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Developing a Generalized Framework for Assessing Safety of Hydrogen Vehicles in Tunnels

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MOTIVATION

Alternative vehicles use of infrastructure requires a **reassessment of safety**

Fire response curves based on hydrocarbon fueled vehicles and cargo are used in the structural design of tunnels

Similar to hydrocarbon vehicles, hydrogen vehicles pose **thermal hazards,** but with characteristics that differ:

- Hotter flames
- Shorter duration
- Highly directed
- Buoyant flammable cloud

High-fidelity **modeling simulations** have been used to support single tunnel safety studies

- High computational costs
- Single tunnel geometry / accident scenarios considered

Goal

Develop a **generalized framework** for assessing safety of hydrogen vehicles in tunnels

- Variety of tunnel geometries
- Different vehicle types/classes
- Multiple crash scenarios

Will require approach to be relatively **computationally inexpensive**

- Allowing assessment of multiple scenarios

Adaptable to alternative fueling types for comparisons

Enable safety of H_2 vehicles in tunnels to be consistently and specifically assessed nationwide

OUTLINE

Modeling Approach

Tunnel Geometry Characterization

Tank Blow Down Calculations

Parametric Sensitivity Studies

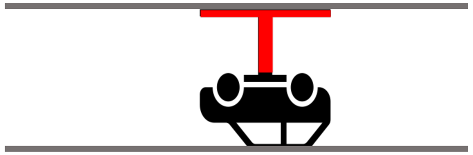
- Tank Size
- Tank Volume
- Tank Orifice
- Tank Fullness
- Fuel Type

Fuel Dispersion

Consequence Metrics

Conclusions

ACCIDENT SCENARIO



Flipped over light duty vehicle

Exposed to external fire causing 2.25 mm Thermal Pressure Relief Device (**TPRD**) to activate

GH_2 fuel tank is 125 L at 70 MPa

- ~5 kg of fuel

GH_2 released through TPRD as jet directed toward the tunnel ceiling

- Ceiling is 3.93 m above release point
- Fuel may immediately ignite as a **jet fire** or have delayed ignition causing an **unconfined overpressure** event

Illustration of accident scenario; image taken from first responder training from www.h2tools.org

Also consider **CNG** and **LPG** vehicles for comparisons

- Assumed same TPRD size as GH_2
- 60 L tank at 25 MPa for CNG (*modeled as CH_4*)
- 50 L tank 80% full of liquid for LPG

Conservative accident scenario previously analyzed used to establish methodology

MODELING APPROACH

Physics Models

HyRAM+ V5.0 Python backend provides temporal blowdown calculations of releases from vehicle fuel tank

- Release assumed to be gaseous
- Choked flow throughout most of blowdown
- Density evolved for LPG instead of pressure

Steady state jet plume and jet flame models of gaseous releases based on pressures and mass flow rates for each blowdown time point

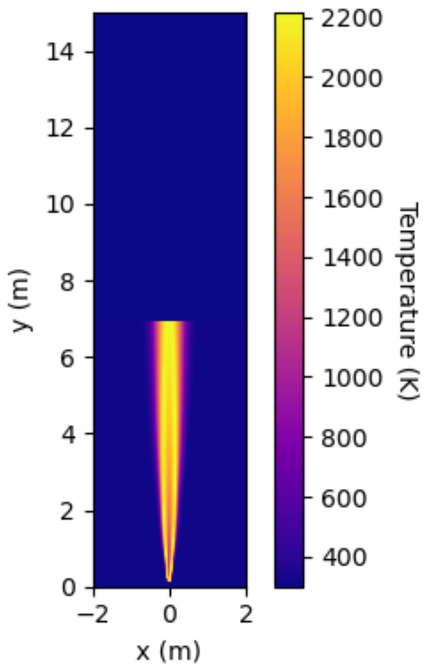
Consequence Models

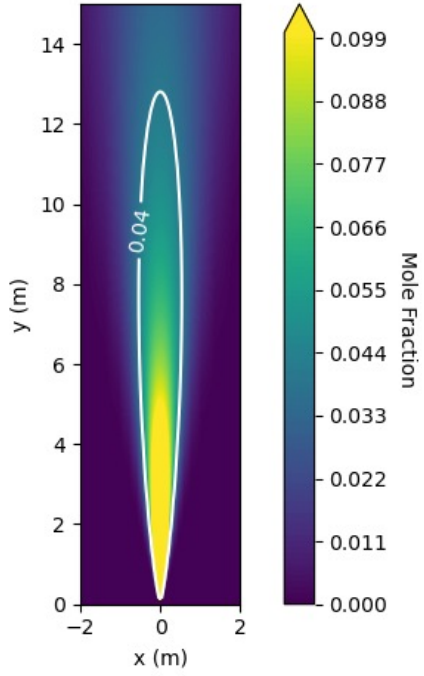
Visible flame length and **positional radiative heat flux** predictions based on steady state jet flame calculations

Flammable mass and **maximum unconfined overpressure** from jet plume calculations

- Overpressure values from 1 m away horizontally to better capture scaling behavior

