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# Alternative Fueled Vehicles in Tunnels

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Federal Highway Administration (FHWA) Webinar

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SAND2023-13387PE

# Agenda

Introduction
- Current status of alternate fuels vehicles in the US
- Literature review
- Hazards for each fuel type

Generalized tunnel analyses
- Tunnel Statistics
- Time-dependent modeling

Next Steps

Questions

# Introduction

Who are we?

- Researchers on fire risks for emerging technologies at Sandia National Laboratories
- Extensive history of research on hydrogen and partnership with the DOE Hydrogen & Fuel Cell Technologies Office (HFTO)

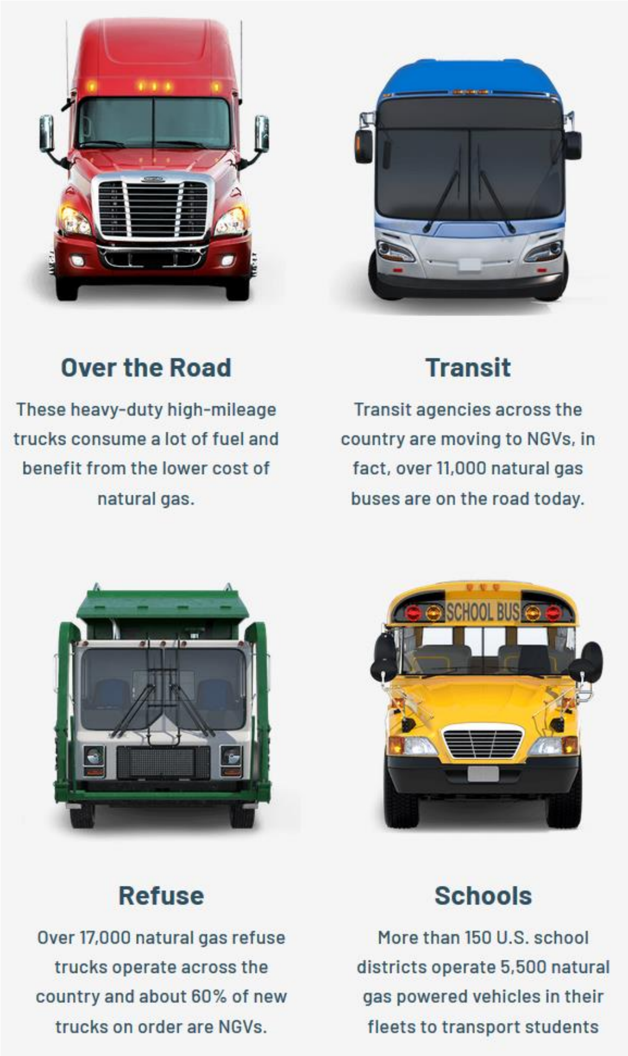
Why are we here?

- Questions on comparative safety – compared to traditional fuels
- Comparative emergency response concerns

# Background

Increasing numbers of alternative fueled vehicles are on the roads in the US

- Battery Electric Vehicles
  - Battery Electric vehicles sold in the United States reached nearly 873,000 so far in 2023, with sales of Tesla, Volvo, Nissan, Mercedes, Hyundai, and Chevrolet. BEVs account for 7.9% of total industry sales
  - https://www.coxautoinc.com/market-insights/q3-2023-ev-sales/
- Natural Gas Vehicles
  - Natural gas powers more than 175,000 vehicles in the United States and roughly 23 million vehicles worldwide.
  - There are more than 1,600 CNG and 140 LNG fueling stations in the U.S., and refueling appliances are available for home use
  - https://www.ngvamerica.org/vehicles/
- Propane Vehicles
  - According to the Propane Education & Research Council, there are nearly 60,000 on-road propane vehicles with certified fuel systems in the United States.
  - Many are used in fleet applications such as school buses, shuttles, and police vehicles
  - https://afdc.energy.gov/vehicles/propane.html
- Hydrogen Vehicles
  - Hydrogen fuel cell vehicles do not use combustion, they use an electrolyte membrane and an electrochemical reaction to create electricity which propels the vehicles
  - https://afdc.energy.gov/vehicles/fuel_cell.html

