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CFD Study to Assess Safety Aspects of TPRD Releases from Heavy-duty Hydrogen Vehicles and Trains in Tunnels

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Heavy-duty vehicles (HDVs) and trains using hydrogen as fuel have significantly larger tanks than smaller fuel cell vehicles (FCVs). The requirement for depressurization time in case of fire may often be the same, thus there may be a need to dimension the thermal pressure relief devices (TPRDs) for significantly higher release rates than used in FCVs. This CFD-study assesses to what extent higher TPRD release rates than typically used for FCVs may be applied without compromising safety. The study has been performed in collaboration with partners in the MoZEES research centre.

1. Introduction

With the use of computational fluid dynamics (CFD) a systematic assessment of the potential explosive cloud development from unintended TPRD-releases for relevant train and heavy-duty vehicle hydrogen tank configurations has been performed, and a selection of the developed explosive clouds have been ignited to study potential explosion effects inside the tunnels. TPRD-releases are initiated by melting metal alloy fuses (110 °C) as a safety measure to empty hydrogen storage tanks exposed to fires. Typical tanks used for automotive applications can be expected to withstand a severe bonfire without failing for 3.5 to 6.5 min (Stephenson 2005), and local hydrogen jet-fires may possibly be more of a concern. If TPRDs should fail or be too slow to empty the tanks in a fire, individual tanks could catastrophically fail while still at a significant pressure with potentially severe consequences inside a tunnel. The motivation of this study is to assess how quickly tanks can be emptied safely through TPRDs to prevent potential higher consequence tank ruptures. More details about TPRDs and fire testing of tanks with focus on private cars can be found (Ulster University and HSE, 2013). In another HyTunnel project deliverable, Cirrone et al. (2019) also presents good insight into the field. Biogas bus tank explosions due to jet-fire (Hagberg et al., 2016) and impact (CTIF 2019) have illustrated the accident potential. Hydrogen transport vehicles (LH_2 or CH_2) are not the focus of this study, consequences from tunnel incidents with such may be more severe but not necessarily worse than incidents with transport trucks for LNG, LPG, petrol and NH_3. Cargo train accidents may be even more severe, but such a tunnel incident will normally only expose the limited crew of the cargo train trained for emergencies, while a truck accident may at worst expose 100s of individuals unrelated to the vehicle causing the accident. This should be kept in mind when discussing the possible TPRD incidents.

2. Road tunnel TPRD assessment for heavy-duty vehicles

Two different tunnels are assessed for the heavy-duty vehicle simulations representing typical high-traffic tunnel profiles used in Norway, see Figure 1 and Norwegian Directorate of Public Roads (2020):

- T10.5 is a U-shaped tunnel required for bidirectional two-lane traffic (2 lanes of 3.5 m with 1 m separation and 1.25 m shoulders, giving a total width of 10.5 m centre height 6.36 m and cross-section 60.6 m^2.
- T9.5 rectangular profile typical for concrete tunnels in urban areas required for dual lane traffic, each lane is 3.5 m with 1.25 m shoulders, height of 5.0 m (traffic requires 4.6 m) and cross-section 47.5 m^2.

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2.1 Scenarios assessed

For the CFD modelling tunnels are 400 m long with TPRD-release scenario in the middle, a scenario that should be representative for any long tunnel. A temperature of 20 °C is assumed but no ventilation, as Middha and Hansen (2009) in a similar study concluded ventilation to have limited impact on explosive cloud sizes. The heavy-duty vehicles are assumed to be equipped with hydrogen tanks of three different sizes, these are 5 kg, 10 kg and 20 kg. Unignited spurious release of single tank TPRD activation was assumed, if release would be initiated by a fire, early ignition and no explosion would be expected. For each tank-size an orifice diameter is selected to release 95% of the hydrogen within 1 min, 3 min and 5 min, respectively. In Table 1 the tank sizes are shown together with the orifice diameters and initial release rates for 1 min, 3 min and 5 min release durations. It is assumed that the largest tank is at 70 MPa, while the two smaller tank sizes are at 35 MPa. Transient release rates using Leachman's NIST equation of state are simulated. For each of these 9 release scenarios three different TPRD-release scenarios are considered, these are:

- Top of vehicle pointing up (elevation 4 m)
- Location 2.3 m above ground (behind drivers' cabin) pointing up
- Below vehicle pointing down (around 1 m above ground)

Horizontal releases are not considered acceptable due to potential direct hazard to surrounding people and vehicles. Scenarios where the vehicle is at significant speed would help dilute gas concentrations efficiently (see train section) and will not be of significant concern. The modelling will only consider worst-case scenarios with typical stand-still, rush-hour situations. It is assumed that the lane where the release takes place is filled with cars with one heavy-duty vehicle for every 10 normal cars. A total of 54 scenarios are considered.