HyRAM+
Hydrogen Plus Other Alternative Fuels Risk Assessment Models





TUNNEL GEOMETRY CHARACTERIZATION

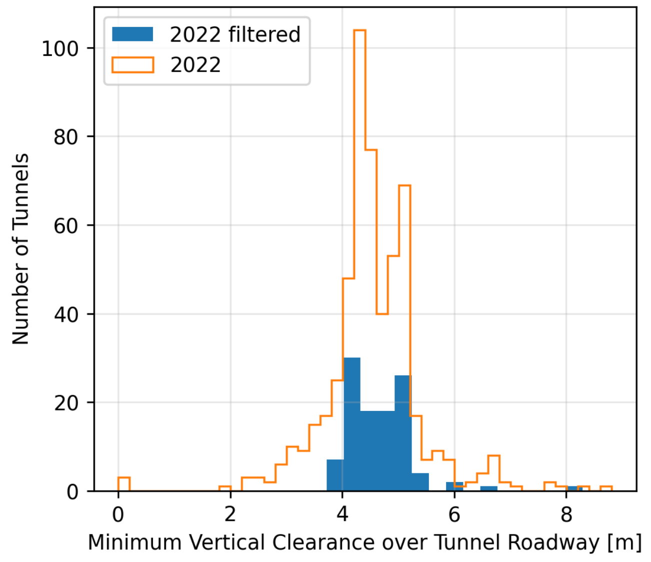
Extracted tunnel characteristic data from U.S. Federal Highway Administration's **National Tunnel Inventory**[1]

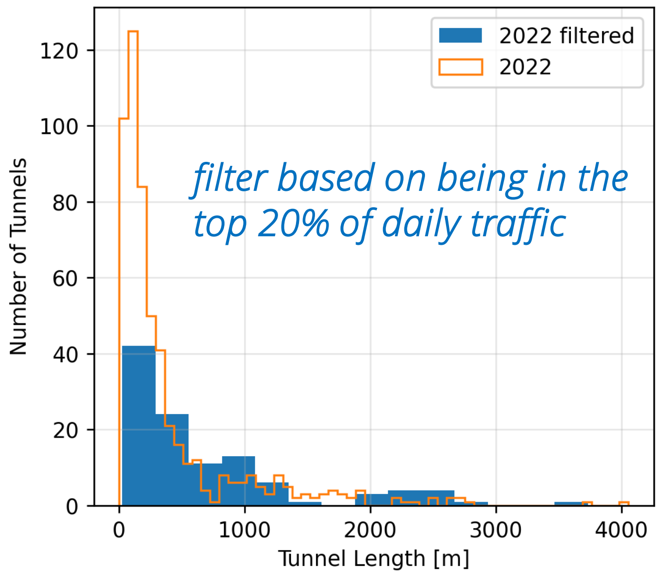
Annual data on tunnel characteristics and inspection results

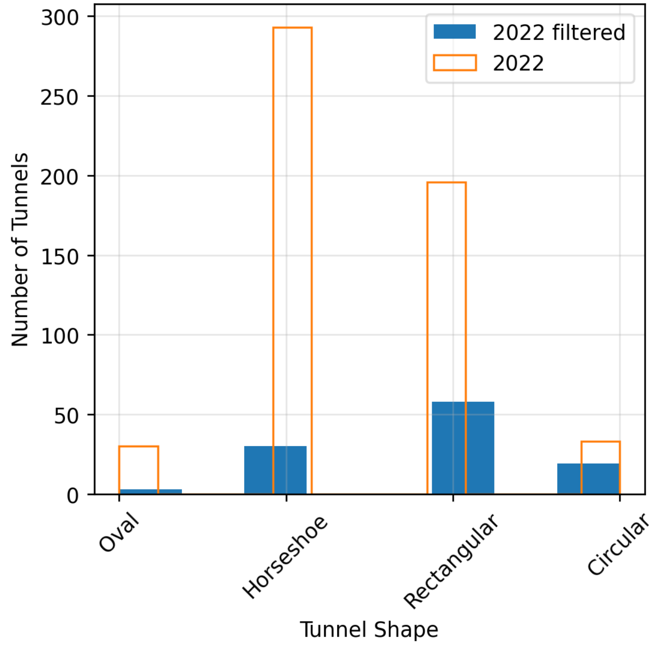
- **Characteristics**: location, year built, average traffic load, length, …
- Inspected **elements**: tunnel liner, roof girders, ceiling slab, ceiling panels, …

Use **tunnel characteristic/element statistics** to focus safety analyses

Determine prevalence and relevance based on **prioritization** such as high daily traffic loads

