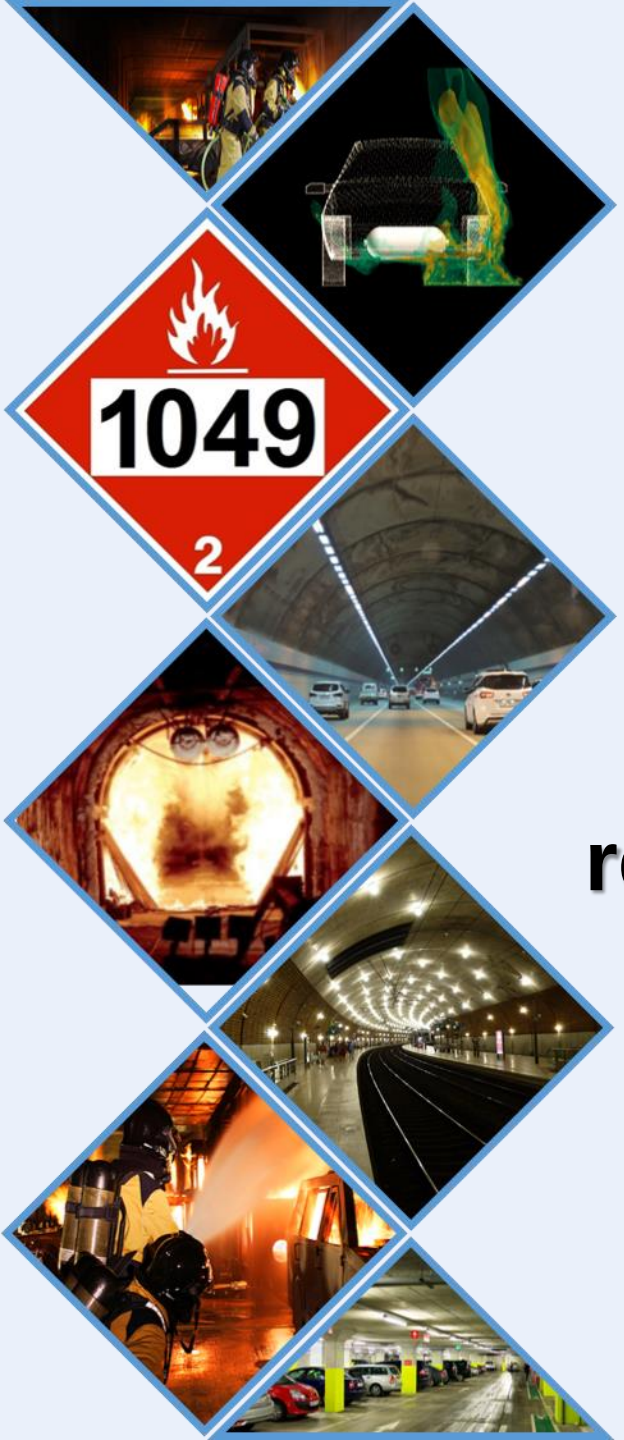


Dissemination Conference of HyTunnel-CS project
14th July 2022, Brussels, Belgium

Deflagration of hydrogen releases in tunnel: large-scale experiments

W. Rattigan, (HSE)

Clean Hydrogen Partnership

Co-funded by the European Union

Overview

Outline of presentation

- Aims of testing
- Experimental setup
- Test programme
- Results
- Summary

Overview

Aims of testing

- Undertake a number of scaled hydrogen jet releases representing the blowdown of a vehicle hydrogen cylinder following the operation of the thermally-activated pressure relief device inside a tunnel.
- Measure the hydrogen concentration profile in the tunnel at several positions downstream of the release point.

Repeat the same tests but with attempted ignition, and

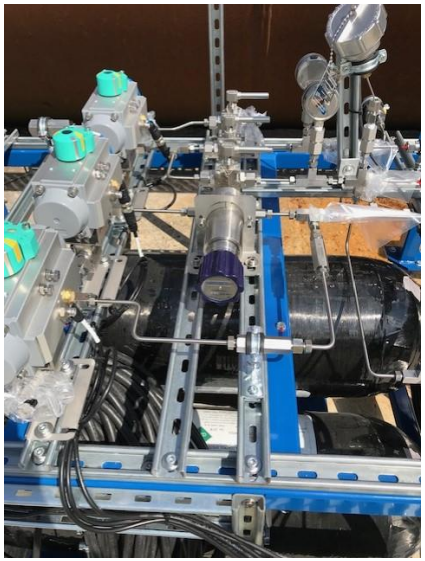
- Measure the overpressure
- Measure flame speed
- Use this empirical data to develop and validate numerical models

Experimental facility

Tunnel

Outside

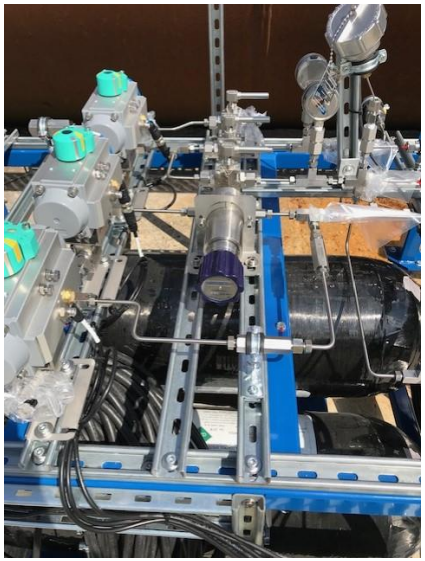
- 70m long, steel tunnel; 3.7 m diameter (able to withstand dynamic pressures > 30 bar).
- Hydrogen gas boosting and storage. (159 L; 700 bar)
- An array of 7 axial fans (able to achieve up to 5 m/s airflow)



Experimental facility

Tunnel

- Release through 2.2, 4.7, 5.0 and 5.7 mm nozzles to simulate car, bus and trains
- Releases from the mid-point of the tunnel (35 m)
- Releases downward (car) & upward (bus and trains)
- Nozzle sizes of 2.2, 4.0, 5.0 & 5.7mm



Experimental facility

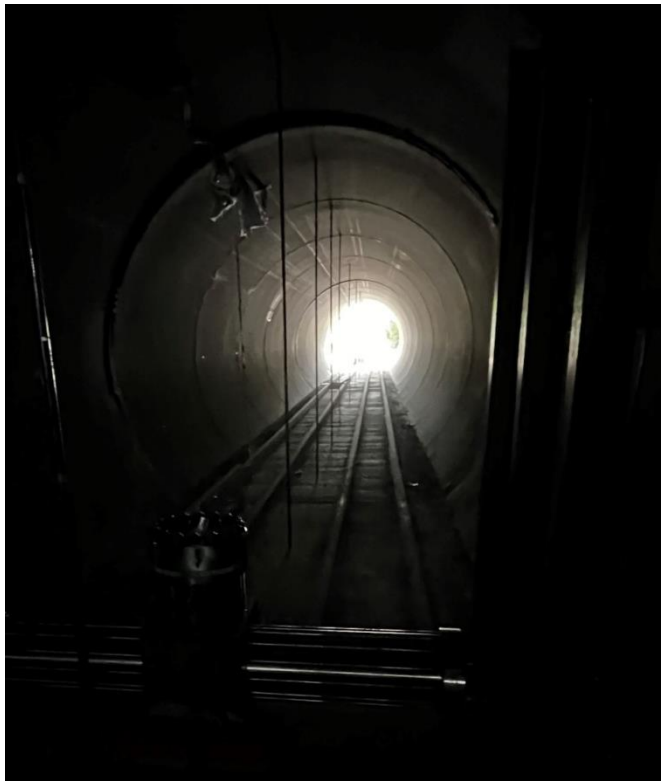
Unignited blowdown release inside a tunnel

- 16 hydrogen sensors on vertical and horizontal arrays (mostly downstream of mid-point >35 m)
- Experimental airflow of 1.25 m/s and 2.4 m/s

Experimental setup

Ignited blowdown release inside a tunnel

- 9 pressure transducers
- 45 fine (0.3 mm) thermocouples mostly downstream of mid-point >35 m)
- Experimental airflow of 1.25 m/s and 2.4 m/s



Test programme

Release scenarios

Test No	Nozzle diameter [mm]	Orientation	Pressure [bar]	Wind Speed [m/s]	
2	2.2	Downward	118	1.25	Car
3	2.2	Downward	118	2.4	Car
4	4.0	Upward	310	1.25	Bus
5	4.0	Upward	310	2.4	Bus
6	4.7	Upward	580	1.25	Train 2
7	4.7	Upward	580	2.4	Train 2
8	5.7	Upward	510	1.25	Train 1
9	5.7	Upward	510	2.4	Train 1
10	***5.7***	***Upward***	***510***	***1.25***	***Train 1***
11	***2.2***	***Downward***	***118***	***1.25***	***Car***
12	***2.2***	***Downward***	***118***	***1.25***	***Car***