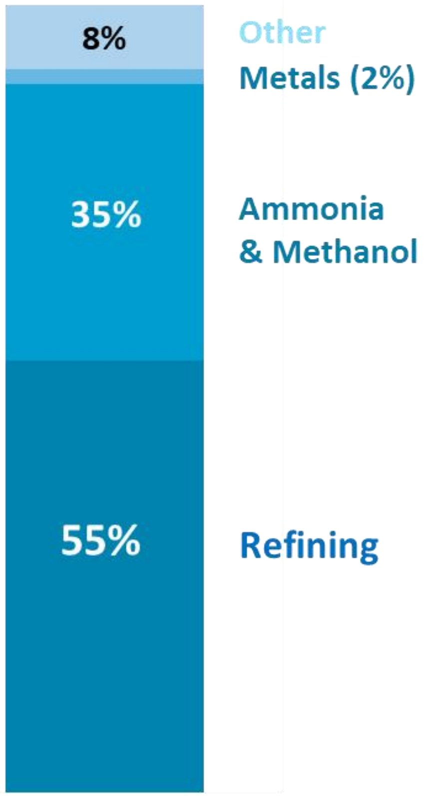



https://www.ngvamerica.org/vehicles/

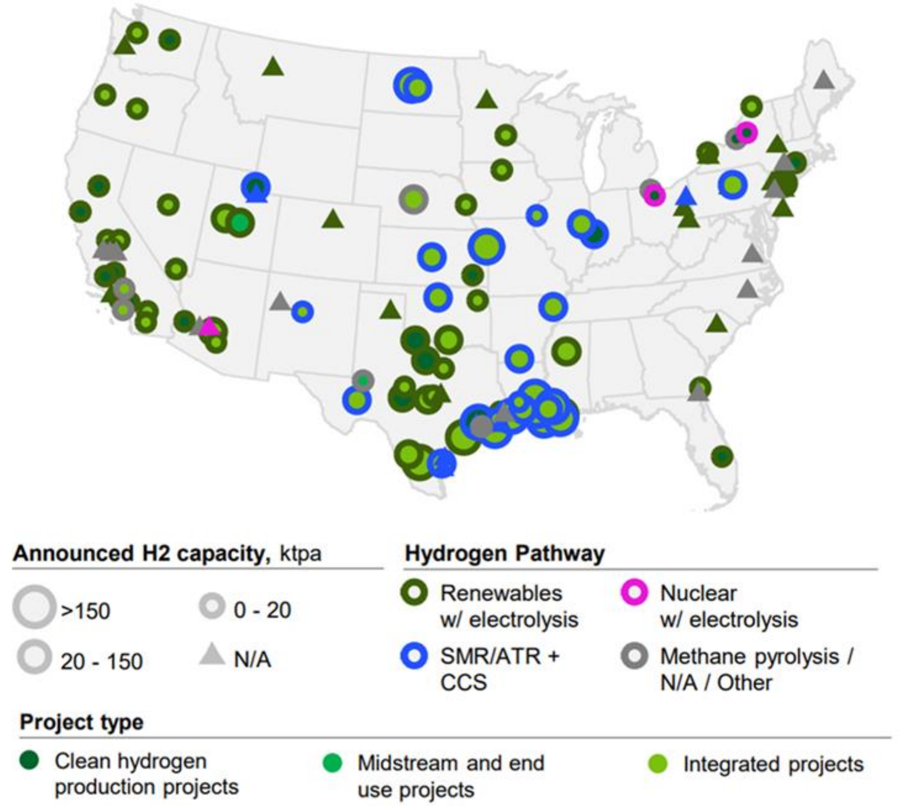
# Snapshot of Hydrogen and Fuel Cells in the U.S

- 10 million metric tons produced annually
- More than 1,600 miles of $H_2$ pipeline
- World's largest $H_2$ storage cavern

## Use of Hydrogen in the U.S. Today




## Current publicly announced clean hydrogen production projects*




## Examples of Deployments

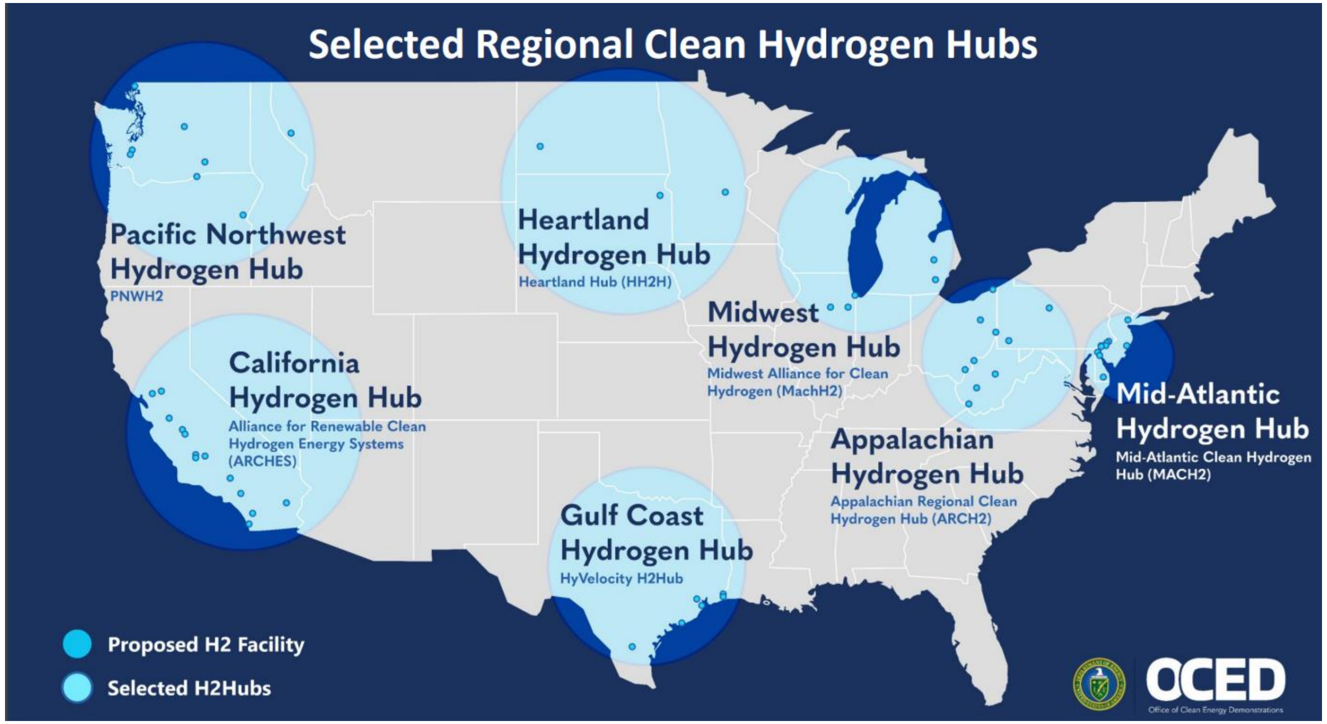
- **>500 MW** Backup Power
- **>60,000** Forklifts
- **>3.7 GW** Electrolyzers
- **~80 – 150** Fuel Cell Buses
- **~50** $H_2$ Retail Stations
- **>16,000** Fuel Cell Cars

# Changing Landscape for Energy

Regional Clean Hydrogen Hubs (H2Hubs)

- Designed to kickstart a national network of clean hydrogen producers, consumers, and connective infrastructure while supporting the production, storage, delivery, and end-use of clean hydrogen.