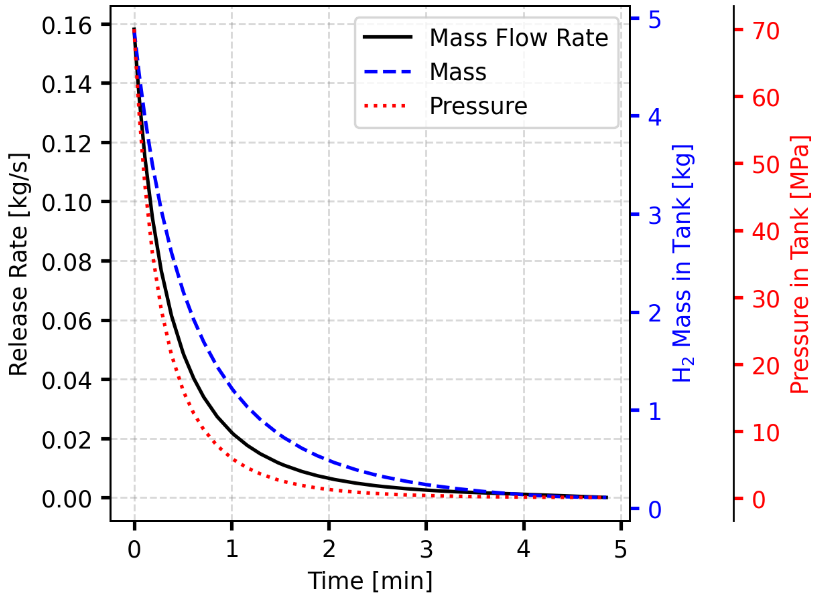


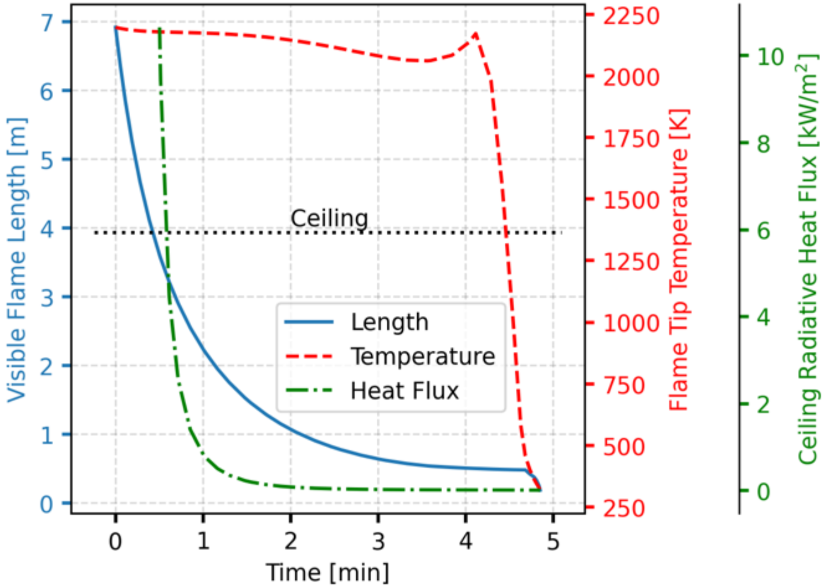




1. https://www.fhwa.dot.gov/bridge/inspection/tunnel/inventory.cfm

TANK BLOWDOWN CALCULATIONS





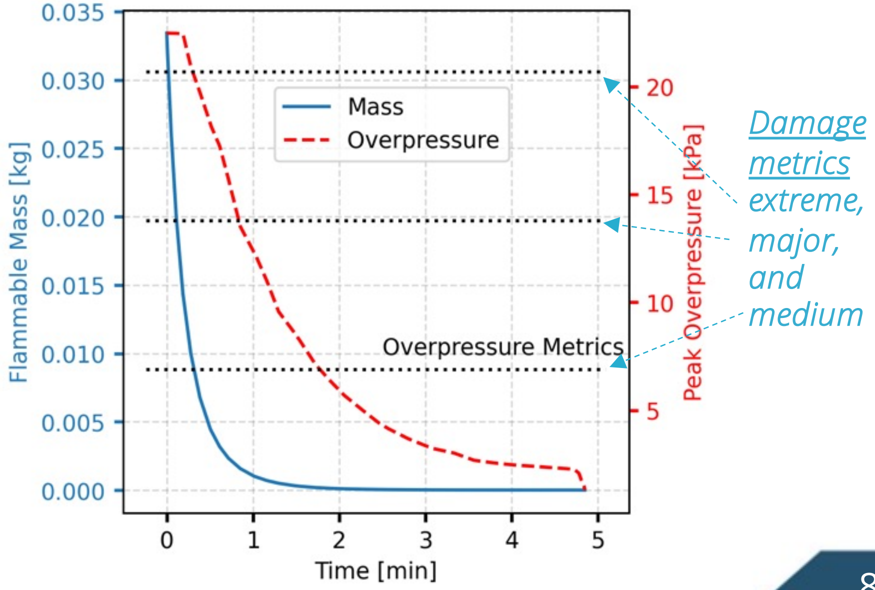
Tank **empties** in less than **5 minutes**

- 75% of mass released in first minute, 95% in under 3 minutes

Flame initially ~7 meters long, but **stops impinging** on ceiling after **25 seconds**

Radiative heat flux to ceiling quickly diminishes after impingement ceases

Overpressure can potentially cause extreme damage (21 kPa), but rapidly decreases to less severe damage within 106 seconds