Test programme

Sensor Positions

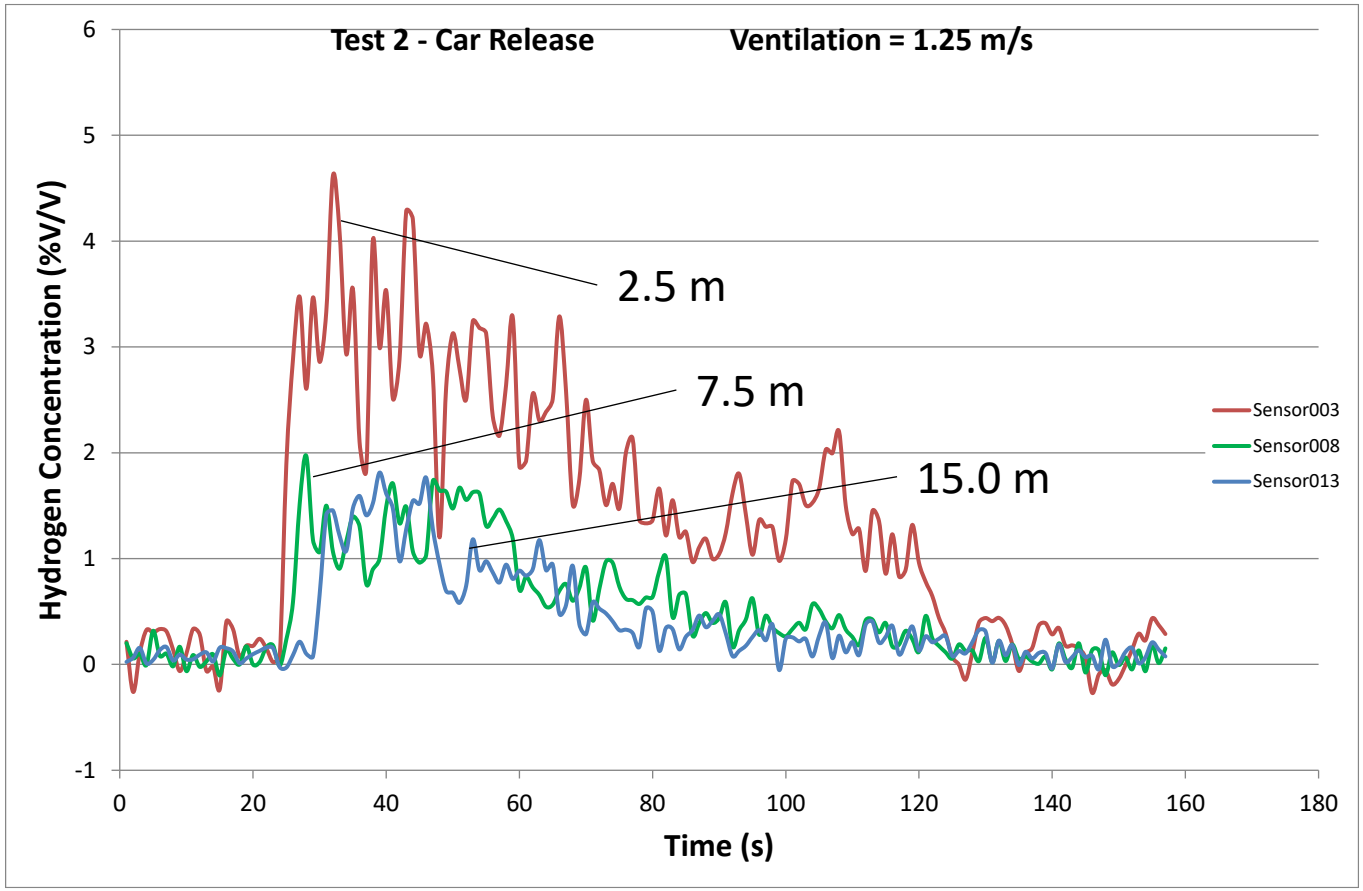
Sensor Number	Distance from release (m)	Sensor Number	Distance from release (m)
001	-1.0	*009*	7.5
002	-1.0	*010*	7.5
003	2.5	*011*	10.0
004	2.5	*012*	10.0
005	2.5	*013*	15.0
026	5.0	*014*	15.0
006	5.0	*015*	15.0
008	7.5	*016*	20.0

- 16 Xensor hydrogen gas sensors
- Located upstream and downstream of release position

Results

Blowdown Test 2

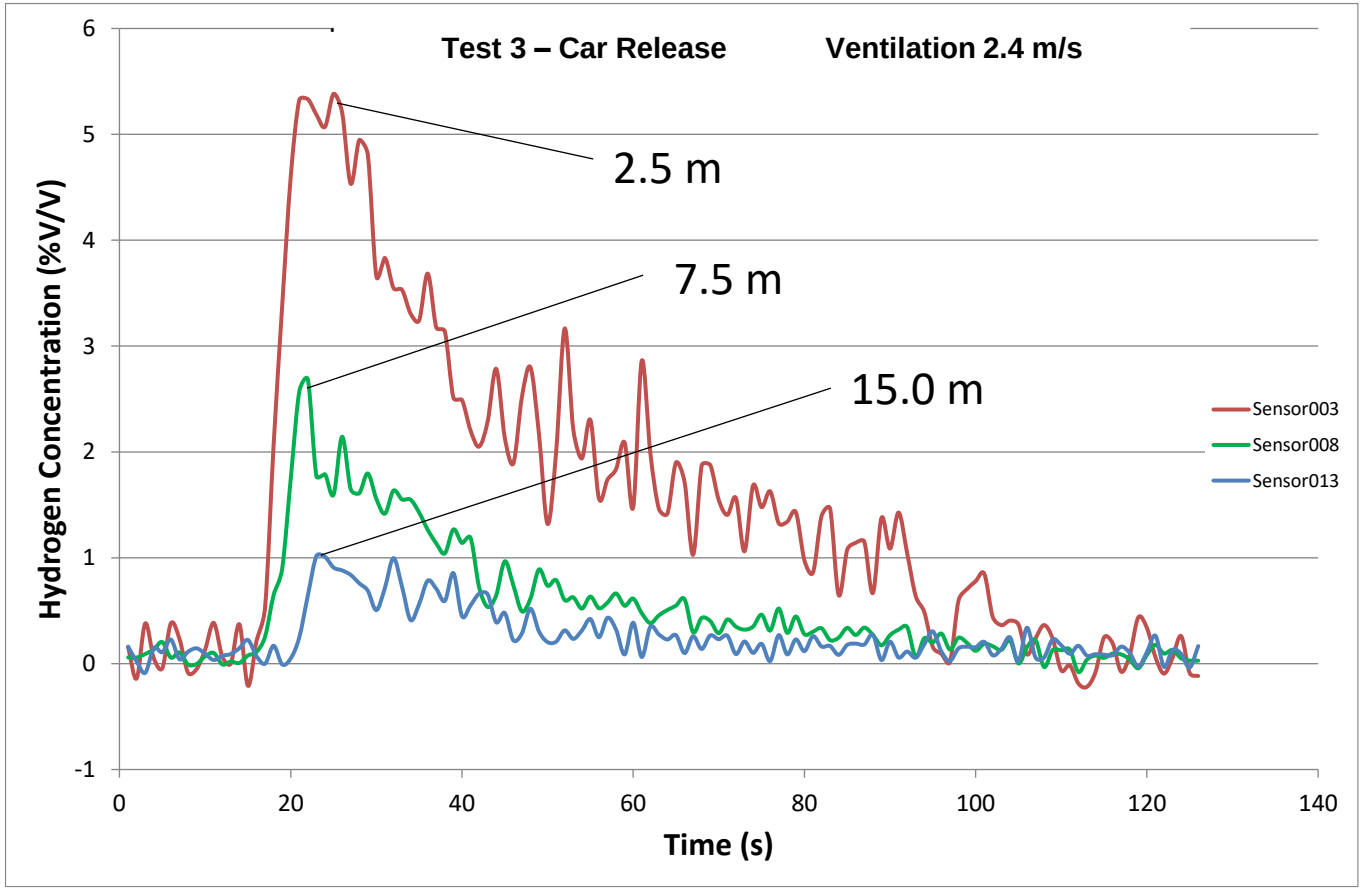
- Car Release
- 118 bar downward release through a 2.2 mm nozzle
- Wind Speed 1.25 m/s
- Peak concentration at sensor 003 (2.5 m) ~4.6%



Results

Blowdown Test 3

- Car Release
- 118 bar downward release through a 2.2 mm nozzle
- Wind Speed 2.4 m/s
- Peak concentration at sensor 003 (2.5 m) ~5.38%

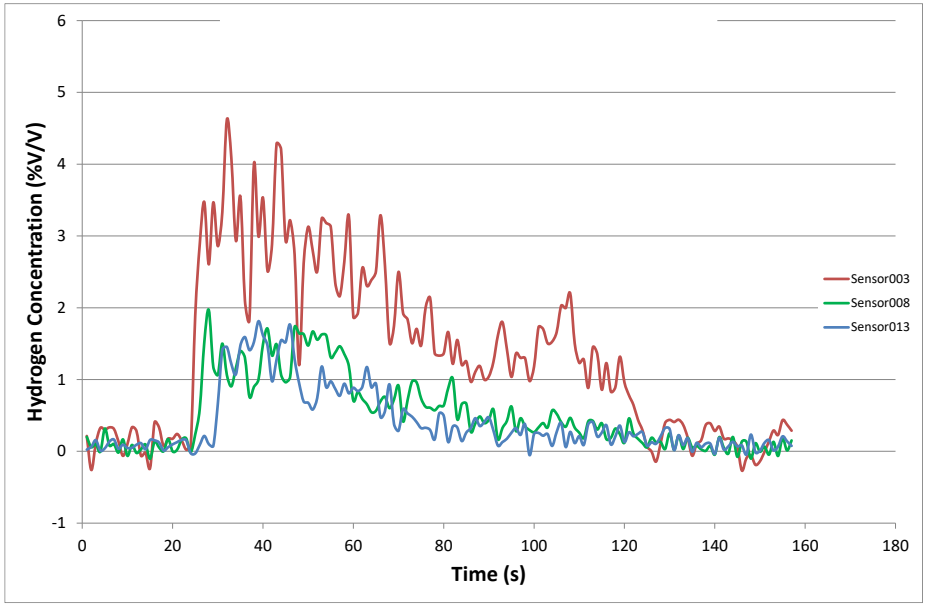


Results

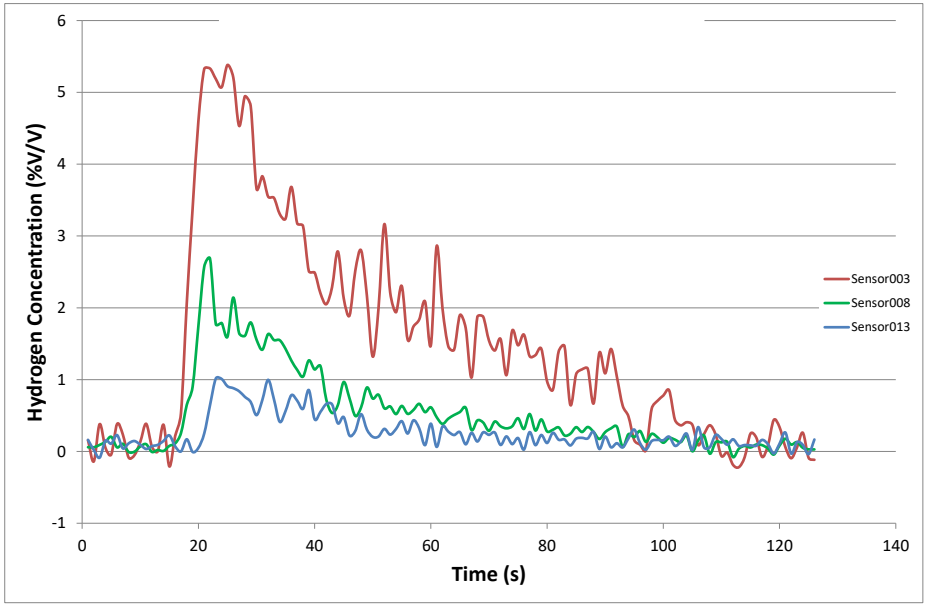
Car Releases - Comparison

- Car Releases
- 118 bar downward release through a 2.2 mm nozzle
- **Higher** Peak concentration 5.38% in test 3
- Higher flow velocity seems to have little effect on concentration detected at sensors