- Funded by the Bipartisan Infrastructure Law (BIL), the H2Hubs will accelerate the commercial-scale deployment of clean hydrogen helping to generate clean, dispatchable power, create a new form of energy storage, and decarbonize heavy industry and transportation.
- 17 states included in the regional hubs




https://www.energy.gov/oced/regional-clean-hydrogen-hubs-selections-award-negotiations

# Literature Review

Goal: Capture the current research on each vehicle type as they relate to hazards in tunnels and begin to evaluate knowledge gaps

Research is grouped by type

- Experiments – Full and medium Scale
- Modeling – Detailed computational modeling that characterizes consequences of different hazard scenarios
- Analysis – Physics and energy balance equations utilized to evaluate hazard scenarios

Plausibility of Hazard Scenarios

Report Published 2020

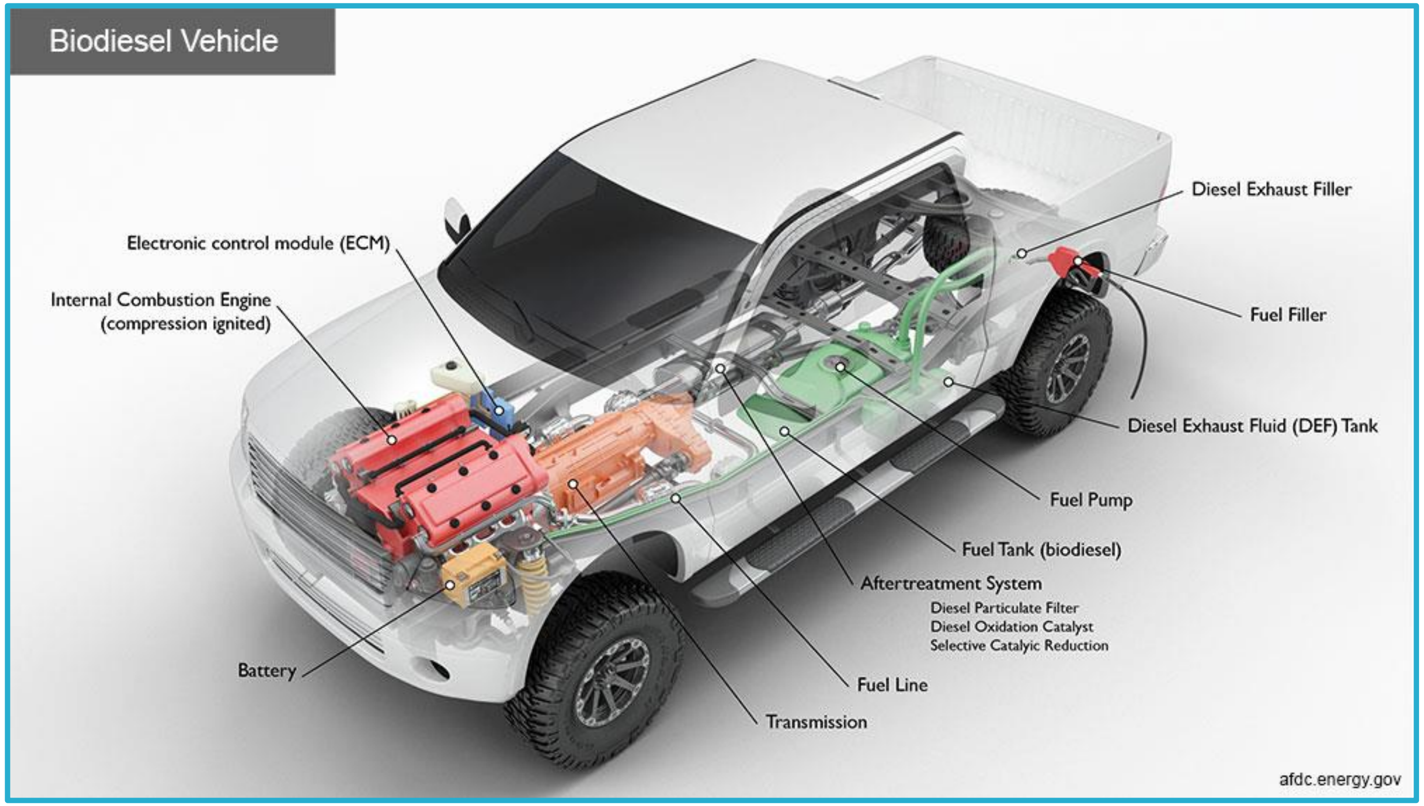
LaFleur, Chris Bensdotter, Glover, Austin Michael, Baird, Austin Ronald, Jordan, Cyrus J., and Ehrhart, Brian D.. Alternate Fuel Vehicles in Tunnels. United States: N. p., 2020. Web. doi:10.2172/1734627.

https://www.osti.gov/biblio/1734627

# Traditional Fuels – Gasoline and Diesel

Unique Hazards

- Gasoline and diesel are liquids and when they are released from a vehicle will create a flammable pool that can travel via gravity drainage
- Storage tanks onboard are plastic or thin metal and vulnerable during incidents
- Gasoline has a low vapor pressure and can be ignited easily on hot components of the internal combustion engine



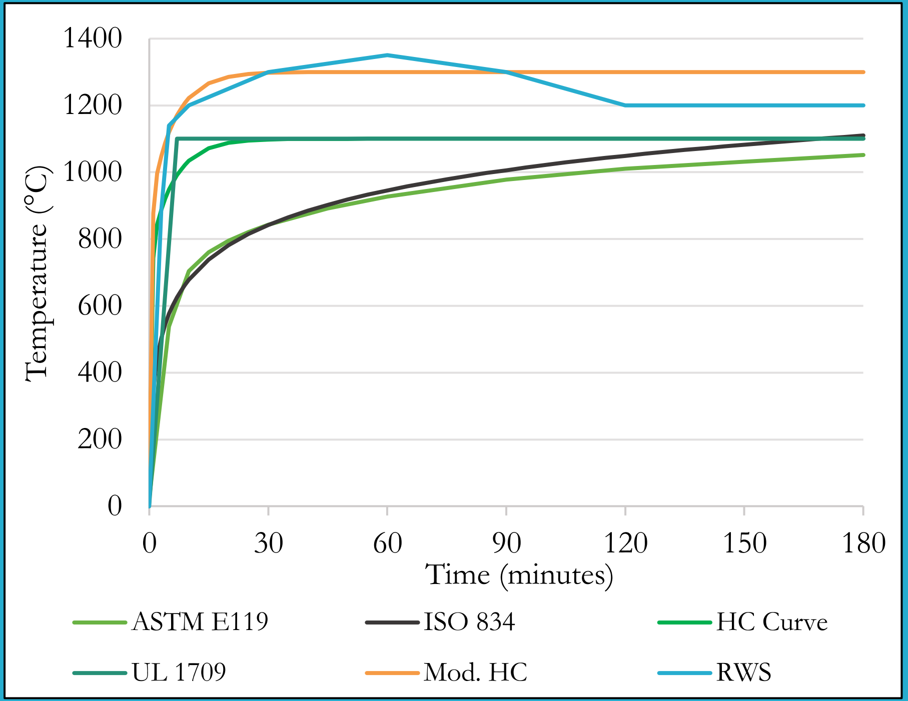
# Traditional Fuels – Gasoline and Diesel