PARAMETRIC SENSITIVITY STUDY

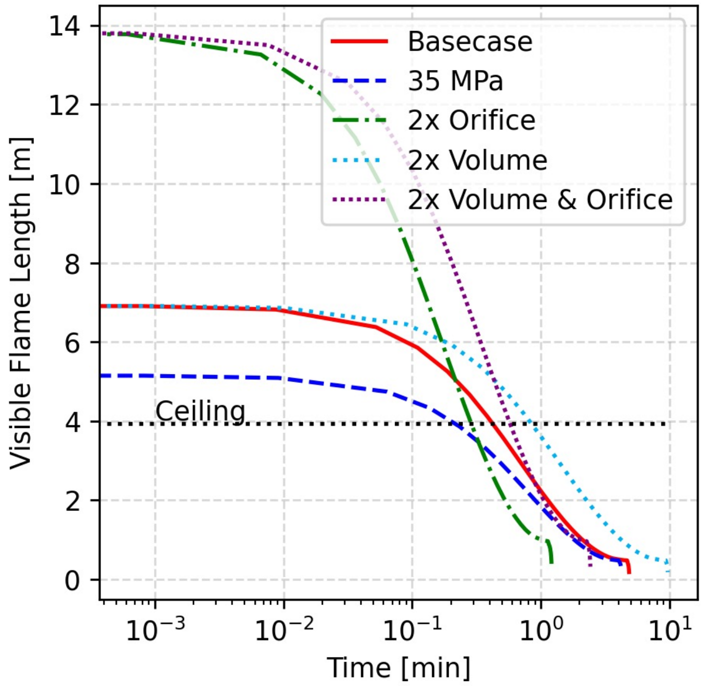
Varying scenario parameters that impact tank blowdown and resulting consequences

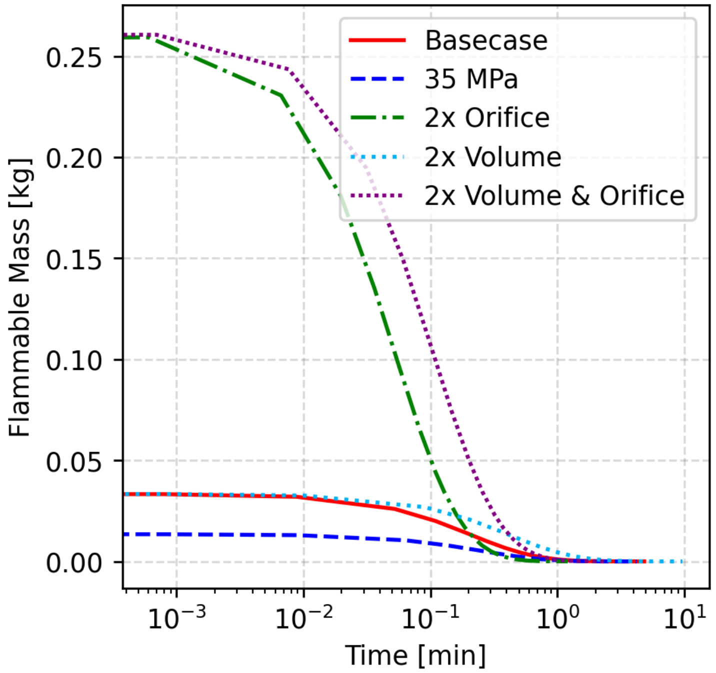
- Holding other parameters at nominal values