Test 2 - 1.25 m/s



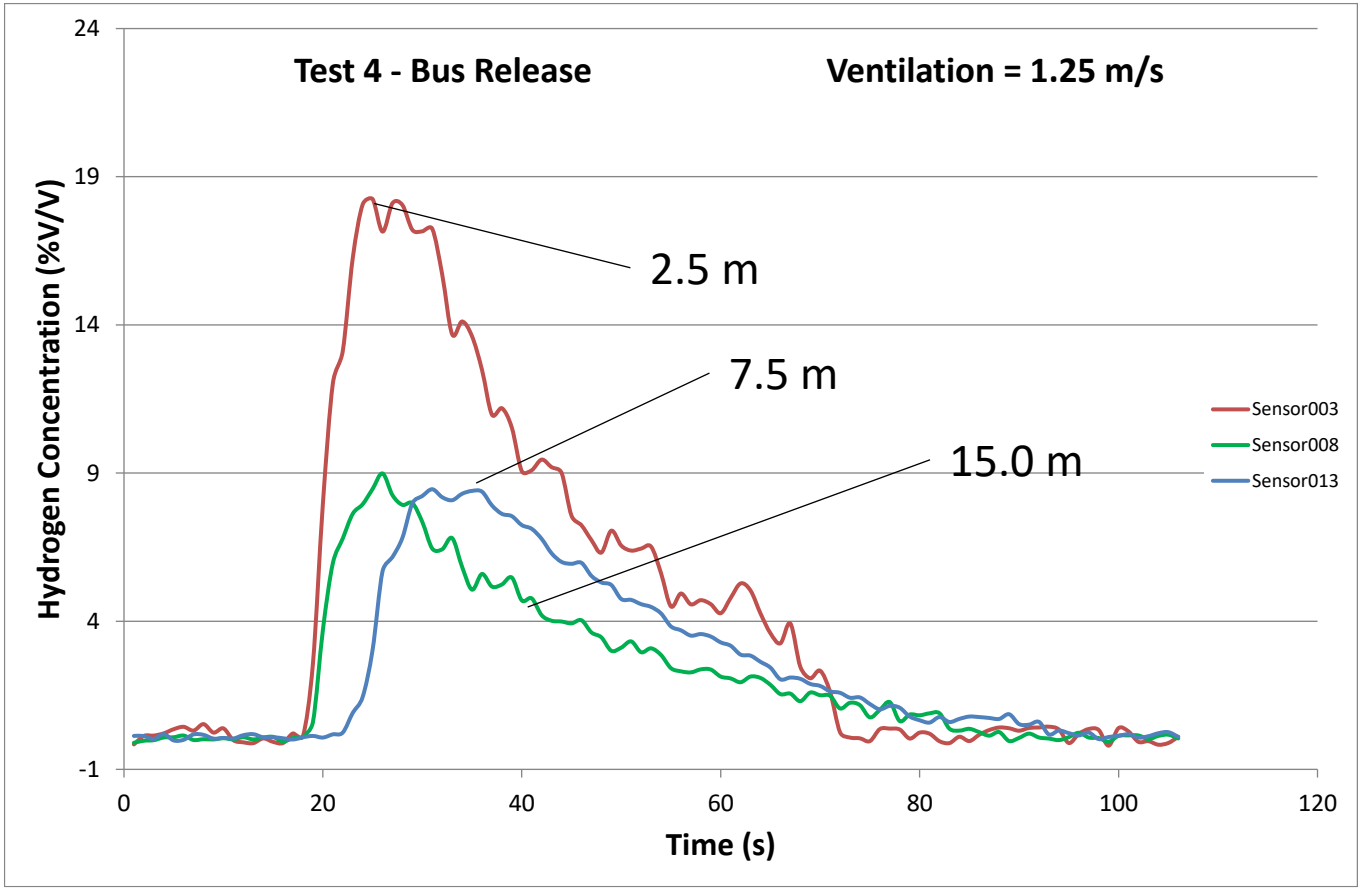
Test 3 - 2.40 m/s



Results

Blowdown Test 4

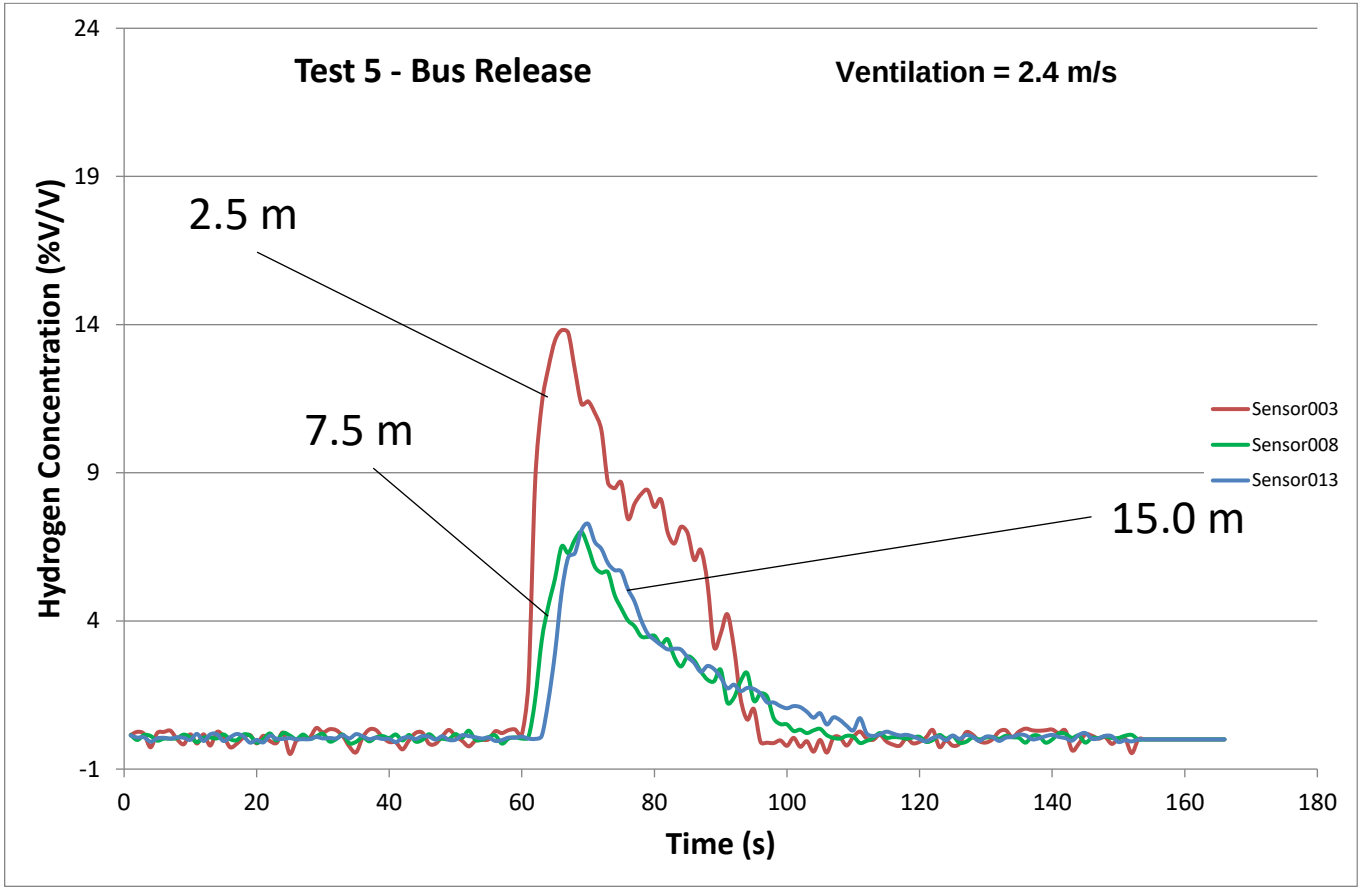
- Bus Release
- 310 bar upward release through a 4.7 mm nozzle
- Wind Speed 1.25 m/s
- Peak concentration at sensor 003 (2.5 m) ~18.24%



Results

Blowdown Test 5

- Bus Release
- 310 bar upward release through a 4.7 mm nozzle
- Wind Speed **2.4 m/s**
- Peak concentration at sensor 003 (2.5 m) ~13.81%



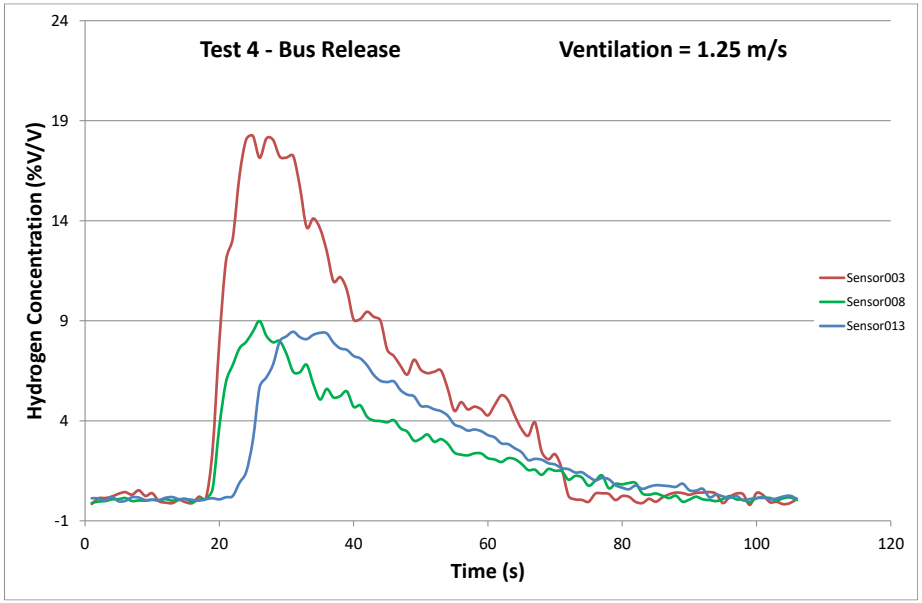
Results

Bus Releases - Comparison

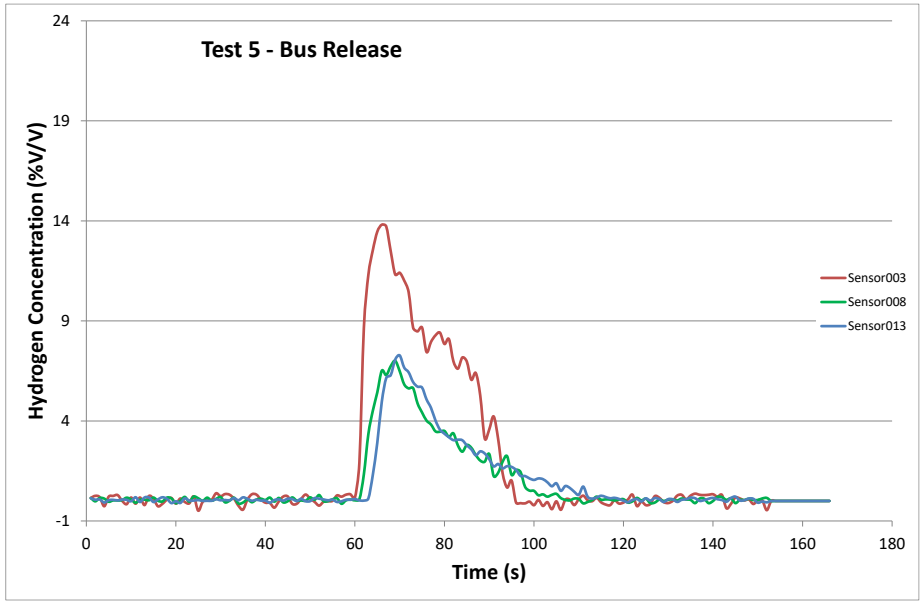
- Bus Releases
- 310 bar upward release through a 4.7 mm nozzle