Major takeaways

- Have been studied for many years resulting in mature models and ventilation requirements
- Identification of Scenarios and Failure Modes – large numbers of research studies have clearly defined failure scenarios, hazard analyses, and consequences

Conclusions and recommendations for research include:

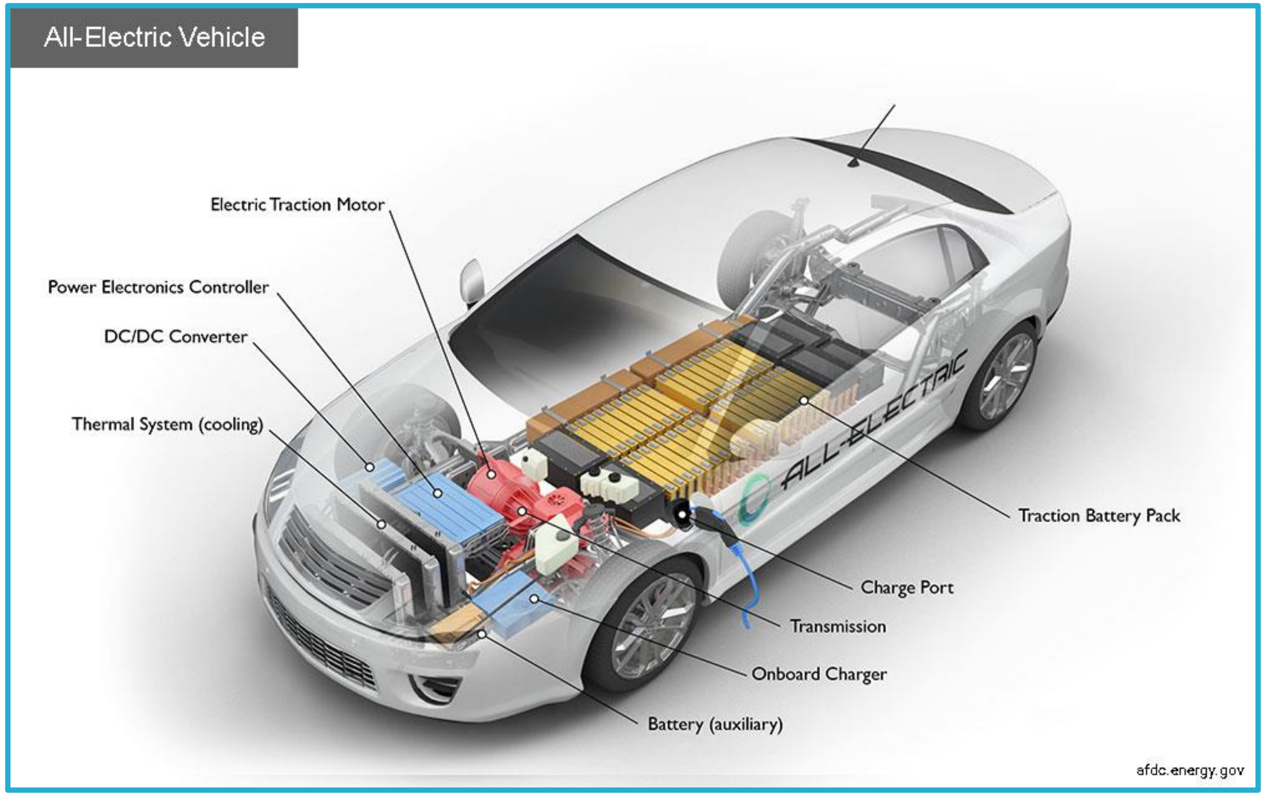
- As traditional fuels evolve (ethanol, bio-diesel)characterization studies will need to keep pace
- As emission technologies advance and engines run with a leaner fuel mixture, further study of the effect on exhaust system components temperatures are needed as this may lead to a greater potential for ignition




**Standard time-temperature fire design curves at tunnel structure interfaces[LaFleur 2020]**

# BEV Unique Hazards

- Batteries can self-ignite and be difficult to extinguish
- Exposed electrical components, wires, and batteries may cause high-voltage shock hazards
- BEVs exposed to floods could lead to high-voltage shock hazards and could cause a fire
- Physical damage to the vehicle or battery can release of toxic and flammable gases
- Batteries exposed to fire can release toxic gases

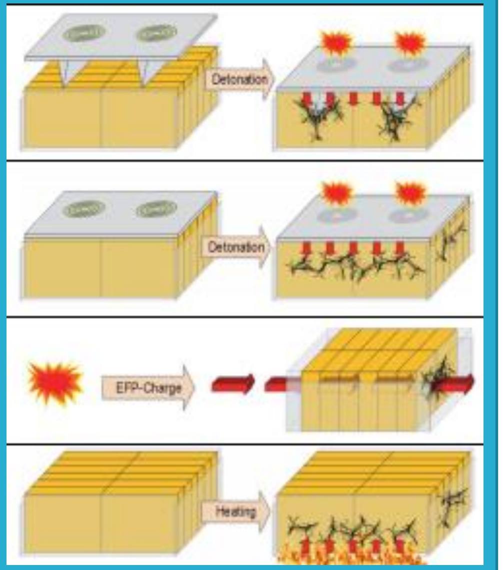


# Battery Electric Vehicles (BEVs)

Major takeaways

- Identification of Scenarios and Failure Modes –
  - Bench-scale abuse testing has defined both cell level and module level scenarios that lead to a failure mode.
  - Vehicle-scale scenarios have been observed in limited experiments, real world crash incidents, or vehicle failures.
- Consequences
  - Limited vehicle-scale tests have been conducted
  - Variations in cell chemistry, capacity, thermal runaway propagation between cells, state of charge, form factor, and other variations affect hazards
  - Hazards associated with BEVs are not as well characterized as some of the other alternative fuel vehicles