Reducing tank pressure decreases extent and duration of consequences

Increasing tank size increases duration of consequences

Increasing orifice size increases consequence magnitude but decreases duration





Varying input parameters allows alternative accident scenarios to be compared

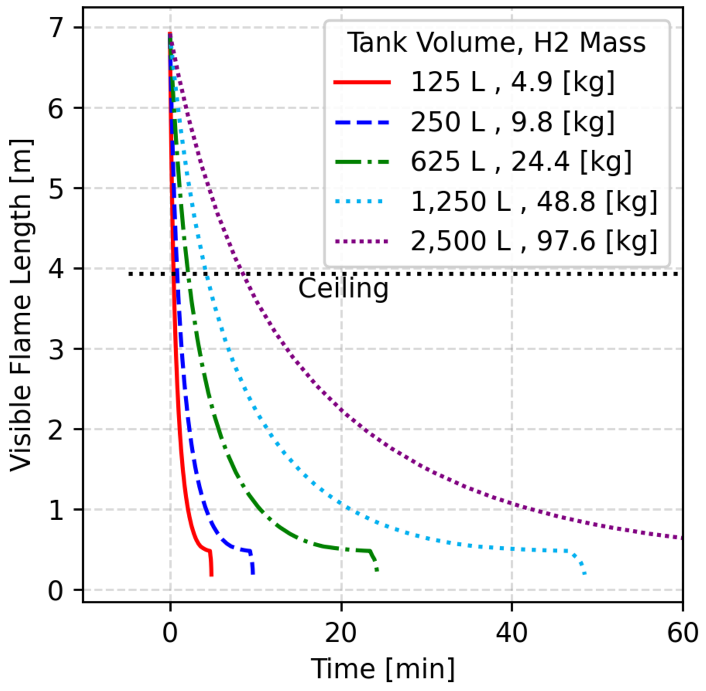
TANK VOLUME STUDY

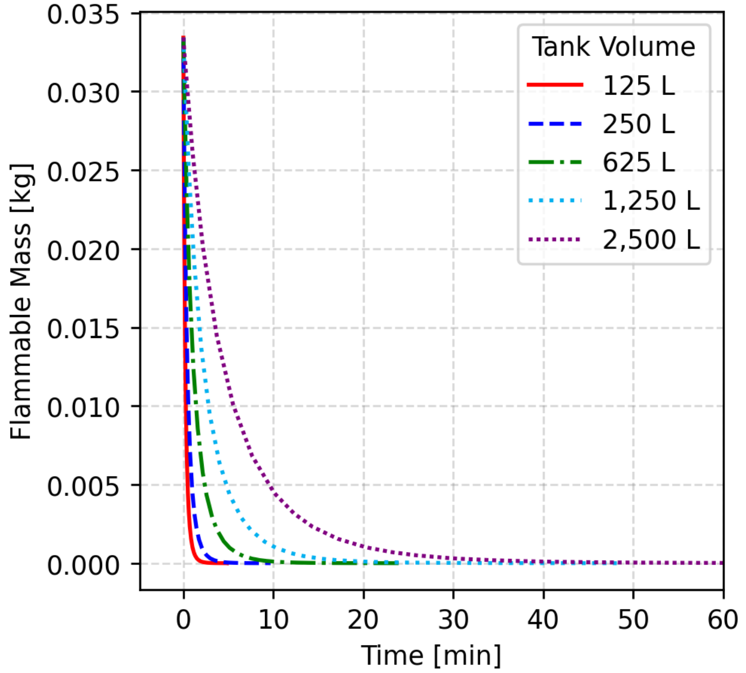
Varying tank volume provides insights into how different **vehicle classes** will impact the blowdown behavior

- 125 L to 2,500 L meant to span from **light duty** to **heavy duty**

Larger tanks increase the duration of consequences but not the magnitude for same leak/orifice size

- Heavy duty vehicles may operate at lower pressures reducing consequence magnitude





Increasing volumes 2x (*250 L*), 5x (*625 L*), and 20x (*2500 L*) from nominal increases total blowdown durations equivalently

Time the jet flame impinges on the ceiling increases

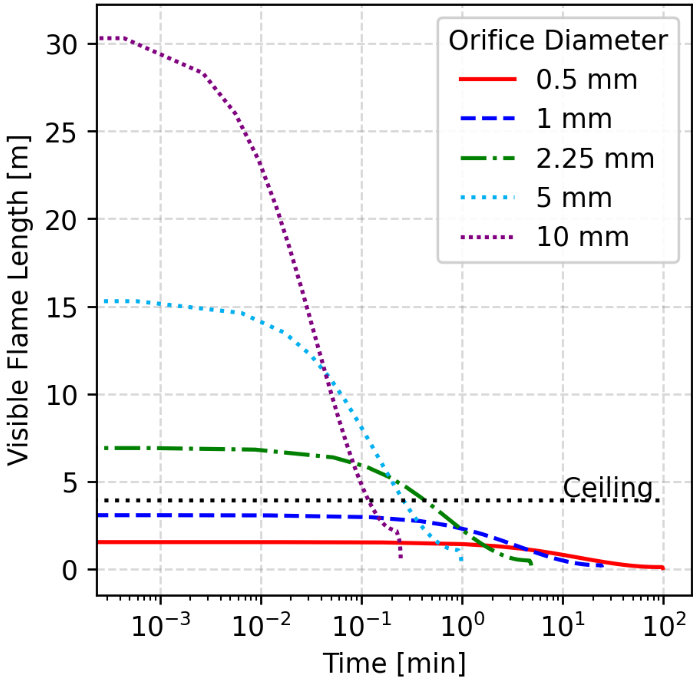
TANK ORIFICE SIZE STUDY

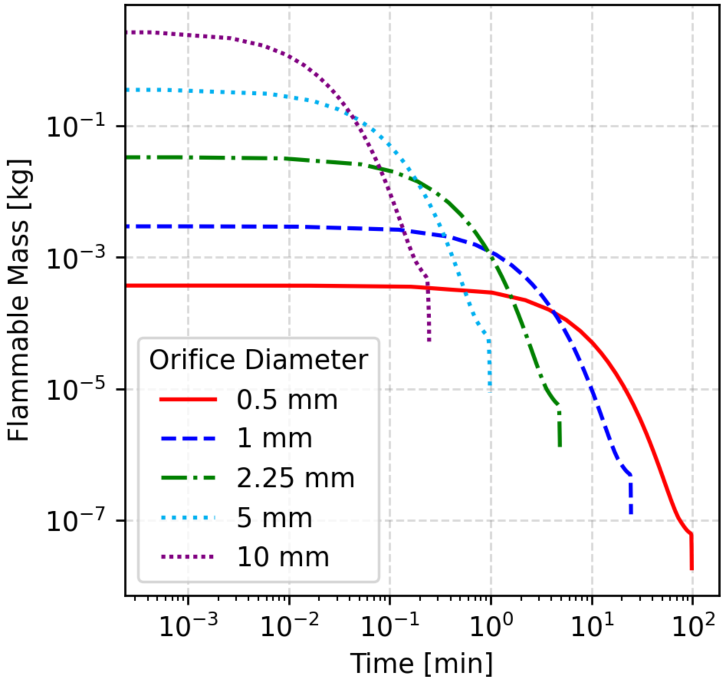
Varying orifice diameter through which fuel is released (**TPRD**) between 0.5 mm and 10 mm