- **Higher** Peak concentration 18.24% in test 4
- Higher flow velocity has marked effect on hydrogen concentration

Test 4 - 1.25 m/s



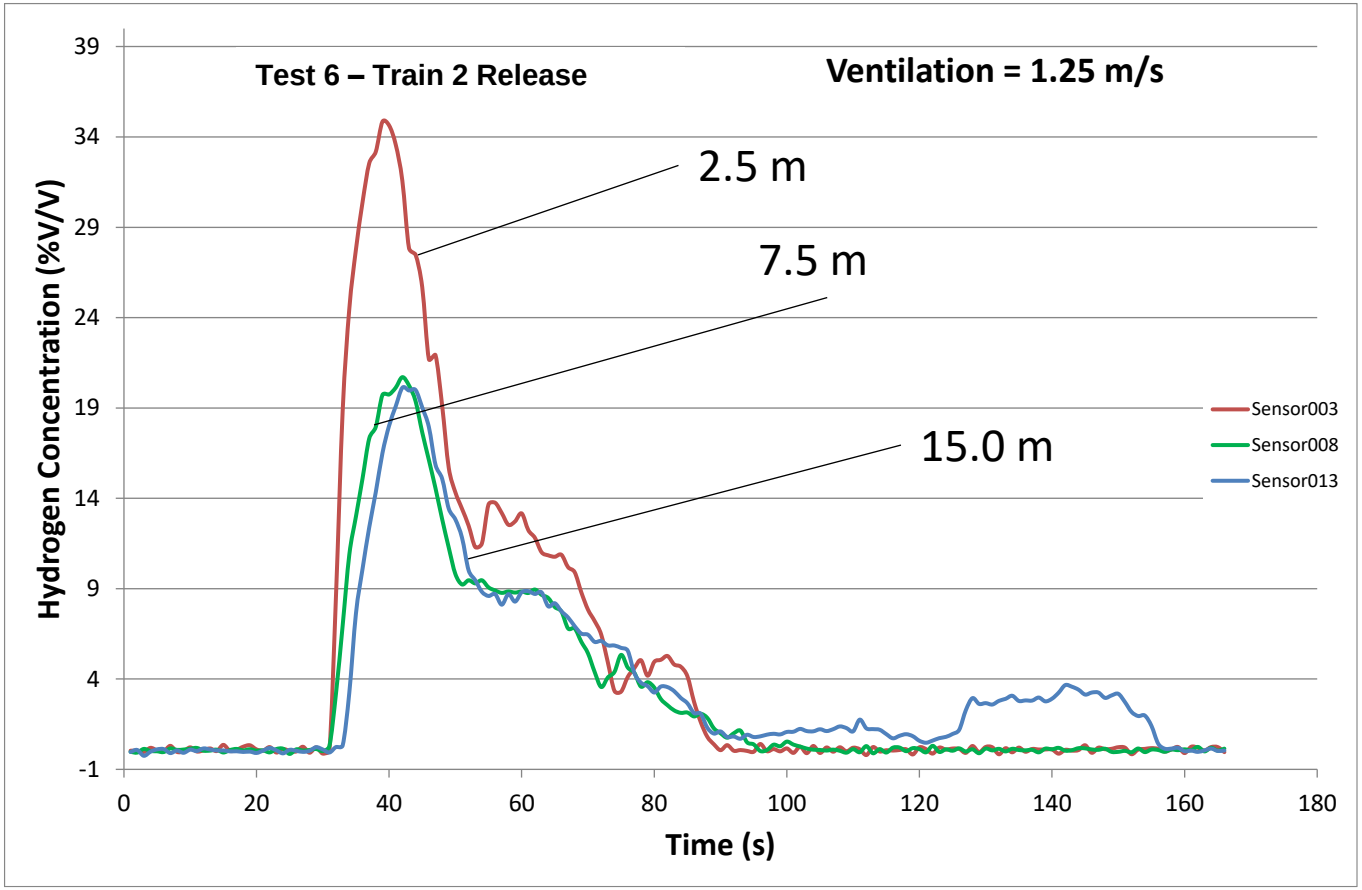
Test 5 - 2.40 m/s



Results

Blowdown Test 6

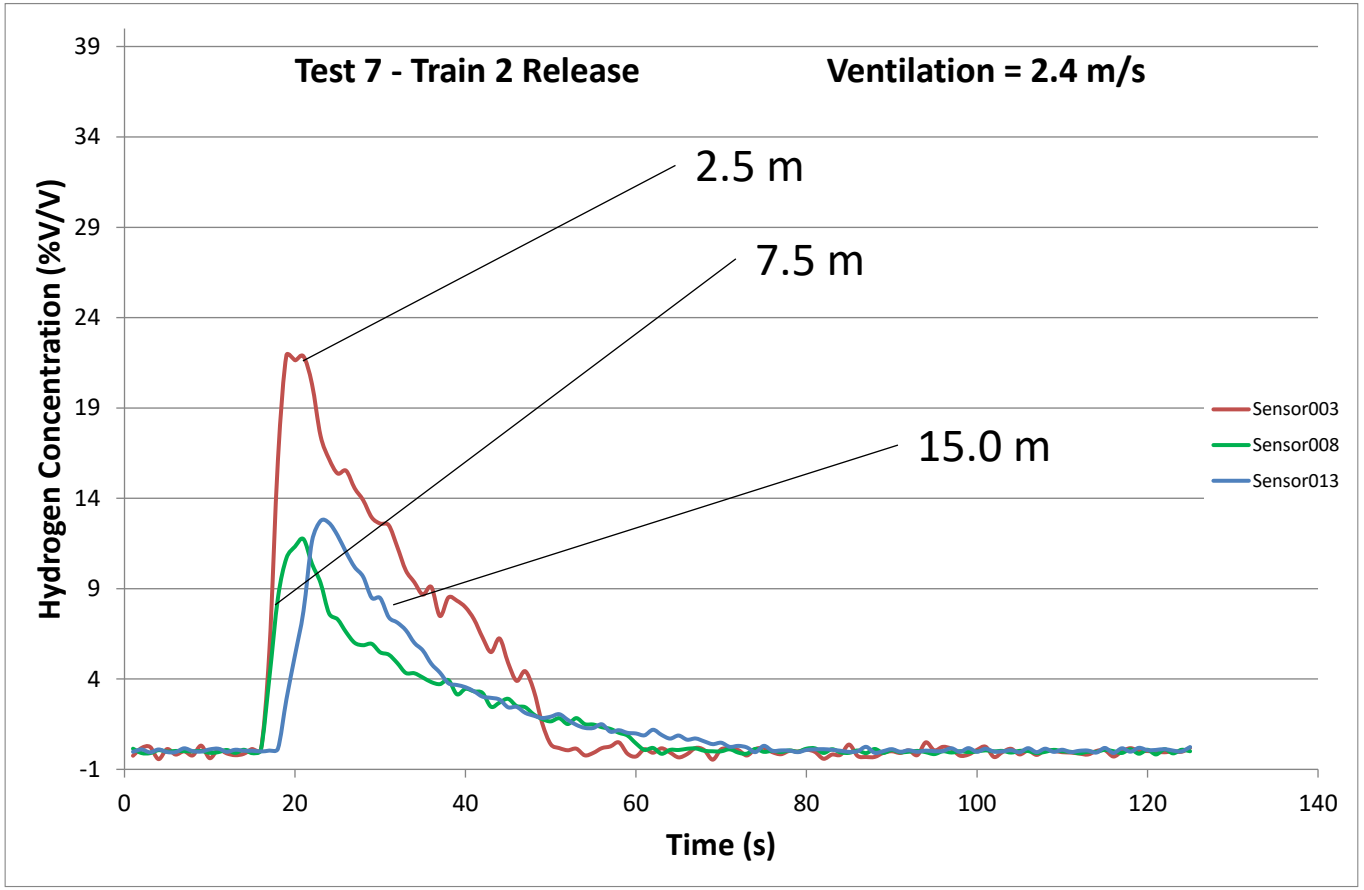
- Train 2 Release
- 580 bar upward release through a 5.0 mm nozzle
- Wind Speed 1.25 m/s
- Peak concentration at sensor 003 (2.5 m) ~34.84%



Results

Blowdown Test 7

- Train 2 Release
- 580 bar upward release through a 5.0 mm nozzle
- Wind Speed **2.4 m/s**
- Peak concentration at sensor 003 (2.5 m) ~21.92%