1. Wedge-Shaped Penetration
2. Blunt Impact
3. Central Puncturing
4. Thermal Stress




**Four test scenarios were evaluated to induce a fire. [Mellert 2018]**

Conclusions and recommendations for research include:

- Better definition is needed of the effect of cell/module chemistry, form factor, electrolyte composition, etc. on the consequence.
- Further study is needed at the larger scale, specifically around conditions that can cause thermal runaway causing vent gas production and fire spread between battery cells.
- Medium- and heavy-duty BEVs are entering the market and the fire, vent gas production, and toxic chemical release risks need to be characterized.

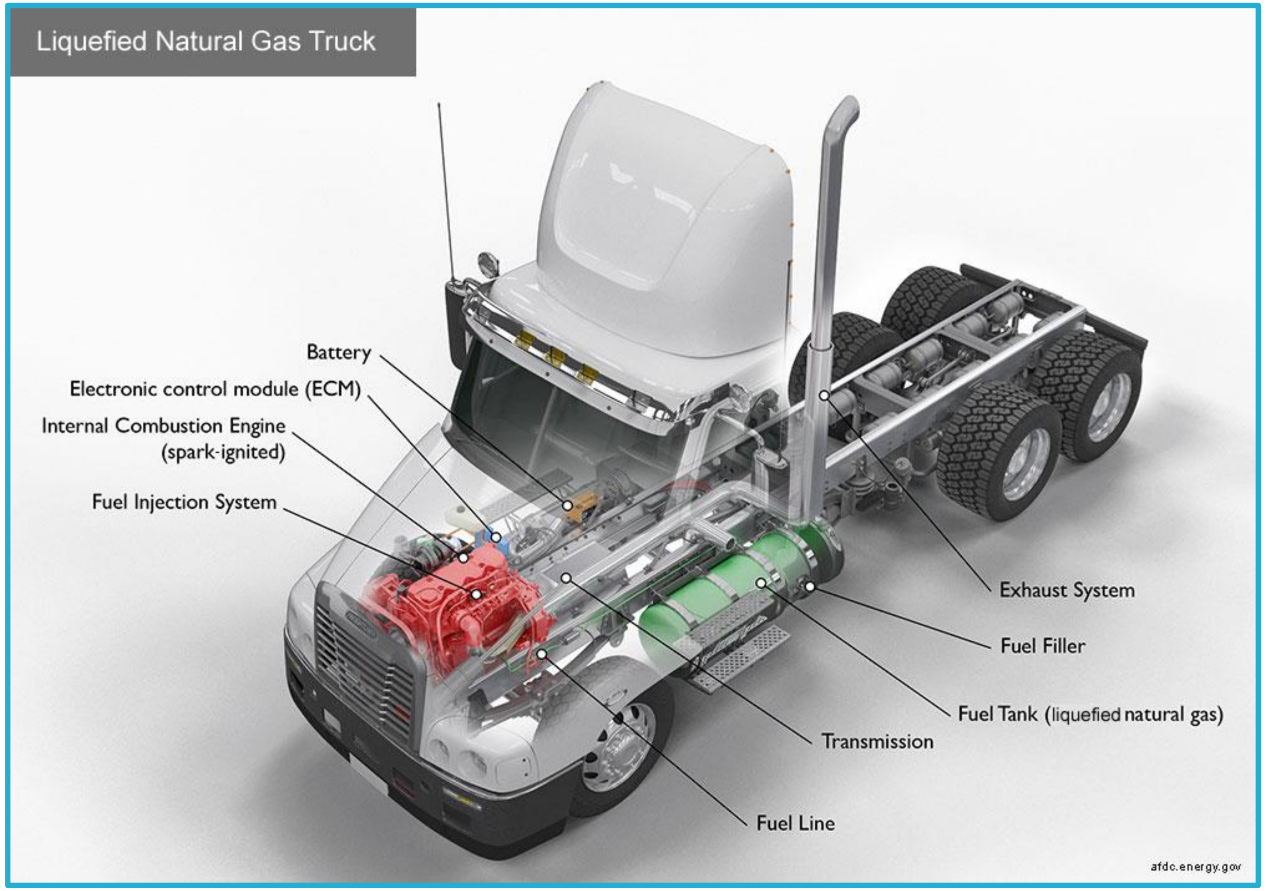
# Natural Gas Unique Hazards

Natural gas can be stored as a liquid on the vehicle

- LNG is a cryogenic fluid in an insulated tank
- Tank is vented when the LNG warms up
- LNG and cold vapor are heavier than air so will “pool” in low areas until it warms if released

Gaseous storage of natural gas is under high pressure (5000psi)

- Storage tank will vent if tank is exposed to external fire to prevent a catastrophic failure



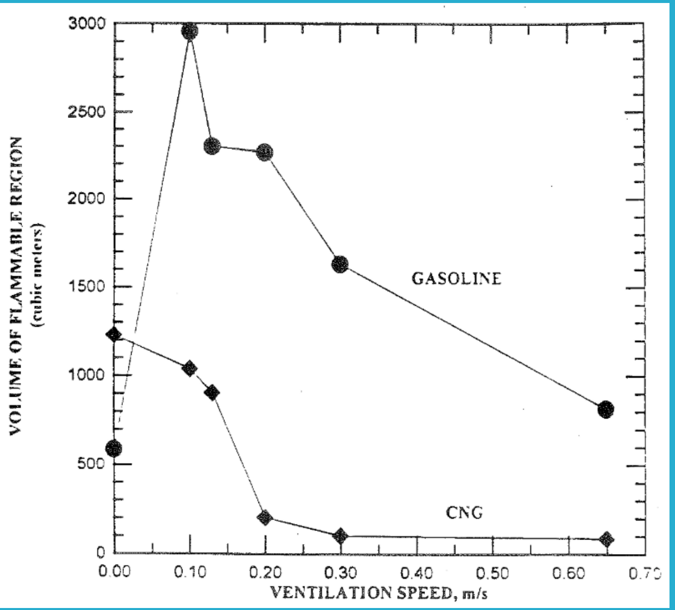
# Natural Gas Vehicles (NGVs)