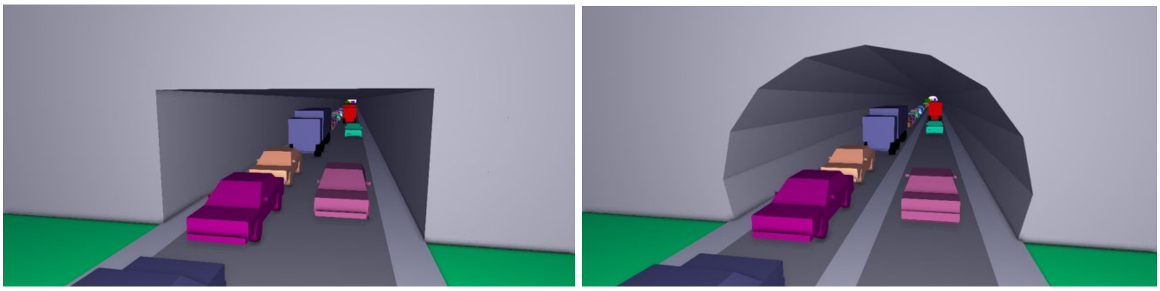

Table 1: Overview of assumed tank sizes, TPRD orifice diameters and initial release rates (T=20 °C).

Tank size	Typical tank	1 min release		3 min release		5 min release	
		Orifice	Rate	Orifice	Rate	Orifice	Rate
5 kg	210 L @ 35 MPa	4.4 mm	272 g/s	2.5 mm	88 g/s	2.0 mm	56 g/s
10 kg	420 L @ 35 MPa	6.5 mm	593 g/s	3.6 mm	182 g/s	2.75 mm	106 g/s
20 kg	490 L @ 70 MPa	6.5 mm	1100 g/s	3.8 mm	375 g/s	3.0 mm	233 g/s

Based on the transient gas cloud development a selection of scenarios was ignited and exploded at different moments in time. The cases exploded were selected to investigate a correlation between gas-cloud size and explosion strength and to understand differences between different release scenarios. The FLACS CFD-model developed by Gexcon was used for the study, following best-practice guidelines for setup-parameters and grid definition.

2.2 Results heavy-duty vehicle TPRD study

All 27 TPRD release scenarios for the rectangular tunnel profile were simulated while for the U-shaped tunnel only the 12 scenarios with initial leak rates above 300 g/s were simulated. In Figure 2 all flammable clouds for the 10 kg tanks for the rectangular tunnel are shown, this plot clearly shows that cloud sizes and concentrations are higher for the shorter blowdown times with the highest initial leak rates (upper plots) but also that cloud sizes are significantly larger for the downwards releases (left) than for the upwards releases (centre and right). Explosive cloud sizes (m^3) as function of time were predicted using the Q9 equivalent cloud approach (Hansen et al., 2013). The maximum cloud sizes as function of TPRD-location/orientation and initial leak rate for all 27 cases simulated in the rectangular tunnel are plotted in Figure 3. The predicted explosive cloud sizes for the U-shaped tunnel were on average 26% smaller, around 30% smaller for the highest release rates, and factor two for the smaller rates. Two of the simulated cases were larger for the U-shaped tunnel. For the rectangular tunnel the upwards release scenarios on average gave more than 60% lower predicted explosive cloud sizes than the downwards release scenarios. Figure 3 shows that explosive cloud sizes generally stay below 1 m^3 for upwards initial release rates below 200 g/s, and increases by factor 10 when initial leak rate is doubled to 400 g/s.