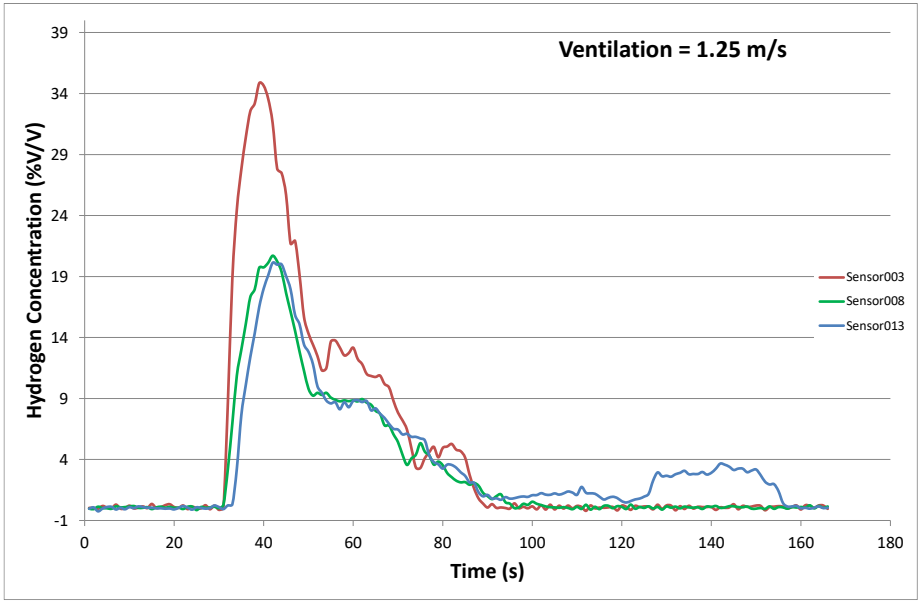


Results

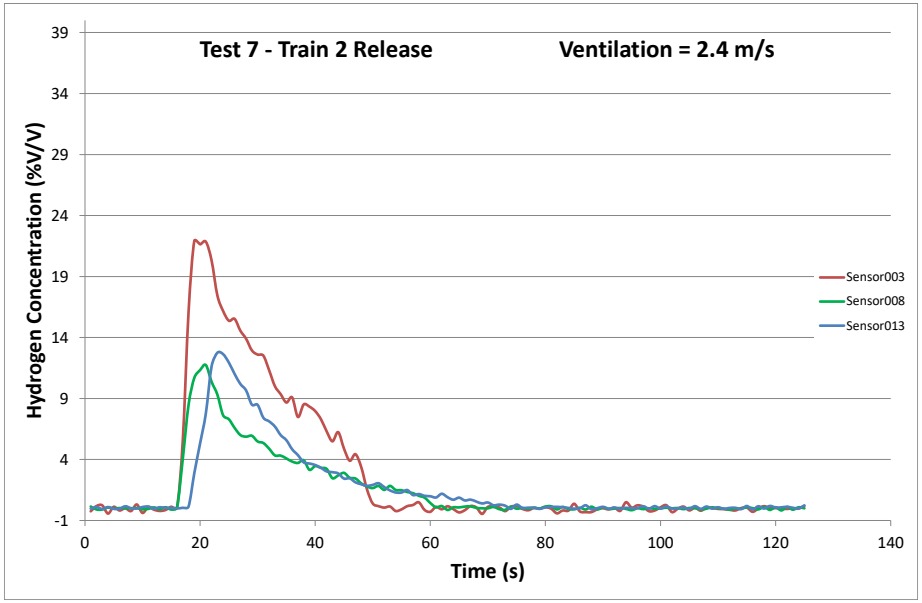
Train 2 Release - Comparison

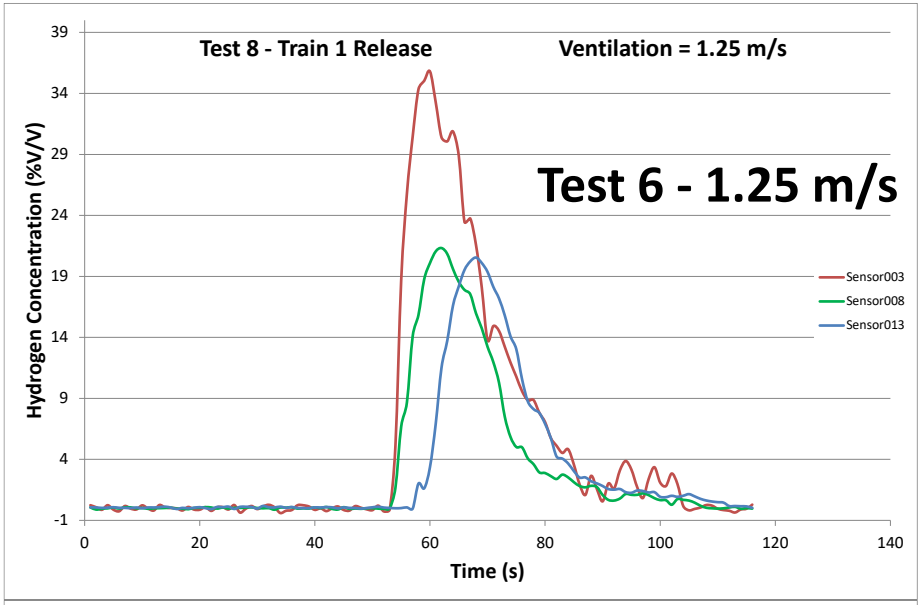
- Wind speeds 1.25 m/s & 2.4 m/s
- 580 bar upward release through a 5.0 mm nozzle
- **Higher** Peak concentration in test 6 - 38.84% (1.25 m/s) vs 21.92% (2.4 m/s)

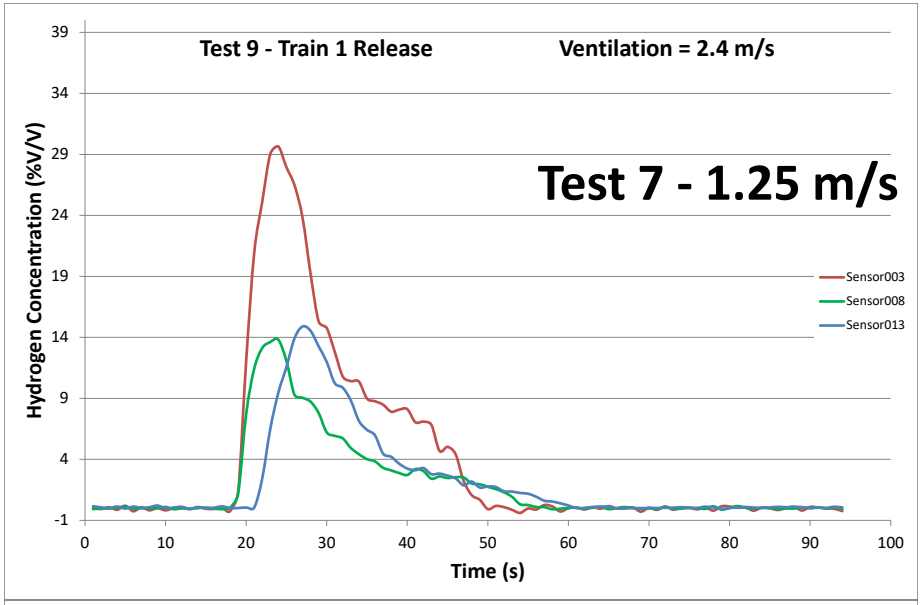
Test 6 - 1.25 m/s

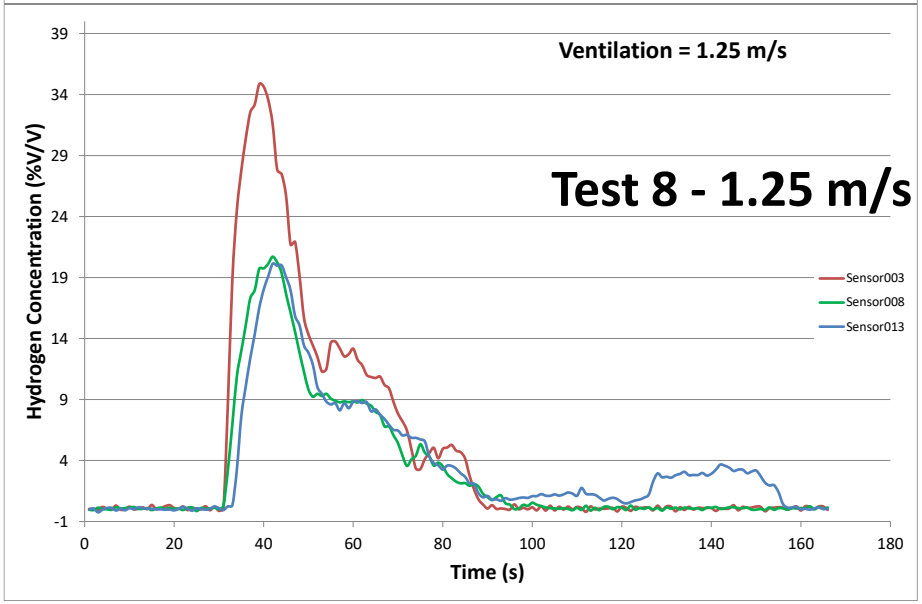


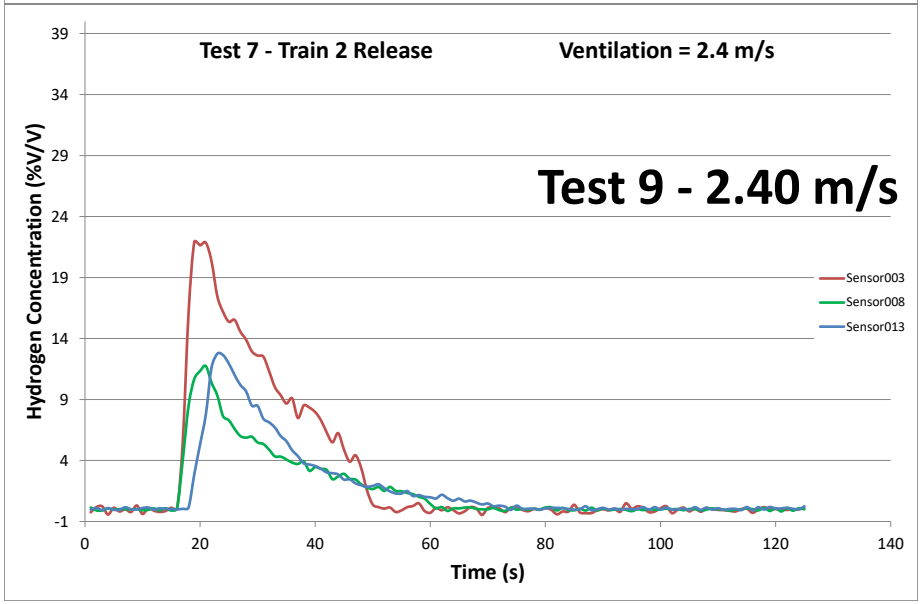
Test 7 - 2.40 m/s




Test 8 - Train 1 Release
Ventilation = 1.25 m/s
Test 6 - 1.25 m/s
Hydrogen Concentration (%V/V)
Time (s)
Sensor003
Sensor008
Sensor013