Major takeaways

- Identification of Scenarios and Failure Modes – multiple research studies have clearly defined failure scenarios and hazard analyses
- Consequences – Multiple experiments and modeling simulations have evaluated scenario consequences of natural gas in confined areas, but not specific to natural gas vehicles as a system

Conclusions and recommendations for research include:

- Evaluation is needed for the risk of spalling of tunnel surface from flame impingement or heat from a NG jet flame.
- Experimental studies of NG dispersion and overpressure in actual or scaled down tunnels should be conducted
- Characterization is needed for partially pre-mixed (realistic extents of pre-mixing) ignition in tunnels to determine maximum overpressure.
- Analysis is needed for large scale NG flames heat transfer analysis. So far only lab-scale or simulated data found in the literature.
- Characterization of the hazards is needed as the scale of vehicle increases for medium and heavy duty vehicles.




Volume of flammable region versus ventilation speed from simulation [Zalosh 1998]

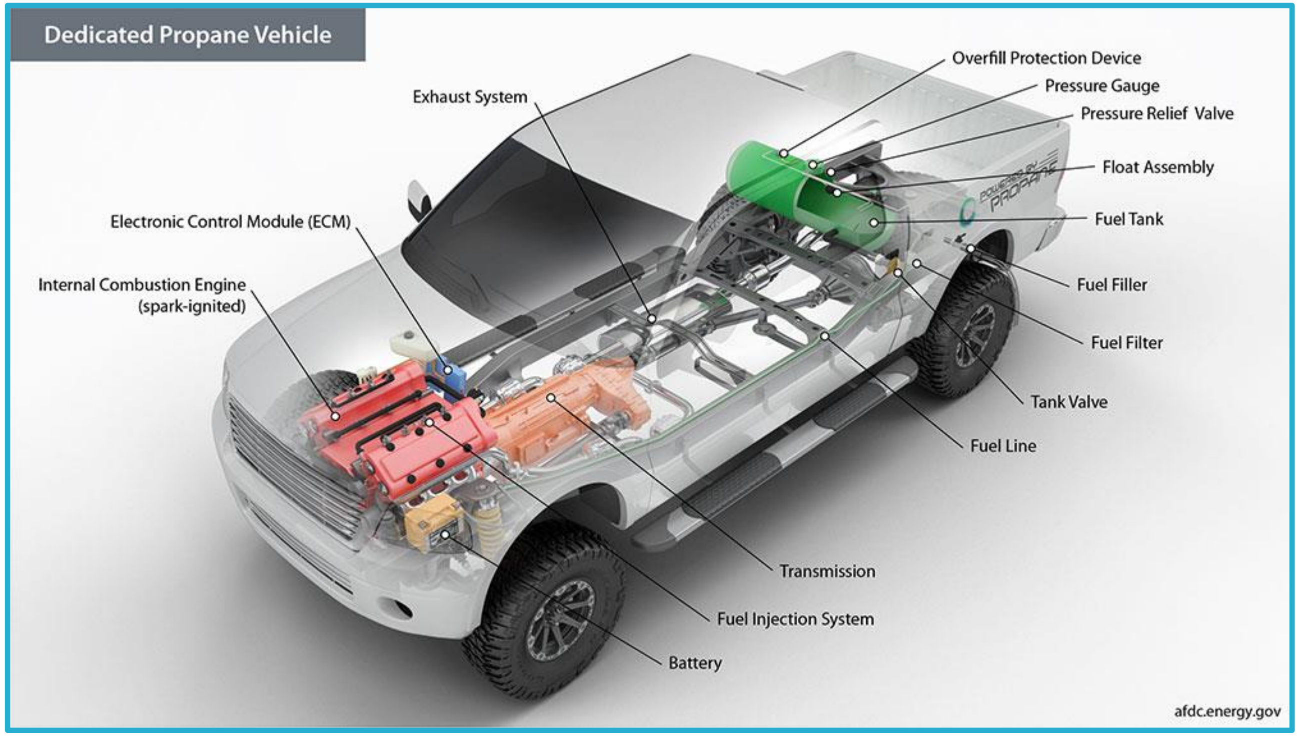
# Propane Unique Hazards

Propane is stored as a liquid on the vehicle

- Pressure in the storage tank maintains the propane as a liquid
- Rapid depressurization of the storage tank can result in a boiling liquid expanding vapor explosion (BLEVE)

Propane vehicles can be manufactured by an OEM or can be converted from a gasoline-fueled vehicle via a conversion kit