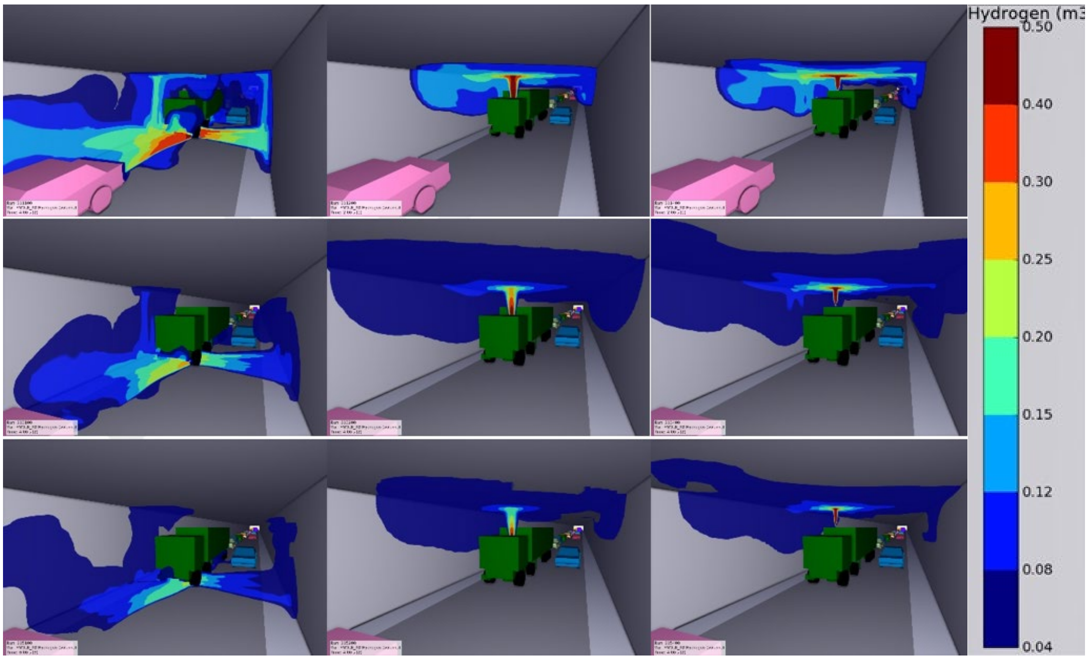

Figure 2: Illustration of hydrogen concentration at maximum reactivity for releases from a 10 kg tank with 1-minute releases in a rectangular tunnel (upper – 593 g/s), 3-minute releases in a rectangular tunnel (middle – 182 g/s) and 5-minute releases in a rectangular tunnel (lower – 106 g/s) for releases downwards from 1 m elevation (left), upwards from 2.3 m elevation (centre) and upwards from 4 m elevation (right).

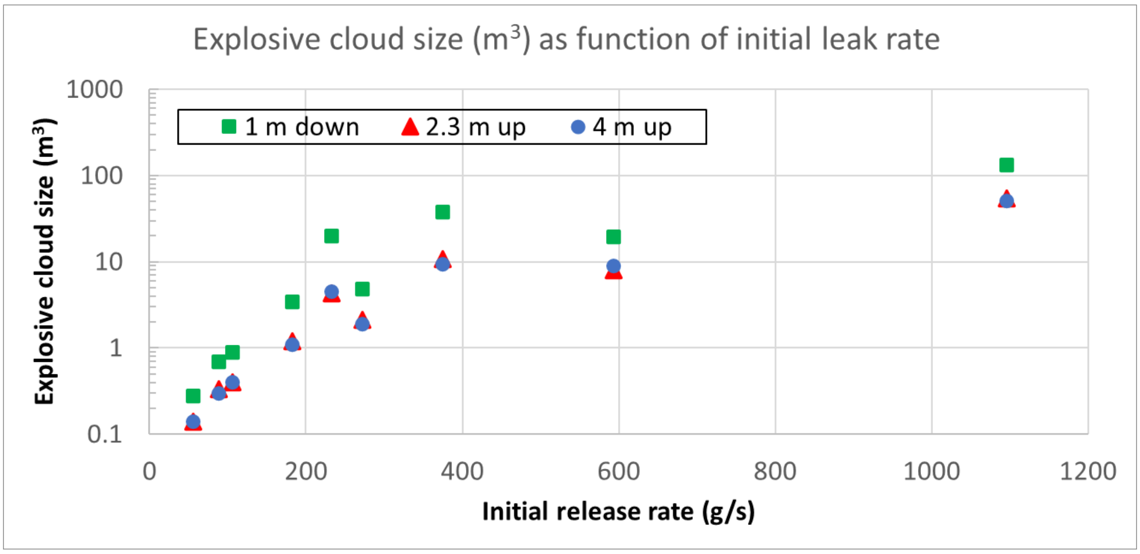

Figure 3: Maximum predicted equivalent stoichiometric cloud size Q9 (m^3) plotted as function of initial leak rate for all simulations performed in the rectangular tunnel.