Test 9 - Train 1 Release
Ventilation = 2.4 m/s
Test 7 - 1.25 m/s
Hydrogen Concentration (%V/V)
Time (s)
Sensor003
Sensor008
Sensor013

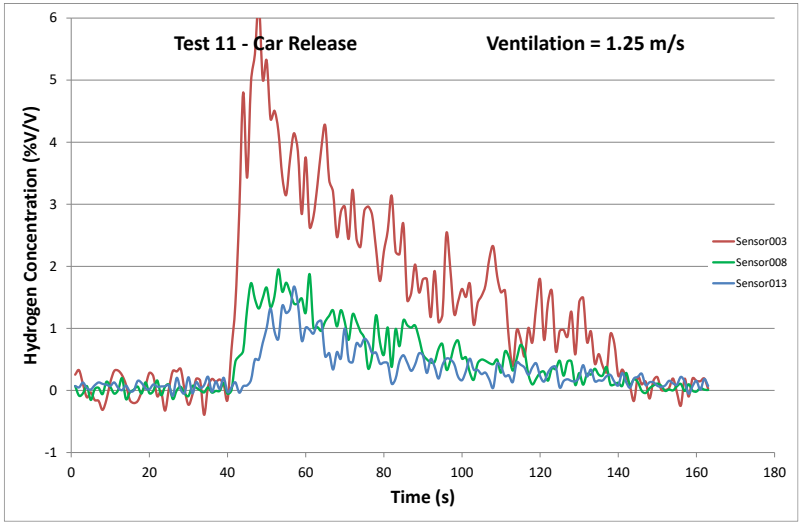

Ventilation = 1.25 m/s
Test 8 - 1.25 m/s
Hydrogen Concentration (%V/V)
Time (s)
Sensor003
Sensor008
Sensor013

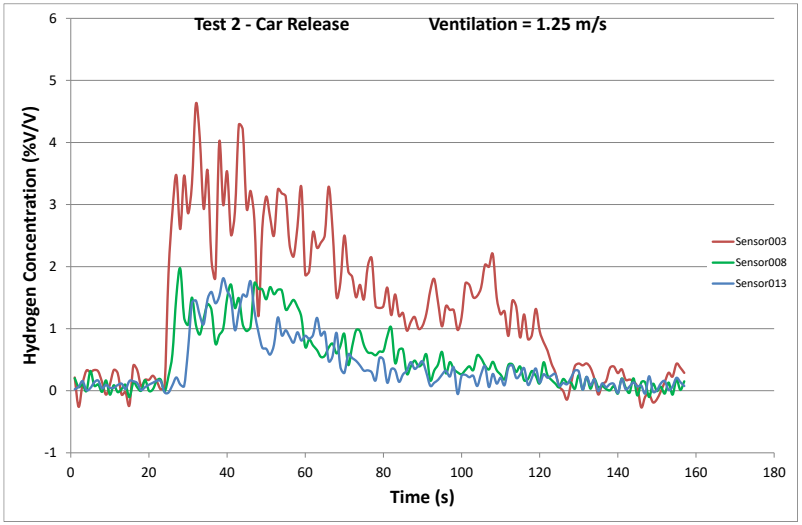

Test 7 - Train 2 Release
Ventilation = 2.4 m/s
Test 9 - 2.40 m/s
Hydrogen Concentration (%V/V)
Time (s)
Sensor003
Sensor008
Sensor013

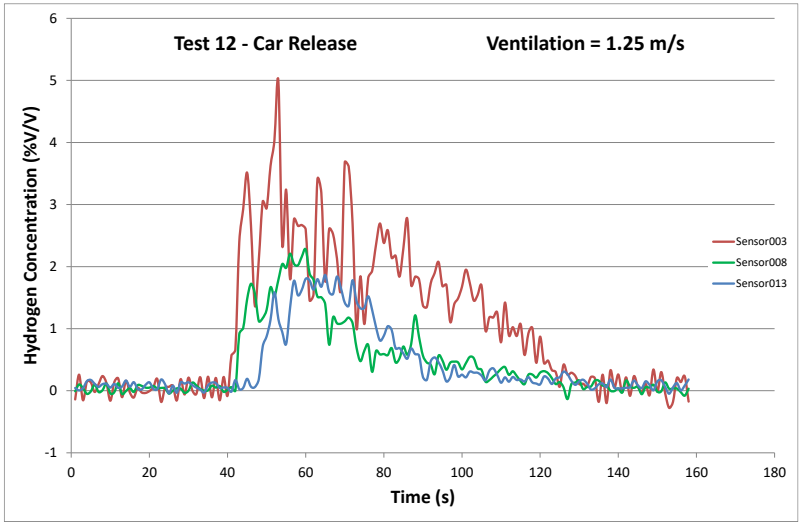
Results

Repeatability

- Car Release
- Test 2, 11 and 12
- Wind speeds1.25 m/s
- 118 bar downward; 2.2 mm nozzle
- Peak concentrations of 4.6%; 6.25 % and 5.0%,
- Good repeatability;







Test programme

Planned release scenarios

	Car		Bus		Train 1		Train 2	
Hydrogen qty (kg)	0.45		3.40		5.07		5.55	
Orifice diameter (mm)	2.2		4.0		5.7		4.7	
Tunnel airflow (m/s)	1.25	2.4	1.25	2.4	1.25	2.4	1.25	2.4
Jet orientation	D	D	U	U	U	U	U	U

- Blowdown release followed by delayed ignition - 8 tests
- Repeat with 2nd ignition delay
- Ignition delays chosen based on simulations to give optimal flammable volume
- Total 16 tests

Test programme

Sensor Positions

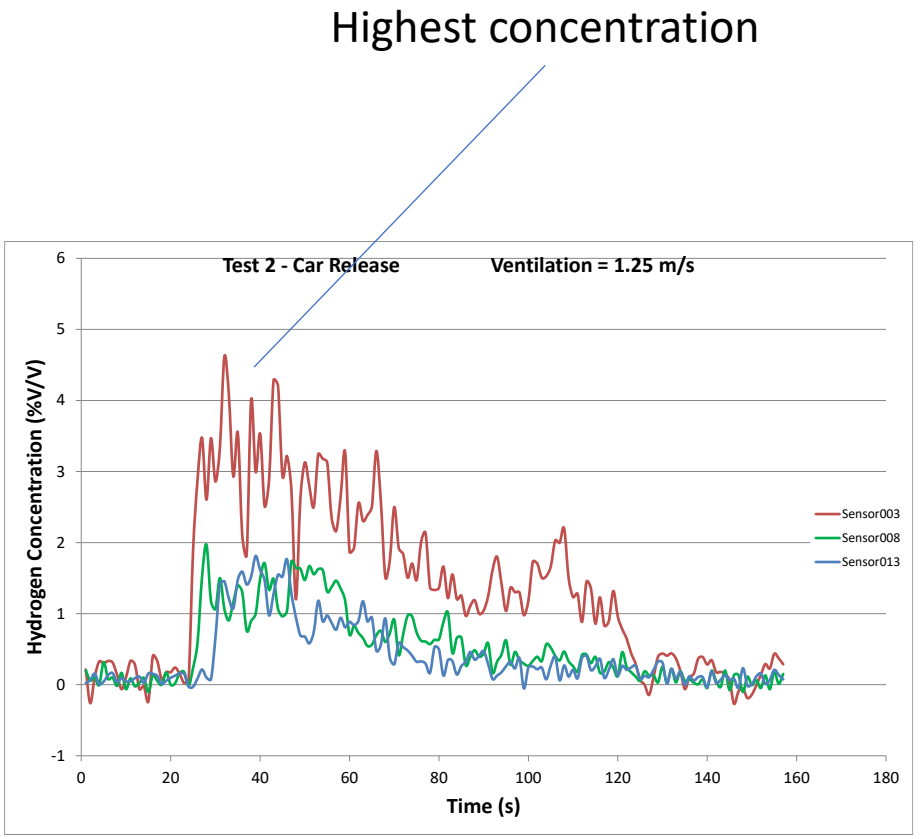
Sensor Number	Axial distance from release (m)
P12	-1.0
P11	1.0
P10	2.5
P9	5.0
P8	7.5
P7	10.0
P5	15.0
P3	20.0

- 9 Kulite HKM-375 pressure transducers
- Located upstream and downstream of release position in walls
- 45 fine wire TCs (0.3) – fast responding to passage of flame – in 9 arrays; 1 upstream and 8 downstream

Results

Test 13 - Car - Blowdown Test (with attempted ignition)

- 118 bar downward release through a 2.2 mm nozzle
- Wind Speed 1.25 m/s
- Igniter 1.0 m downstream from release; 0.3 m above the ground
- Ignition delay = 10s; Ignition Duration = 10s
- **NO IGNITION**
- **NO PRESSURE OR FLAME DATA**



Results

Car - Ignited Blowdown Tests

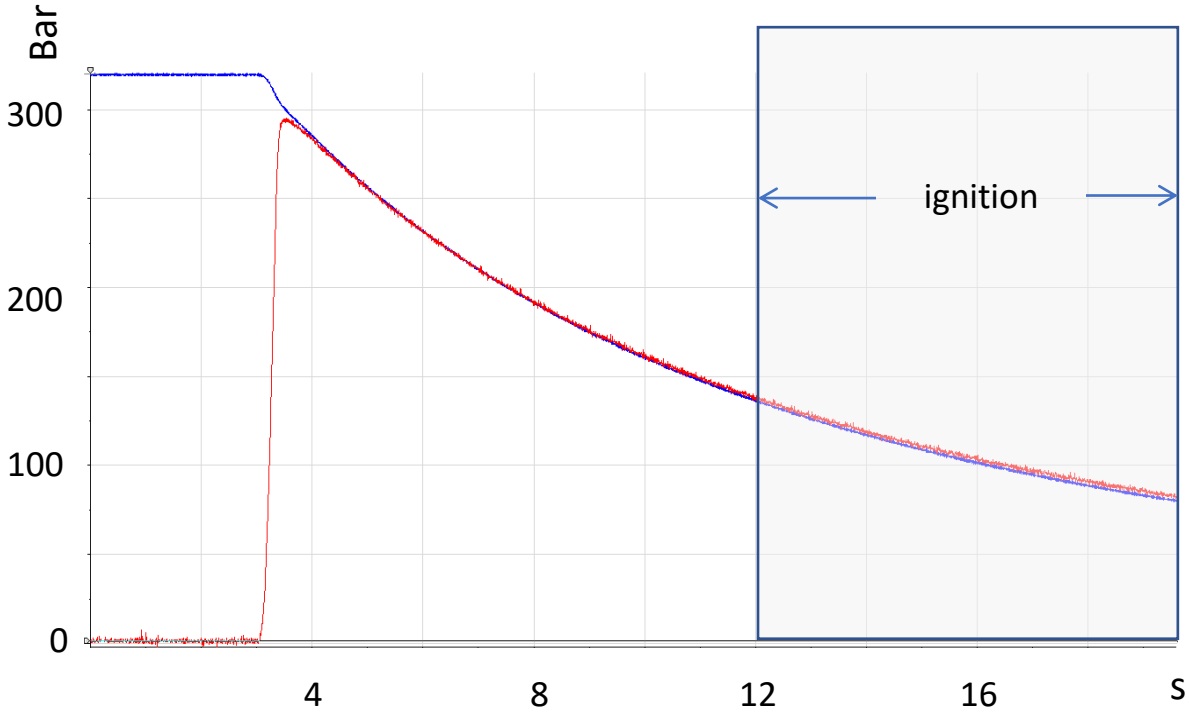
- 118 bar downward release through a 2.2 mm nozzle
- Wind Speed 1.25 m/s
- Ignition position changed (closer to release) after 3 tests
- Ignition duration varied – on for duration of blowdown
- **NO IGNITIONS IN ANY TEST**