- Reflects impact of different TPRD designs or potential leaks from the vehicle

Increasing the orifice size increases the consequence magnitude but decreases the duration

Orifice Diameter (mm)	Maximum flame length (m)	Maximum flammable mass (kg)	Total blowdown time (min)
10	30.7	2.76	0.25
0.5	1.54	3.72E-04	98.2



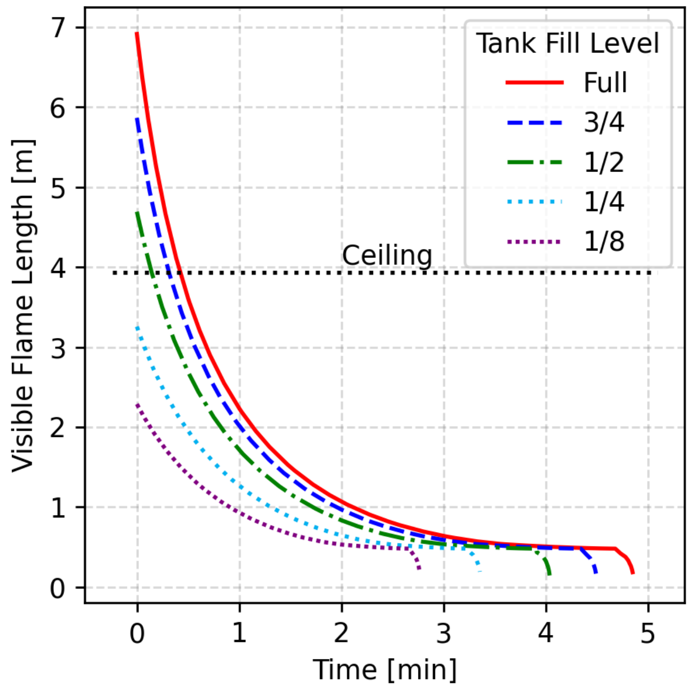


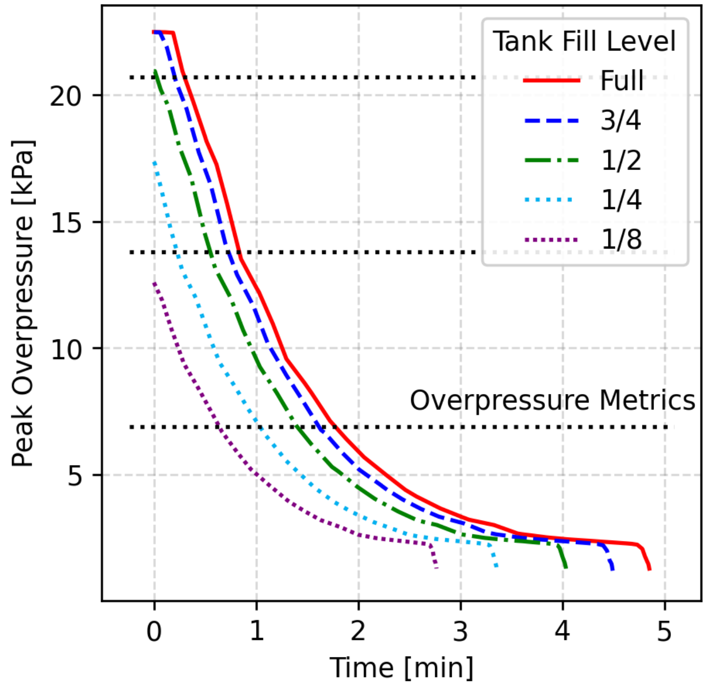
TANK FULLNESS STUDY

Varying fullness of tank (**% full**) between 100% and 12.5%

- Assuming full vehicle tank at time of accident is conservative; exploring impact of different realities

Less full tanks have lower consequences for shorter durations





Flame from ¼ full tank never reaches the ceiling and does not reach peak overpressures necessary to cause extreme damage