- Conversion kit reliability my be questioned



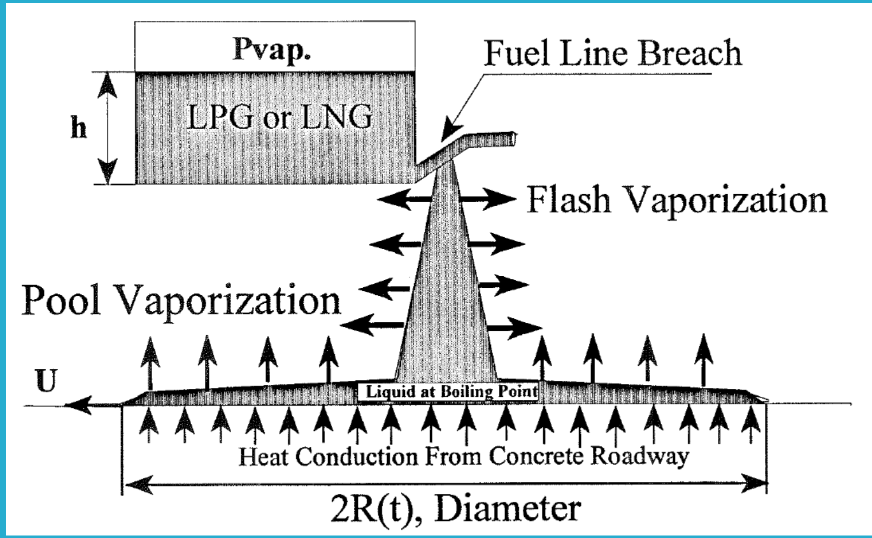
# Propane Vehicles

Major takeaways

- Identification of Scenarios and Failure Modes – a probabilistic risk analysis identifying and evaluating scenarios for different fuels in a tunnel was preformed
- Consequences – Modeling of the dispersion of propane and the explosive load for worst case concentration in a tunnel scenario were conducted

Conclusions and recommendations for research include:

- Conduct a more thorough evaluation of failure modes for propane vehicles of all sizes
- Evaluate the heat release rate, temperature, and structural damage resulting from different failure modes
- Evaluate the effect that overpressure and deflagration of released propane has on structural components of tunnels
- Evaluate the effects of ventilation, obstructions, and tunnel geometry on the consequence of failure  modes




Relevant Phenomena in Mathematical Model of LPG Spill and Vaporization [Zalosh 1998]

# Hydrogen Unique Hazards

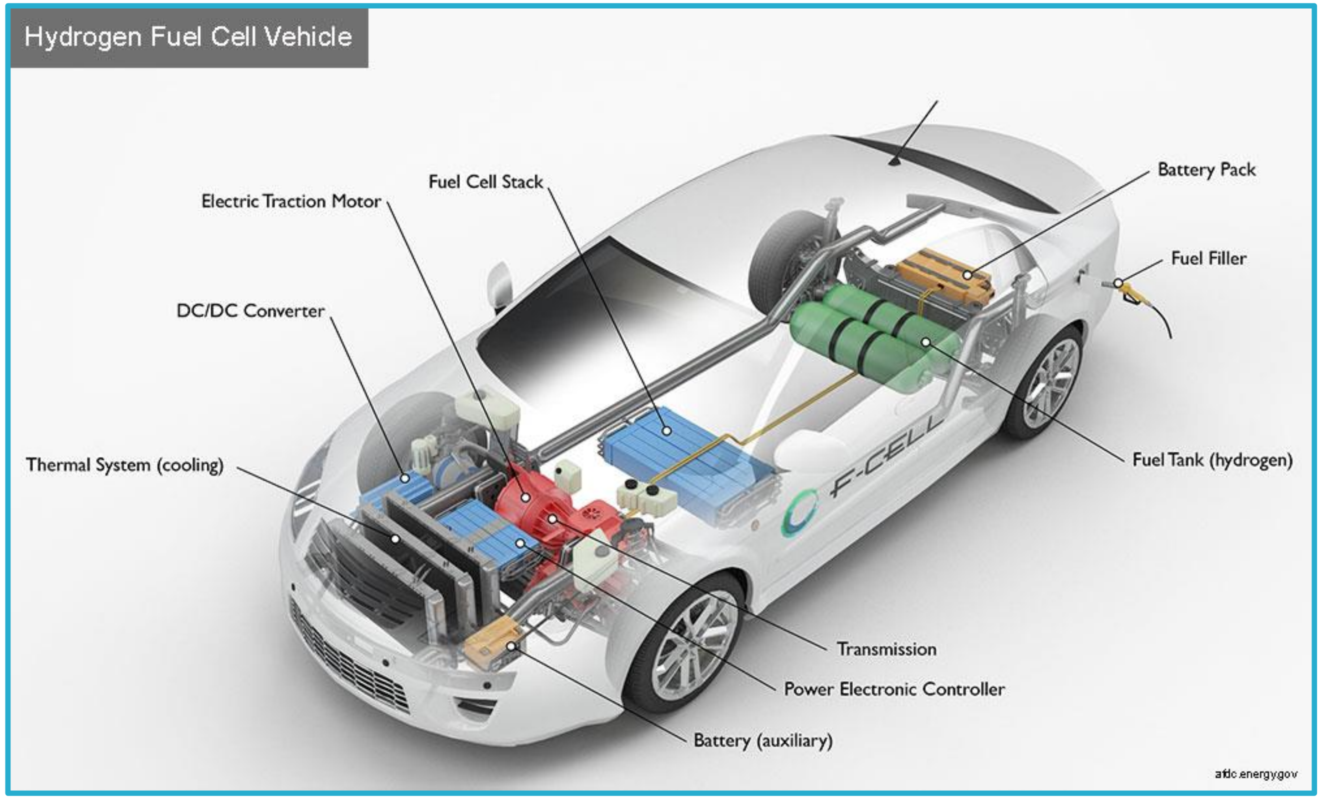
Gaseous storage of hydrogen is under high pressure (10,000 psi)

- Storage tank will vent if tank is exposed to external fire to prevent a catastrophic failure

For Heavy Duty vehicles, hydrogen can be stored as a liquid

- LH2 is a cryogenic fluid in an insulated tank
- Tank is vented when the LH2 warms up

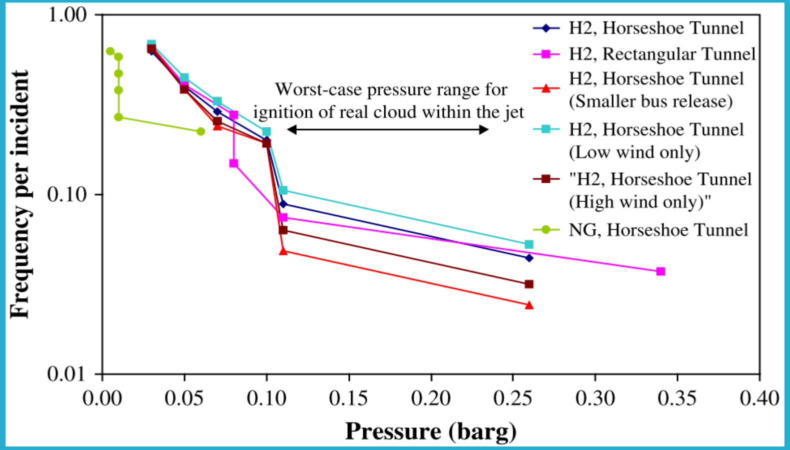
Hydrogen can ignite at a large range of concentrations (4% - 75%) making it more flammable than most fuels