Test	Ignitor Location 35 m + X [m]	Ignition Delay (duration) [s]	Ignited? [Y/N]
13	**1.0**	**20 (1.3)**	**N**
14	1.0	10 (10)	N
15	1.0	0 (30)	N
17	0.5	10 (30)	N
18	0.5	0 (60)	N
19	0.5	0 (60)	N
20	0.5	0 (60)	N

Results

Test 21 Ignited Blowdown

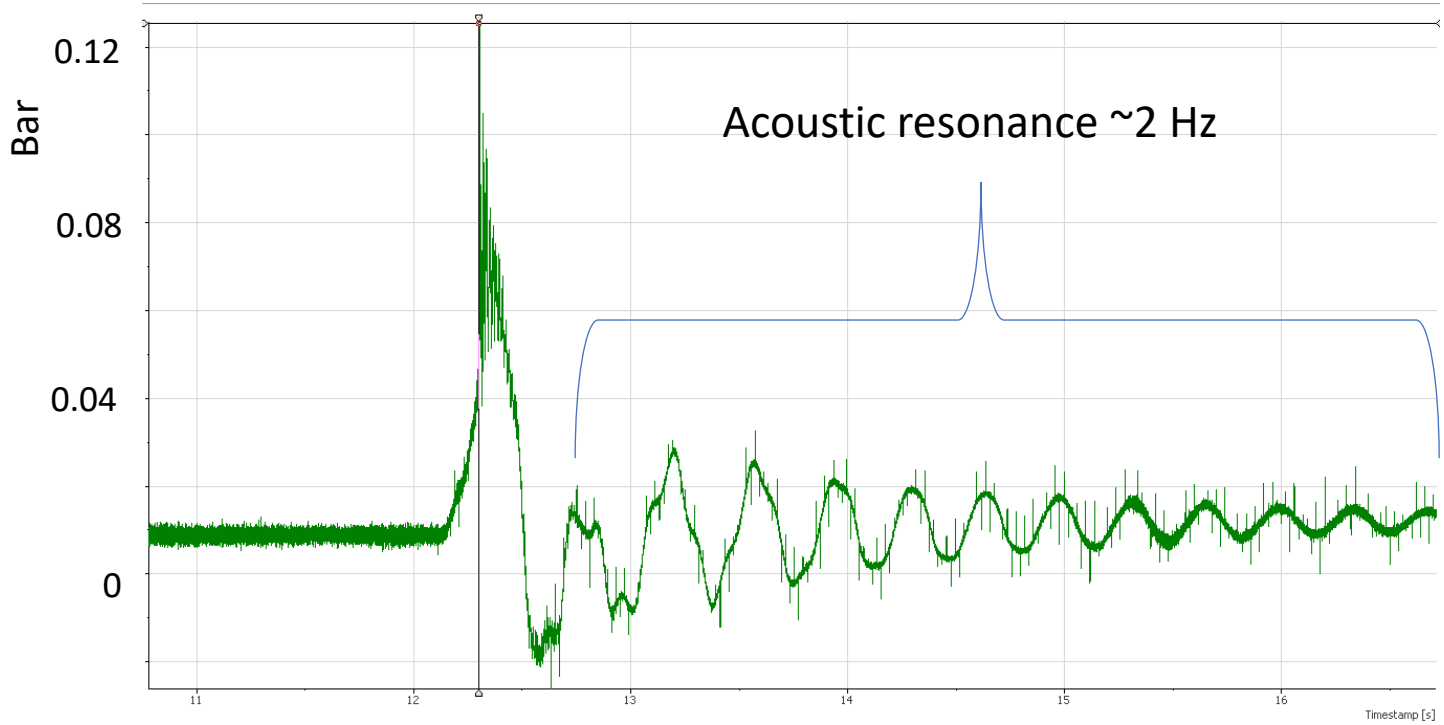
- Bus Release
- 310 bar upward release through a 4.7 mm nozzle
- Wind Speed 1.25 m/s
- Peak concentration (at sensor 003; test 4) = 18.24
- Igniter 3 m downstream, 0.3 m from ceiling (x=34, z=3.4)
- Ignition delay 12 s (10 s duration)



Results

Test 21 Ignited Blowdown

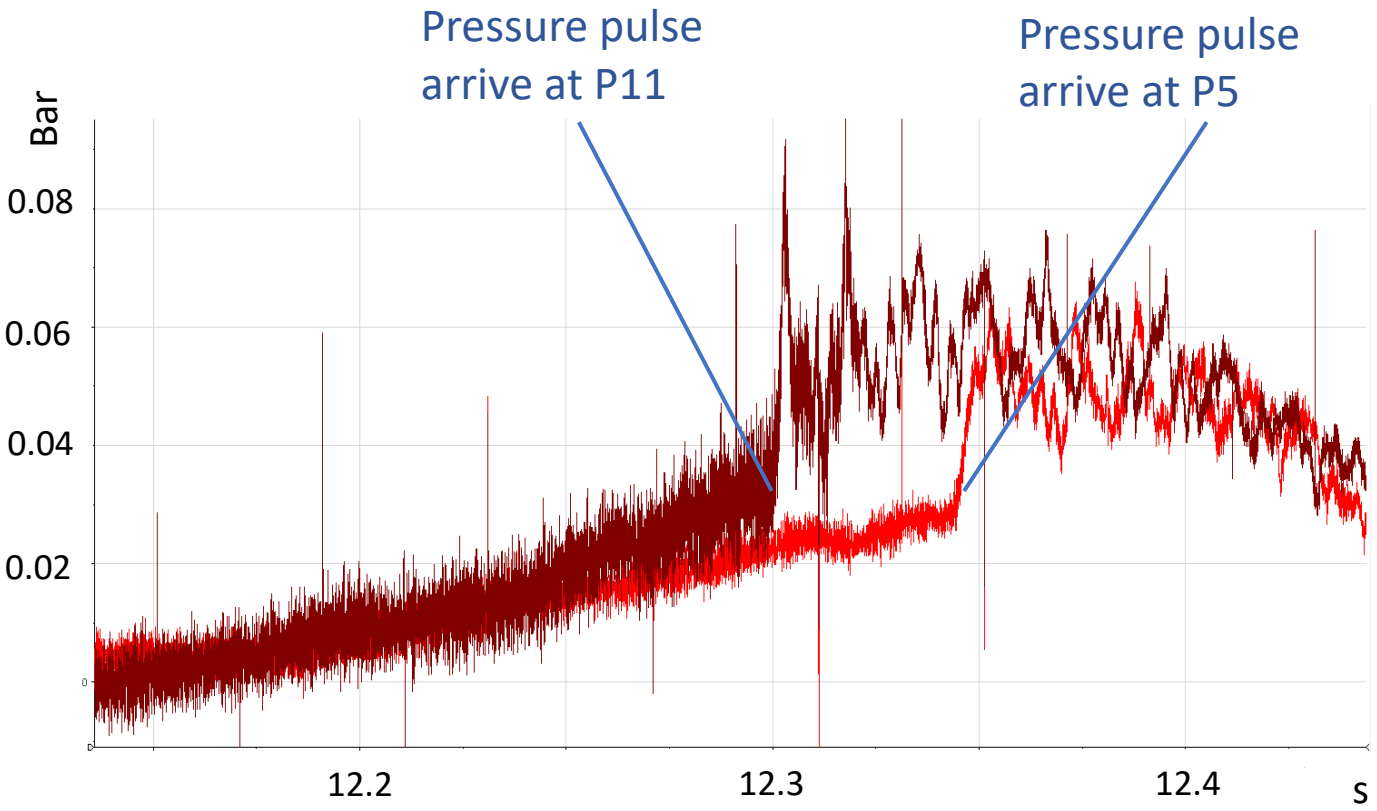
- Bus Release
- 310 bar upward release through a 4.7 mm nozzle
- Wind Speed 1.25 m/s
- Peak concentration (at sensor 003; test 4) = 18.24
- Igniter 3 m downstream, 0.3 m from ceiling (x=34, z=3.4)
- Ignition delay 12 s (10 s duration)
- Peak pressure around 120 mbar on P12 (-1.0 m)