Selected maximum explosive clouds from TPRD-releases were ignited and exploded.

- 1 min release scenario downwards from 5 kg tank with initial leak rate of 286 g/s ignited at maximum cloud size 5 m^3 after 5 s, this gave blast pressures along the tunnel of 3-4 kPa.
- 1 min release scenario downwards from 10 kg tank with initial leak rate of 593 g/s ignited at cloud size 17 m^3 after 10 s, this gave blast pressures along the tunnel of 5-6 kPa.

- 1 min release scenario downwards from 20 kg tank with initial leak rate of 1100 g/s was ignited at cloud size 135 m^3 after 20 s, this gave blast pressures along the tunnel around 50 kPa.
- 1 min release scenario upwards from 4 m elevation from 20 kg tank with initial leak rate of 1100 g/s ignited at cloud size 40 m^3 after 10 s, this gave blast pressures along the tunnel around 15 kPa.

If these explosions would happen, concerns for the safety of people would be e.g. local flame exposure around the incident for downwards release and significant blast pressures near the explosion zone. Except for the weakest of the simulated explosions, airbags of cars moving at speed could be activated, potentially causing vehicle collisions along the tunnel. People inside cars would be expected well protected from blast pressures by the robust windshields. For the strongest explosion people walking along the tunnel could be thrown off their feet by the significant explosion wind with potential for major injuries.
A TPRD-release with 233 g/s was also simulated as a jet-fire, releasing heat of almost 30 MW, both for no wind and 3 m/s wind from one side. In the simulations a layer of hot gases would form in the upper half of the tunnel, so that people below this layer could avoid the hot gases. For long tunnels there may be high or low points along the tunnel where the hot gas layer could locally reach the floor.
To conclude, TPRD-releases upwards with maximum initial leak rates around 200 g/s should be tolerable and not represent any significant risk to people in the tunnel. For larger release rates blast pressures could be more of a concern, potentially activating airbags in cars or exposing people in the tunnel to dangerous blast.

3. Railroad tunnel TPRD assessment

Two tunnel shapes have been assessed, see Figure 4 and JVB (2011), these are:
- Single-track railway tunnel (type A), which is 6.7 m wide and 7.35 m tall and area 45 m^2.
- Double-track railway tunnel (type A), which is 11.9 m wide and 8.5 m tall with area around 90 m^2.

In the simulations the tunnel length is 400 m which is sufficiently long so that the tunnel openings will not influence the simulation results. The TPRD release location is assumed in the middle of the tunnel. For this study the tunnel surfaces are assumed smooth.

3.1 Scenarios assessed

Two hydrogen cylinder bank configurations, 45 and 100 kg at 35 MPa, are assumed for which TPRDs are activated simultaneously. 3 TPRD release durations, 5 min, 10 min and 20 min, are considered. For all cases the TPRD is located on top of the locomotive pointing upwards. The train is assumed to be at no speed, at 36 km/h and 90 km/h, train speeds are modelled using wind. For each of 3 wind speeds and 2 tunnels 6 release scenarios will be considered, see Table 2. For longer release times fire protection of tanks may be required.

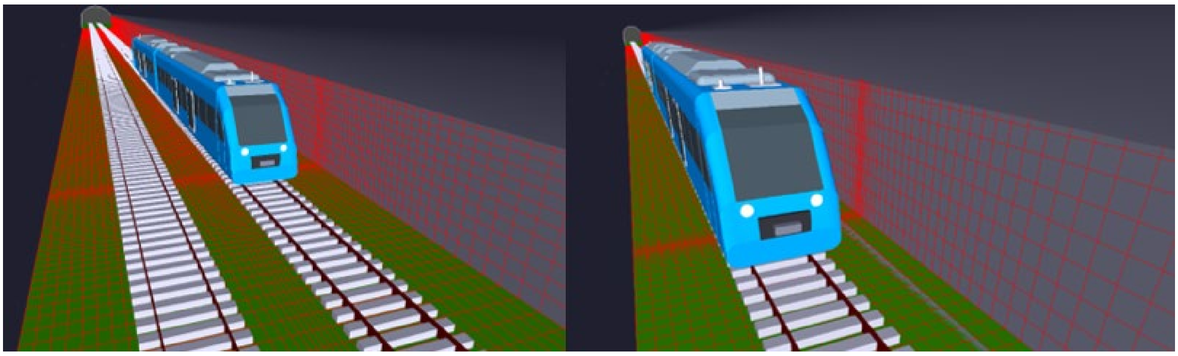

Figure 4: Illustration train in two-track tunnel (left) and single-track tunnel (right).