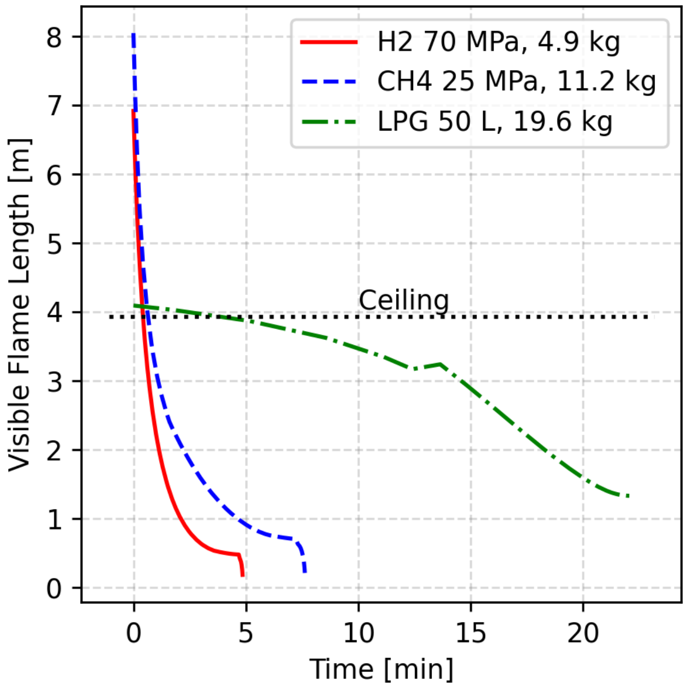
FUEL TYPE STUDY

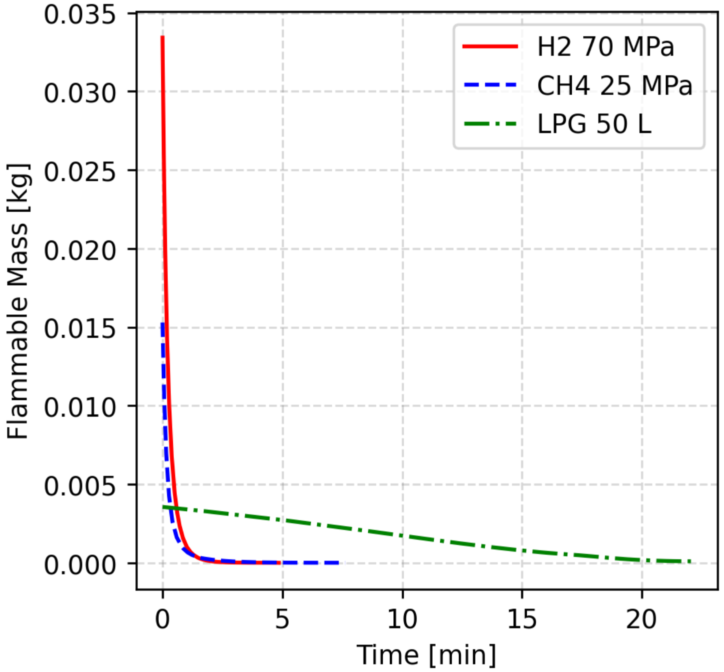
Comparisons against other fuels provides perspective for H_2 predictions