Results

Test 21 Ignited Blowdown

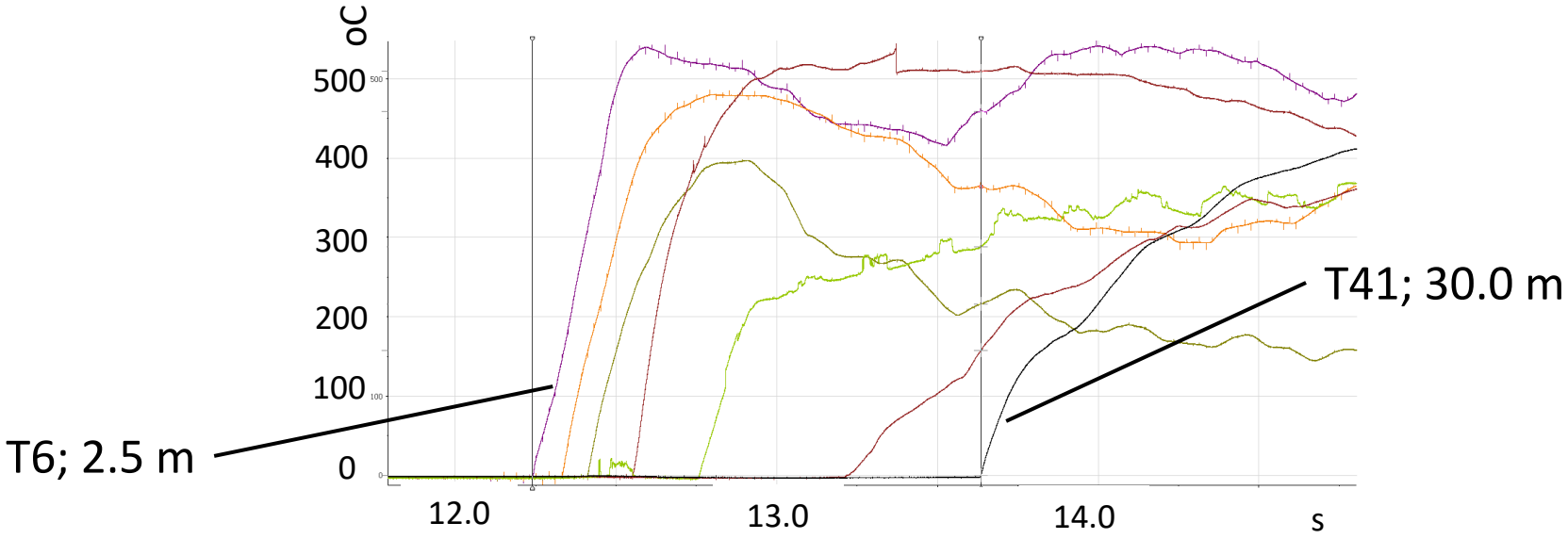
- Pressure pulse P11 (brown) and P3 (red)
- Separation of sensors (dX) = 19m
- Difference in arrival of shock; dT = 44 ms
- Shock speed ~437 m/s
- Consistent with the speed of sound in a hydrogen air mixture



Results

Test 21 Ignited Blowdown

- Thermocouple arrays (high); 3.25 m)
- Separation, first, last = 27.5 m
- dT = 1.39 s
- Average flame speed ~ 20 m/s



Results

Test 21 Ignited Blowdown

- Thermocouple arrays (high); 3.25 m)
- Separation, first, last = 27.59m
- dT = 1.39 s
- Average flame speed ~ 18 m/s

Results

Test 22 Ignited Blowdown

- Bus Release
- 310 bar upward release through a 4.7 mm nozzle
- Wind Speed **2.40** m/s
- Peak concentration 13.81 %; Sensor003
- Igniter 3 m downstream, 0.3 m from ceiling (x=34, z=3.4)
- Ignition delay 12 s (10 s duration)
- **NO IGNITION**

Results

Test 23 Ignited Blowdown

- Bus Release – Repeat of test 21, except…
- longer ignition delay (15 s)
- 310 bar upward release through a 4.7 mm nozzle
- Wind Speed 1.25 m/s
- Peak concentration 18.24 %?
- Igniter 3 m downstream, 0.3 m from ceiling (x=34, z=3.4)
- Ignition delay 12 s (10 s duration)
- Peak pressure around 60 mbar

Results

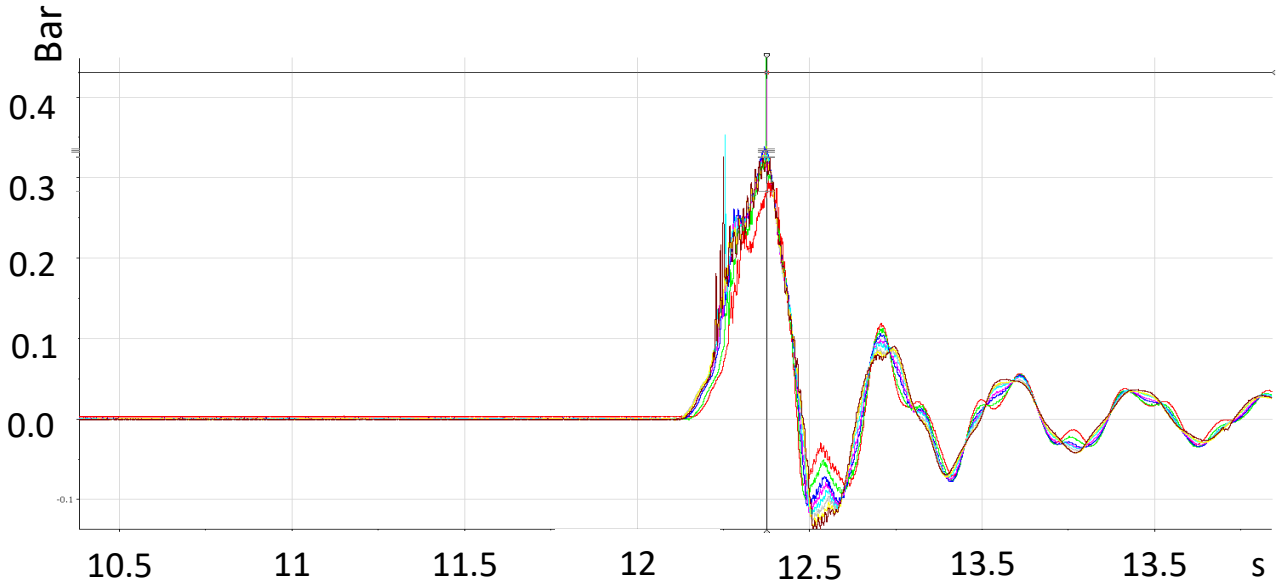
Test 24 Ignited Blowdown

- Bus Release – Repeat of test 22, except…
- longer ignition delay (**15 s**)
- 310 bar upward release through a 4.7 mm nozzle
- Wind Speed **2.40** m/s
- Peak concentration 18.24 %?
- Igniter 3 m downstream, 0.3 m from ceiling (x=34, z=3.4)
- Ignition delay 12 s (10 s duration)
- **NO IGNITION**

Results

Test 25 Ignited Blowdown

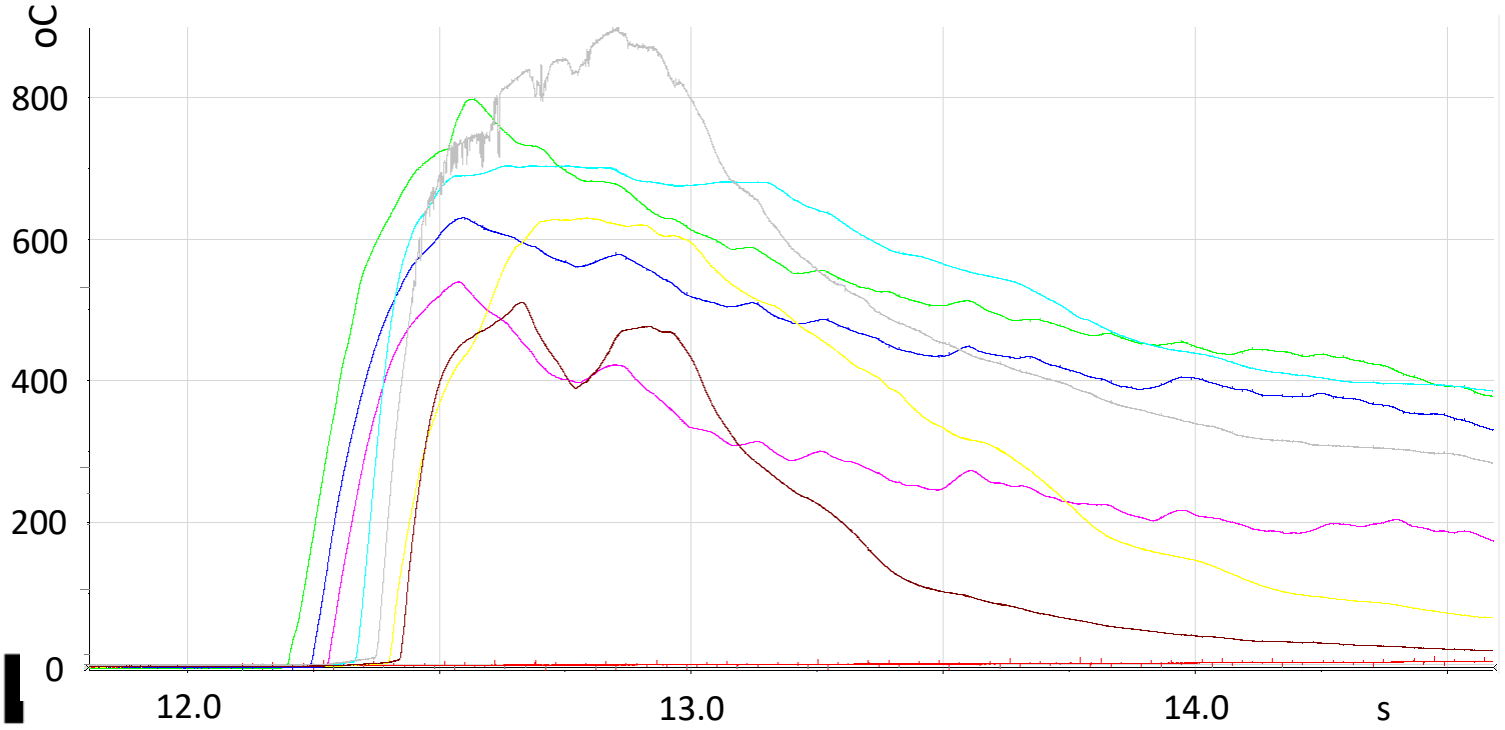
- Train 2 Release
- 580 bar upward release through a 5.0 mm nozzle
- Wind Speed 1.25 m/s
- Peak concentration 34.84 %?
- Igniter 3 m downstream, 0.3 m from ceiling (x=34, z=3.4)
- Ignition delay 12 s (10 s duration)
- Typical pressure around 320 mbar
- Peak pressure around 450 mbar (on P12; -1.0 m)
- Shock speed around 440 m/s



Results

Test 25 Ignited Blowdown

- Thermocouple arrays (high); 3.25 m
- Separation dX, first to last TC = 25 m
- dT = 0.22 s
- Average flame speed ~ 113 m/s



Results

Summary

- Successfully completed 11 large scale blowdown tests
- Measured hydrogen concentration as a function of time for all tests
- Successfully completed 12 blowdown tests with **attempted** ignition
- Pressure data and flame speed data recorded for all tests
- The resulting data has been used by project partners to validate numerical models
- Further tests planned including with scaled vehicles (help to understand the effect of blockage on dispersion and blast)

Acknowledgements

This project has received
funding from the Fuel Cells
and Hydrogen 2 Joint Undertaking
(now Clean Hydrogen Partnership)
under Grant Agreement No 826193.
This Joint Undertaking receives support
from the European Union's Horizon 2020 Research
and Innovation program, Hydrogen Europe and Hydrogen
Europe Research.