Table 2: Overview of assumed bank sizes, TPRD orifice diameters and initial release rates (T=20 °C).

Tank size	Tank pressure	5 min release		10 min release		20 min release	
		Orifice	Rate	Orifice	Rate	Orifice	Rate
45 kg	350 bar	6.0 mm	508 g/s	4.25 mm	250 g/s	3.0 mm	127 g/s
100 kg	350 bar	9.0 mm	1145 g/s	6.3 mm	561 g/s	4.5 mm	286 g/s

3.2 Results hydrogen train TPRD study

Simulations were performed in the single-track tunnel with 5 min and 20 min time until 95% of the hydrogen released, each scenario with no wind, with 36 km/h and 90 km/h wind to simulate a moving train. In Figure 5 two scenarios with 100 kg bank and 20 min release time with initial rate 286 g/s are shown for a train not moving and moving with 36 km/h. From the picture it is very clear that a much smaller cloud is predicted when the train is moving. For the single tunnel the 36 km/h speed reduces the explosive cloud size by factor 9, while 90 km/h reduces the cloud size by factor 20 for the 3-4 cases studied. The cloud sizes for the double tunnel were reduced by factor 4 (no wind), by 30% at 36 km/h while no further reduction was seen for 90 km/h. In Figure 6 the predicted cloud sizes for the single tunnel are shown. For the worst-case release with 100 kg bank released in 5 min the predicted explosion pressures along the tunnel with ignition after 15 s was 30 kPa for train standing still, 14 kPa for train at 36 km/h and 5 kPa for train at 90 km/h. For ignition after 60 s a 330 m^3 explosive gas cloud was predicted, with explosion pressures around 70 kPa and duration of 1 s. Due to very robust window requirements the passenger compartment windows might withstand such loads. People walking along the train would be at severe risk due to the expected explosion wind. Predicted explosion pressures as function of explosive cloud size for both the HDV and train study are shown in Figure 7.

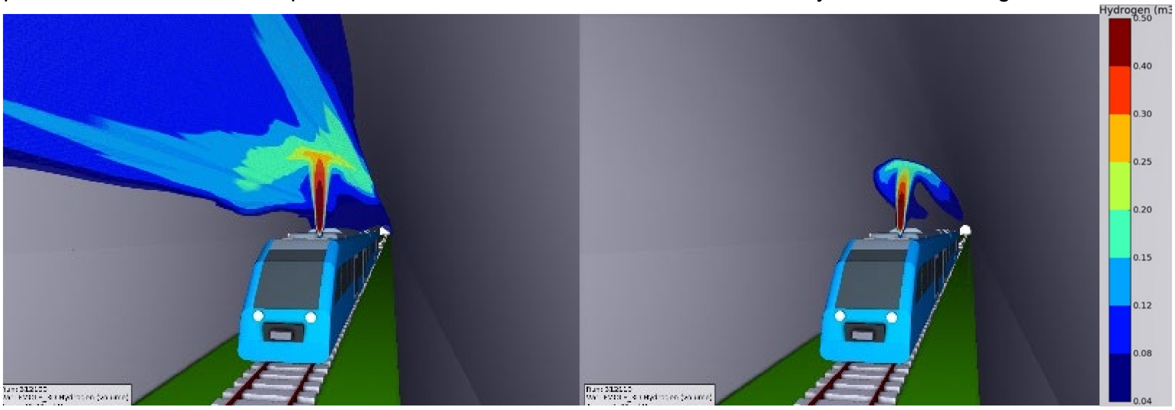

Figure 5: Flammable cloud from 4.5 mm TPRD release with initial rate 286 g/s for train at rest (left) and at 36 km/h (right).