- Comparable, fieldable CH_4 and LPG vehicle tanks estimated; not equal masses

CH_4 and H_2 consequences more similar in duration and characteristic

LPG consequences less severe but longer duration due to larger mass of fuel



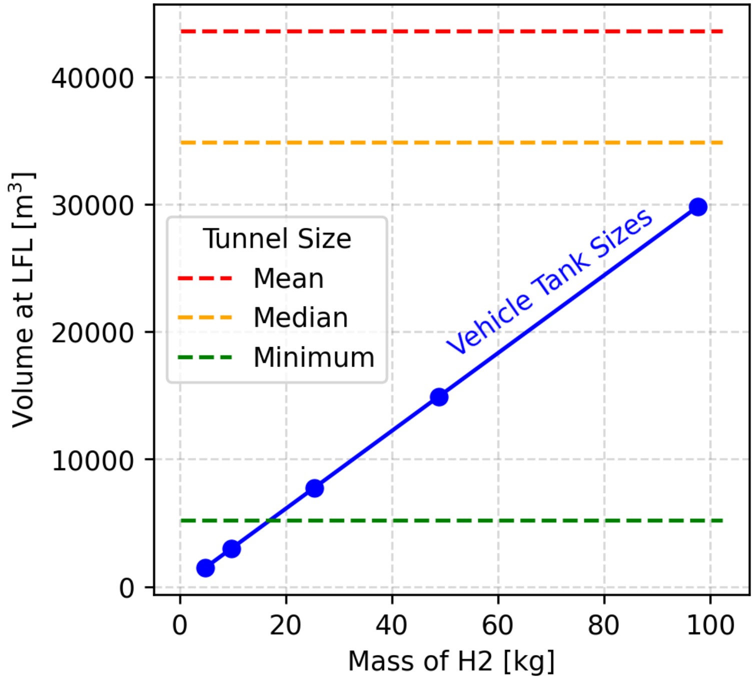


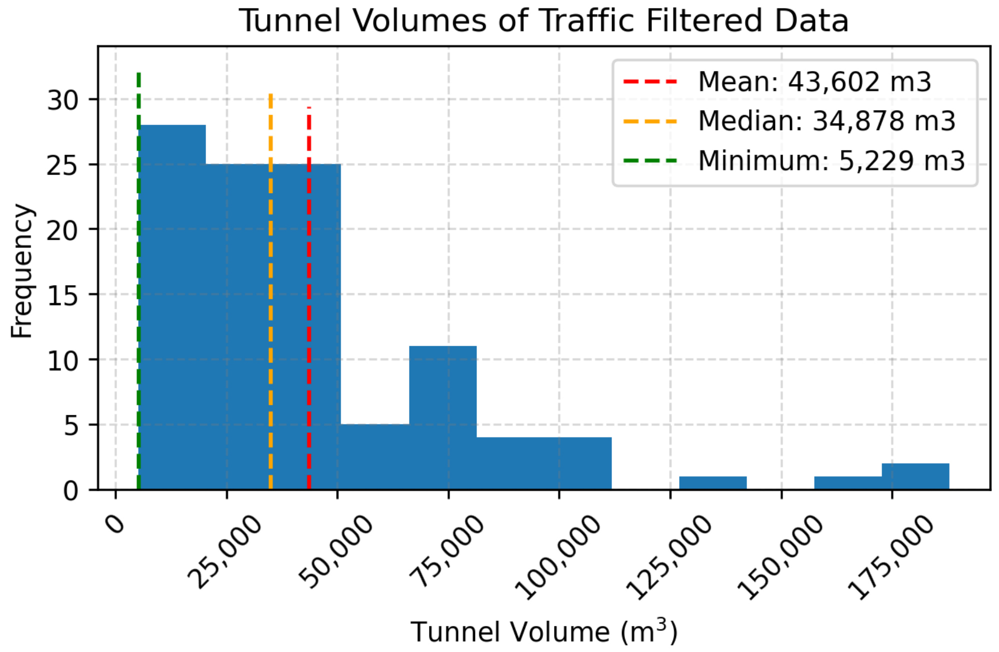
FUEL DISPERSION

Possibility of **accumulating large flammable mass** in tunnels is another safety concern

Initial investigation looks at **physically impossible bounding case** of total volume of fuel at lower flammability limit (*4% by volume*) for different tank sizes

- LFL volume compared to tunnel volume statistics





Tunnel volumes estimated based on tunnel shape, vertical clearance, width (roadway, sidewalks), and length from **National Tunnel Inventory** data

- Top 20% in terms of daily traffic

Light duty vehicles (5/10 kgs H_2) only fill up volumes (1,500/ 3,000 m^3) smaller than smallest tunnel considered (5,200 m^3)

Ignoring dissipation and ventilation

CONCLUSIONS

First steps in developing a **generalized tunnel safety analysis framework** for alternative fueled vehicles

Representative ranges of tunnel characteristics can be found in **U.S. DOT's National Tunnel Inventory** (*over 550 tunnels*)

Lower-order consequence models enable efficient exploration of a wide range of crash scenario parameters (tank volume, orifice size, …) and comparisons to other fuel types

Consequence models provide **temporally evolving** estimates of **hazards** potentially impacting tunnel structures including flame impingement and peak overpressures

Future work:

- Integrate information from tunnel design codes and standards
- Material response characterization to determine potential damage extents

Thank You for Your Attention

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Reference Slides

CONSIDERING CONSEQUENCE METRICS

Sensitivity study results tabulated based on consequence metrics

Time (min) Until Consequence Metric Reached *1 m from leak*					
Metrics	**Study**				
	Parameter Study				
	Basecase	**35 MPa**	**2x Orifice**	**2x Volume**	**2x Volume & Orifice**
4.732 kW/m2	0.40	0.20	0.28	0.80	0.55
6.9 kPa	1.73	1.48	0.72	3.46	1.44
Ceiling Impingement	0.43	0.22	0.29	0.85	0.58
	Orifice Diameter Study				
	0.5 mm	***1 mm***	***2.25 mm***	***5 mm***	***10 mm***
4.732 kW/m2	0.00	0.00	0.40	0.25	0.11
6.9 kPa	3.28	3.79	1.73	0.62	0.24
Ceiling Impingement	0.00	0.00	0.43	0.26	0.12
	Tank Volume Study				
	125 L	***250 L***	***625 L***	***1,250 L***	***2,500 L***
4.732 kW/m2	0.40	0.80	2.01	4.00	8.04
6.9 kPa	1.73	3.46	8.78	17.55	34.62
Ceiling Impingement	0.43	0.85	2.12	4.26	8.54
	Tank Fullness Study				
	Full	***3/4***	***1/2***	***1/4***	***1/8***
4.732 kW/m2	0.40	0.29	0.12	0.00	0.00
6.9 kPa	1.73	1.60	1.38	1.02	0.62
Ceiling Impingement	0.43	0.32	0.15	0.00	0.00
	Fuel Type Study				
	H2 70 MPa	***CH4 25 MPa***	***LPG 50 L***		
4.732 kW/m2	0.40	0.17	0.00		
6.9 kPa	1.73	0.93	16.48		
Ceiling Impingement	0.43	0.65	3.83		

CONSEQUENCE MODELS STEADY STATE ASSUMPTION

HyRAM+ v5.0 consequence models used steady state models whose mass flow rates do not exactly match those from blowdown calculations when matching pressure values

Error is relatively small, but steady state flowrates are smaller than those predicted by blowdown resulting in underprediction of consequences

Largest errors occur early in blowdown when consequences are still typically damaging even in steady state predictions

Comparison of mass flow rates predicted by HyRAM+ blowdown calculations and steady state consequence models