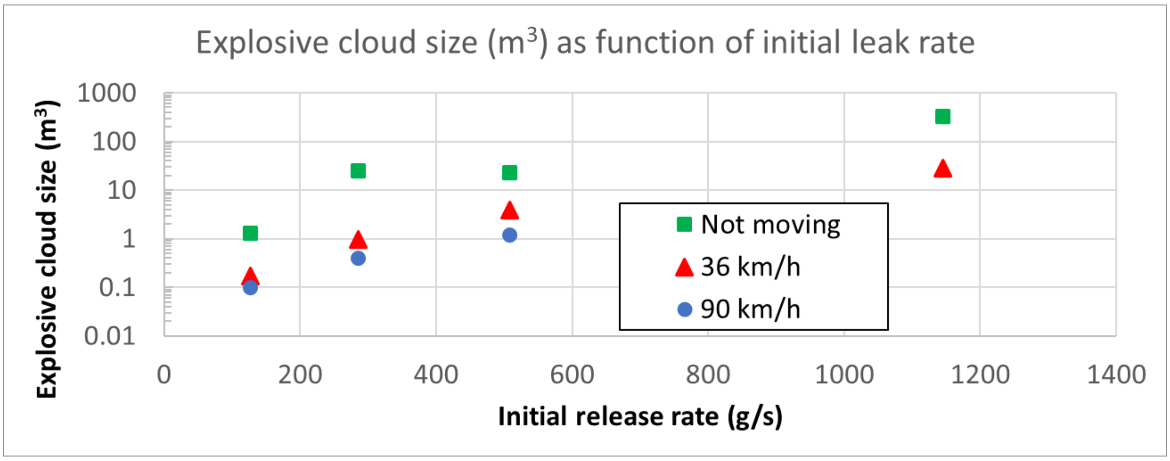

Figure 6: Maximum predicted equivalent stoichiometric cloud size Q9 (m^3) plotted as function of initial leak rate for all simulations performed in the single-track railway tunnel.

From the train studies the following conclusions can be drawn:

- TPRD releases while the train is moving (36 km/h or more) will not represent any significant risk to people, a recommended strategy may be to continue moving out of the tunnel if there should be a TPRD release.
- By limiting the TPRD orifice so that the maximum release rate can be kept below 200 g/s this will ensure small explosive clouds and consequences and a limited concern if a cloud is ignited. For people protected inside trains initial release rates up to 500 g/s are likely no major concern. For people evacuating outside a train this increased release rate may represent a significant danger due to a strong explosion wind.

- For larger storage banks the release times may need to be extended to 10 min or more, and it should be ensured that tanks are robust enough or given additional fire protection to survive the exposure time.

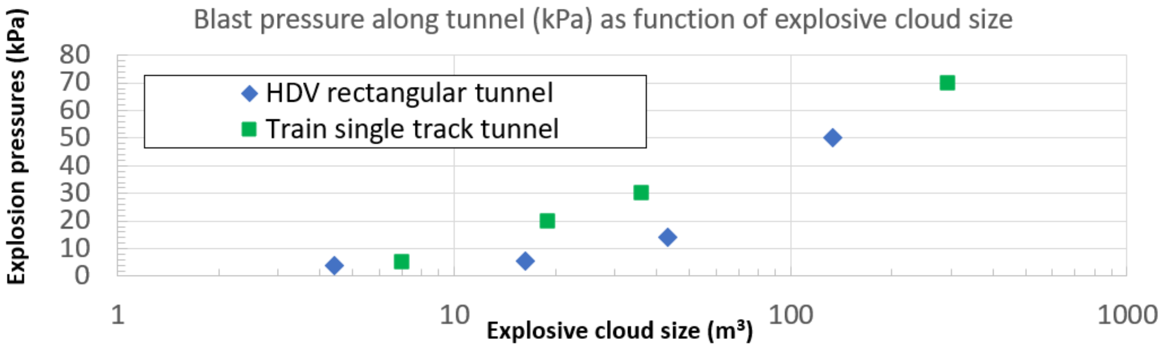

Figure 7*:* Explosion pressure along tunnels as function of explosive cloud sizes.

4. Conclusions

Possible consequences from TPRD releases with delayed ignition have been assessed with CFD simulations. The purpose was to identify the maximum tolerable release rates inside narrow tunnels from heavy-duty hydrogen fuelled vehicles and trains to optimise TPRD blowdown times to limit the risk for tank rupture in case of fire. One conclusion from the study is that HDV TPRDs should be directed upwards rather than downwards to limit the size of reactive clouds and potential local risk to people around a release. It is further recommended to keep TPRD release rates below 200 g/s as the study indicated that explosion pressures would increase significantly for larger release rates. Risk for both releasing airbags of cars in motion throughout the tunnel and strong explosion wind pushing people in the tunnel off their feet may also increase if release rates above 200 g/s are chosen. For trains somewhat higher release rates may be tolerable if people remain inside the trains in an emergency, for people outside the trains a high explosion wind may be a concern for leak rates well above 200 g/s. For trains emergency venting times above 10 min could require additional fire protection to ensure that the tanks will survive an external fire.

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