# Hydrogen Fuel Cell Electric Vehicles (FCEVs)

Major takeaways

- Identification of Scenarios and Failure Modes –
  - A scenario identification study was conducted that documented the risk significant initiating events in terms of hazards involving hydrogen FCEVs .
  - The failure modes with potentially hazardous consequences identified in the scenario identification effort included both immediate and delayed ignition of released hydrogen.
- Consequences –
  - Modeling and measurements of the consequences including overpressure, heat release rate, hydrogen dispersion, and resulting structural damage have been made to determine the extent of the hazard.
  - Comparison studies have been conducted between the modeling and experimental studies to validate the results.



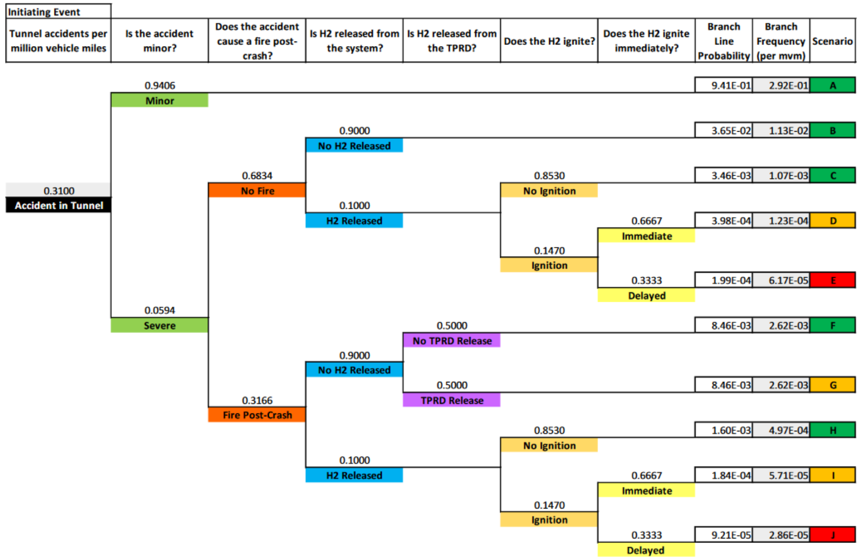

Exceedance curves for overpressure values per fuel type [Middha 2009]

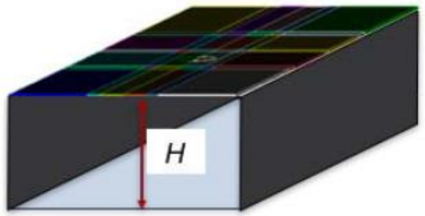
Conclusions and recommendations for research include:

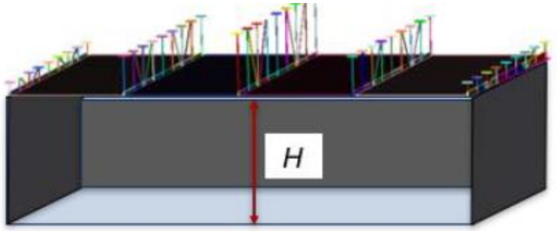
- Conduct studies to understand how the increase of energy onboard affects the hazard as larger classes of vehicles are developed
- Evaluate the effect of ventilation on the risk of spontaneous ignition in a tunnel
- Characterize the extent to which hydrogen can accumulate due to partial confinement and restriction, rather than complete confinement

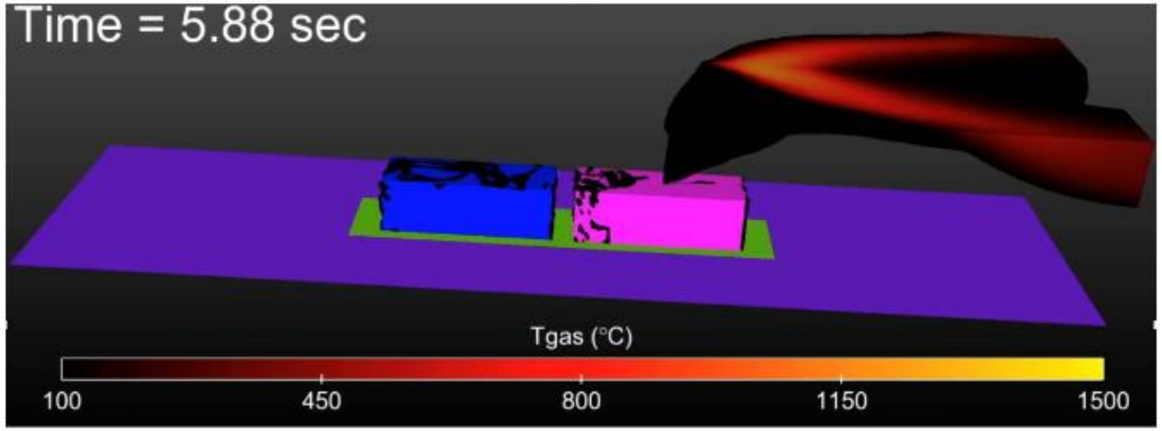
# PAST WORK

- Likelihood assessment of possible outcomes suggests majority of crashes have no additional hazard beyond crash itself
  - Jet fire is most likely hazardous condition
- 3 tunnels in Boston, MA assessed for jet fires under different ventilation conditions
  - Ted Williams, CANA, Sumner
- High-fidelity simulation assumes maximum mass flow rate is constant for release time
  - Smaller leak and time-dependent flow rate are more difficult to model
  - Total of 29 kg of hydrogen released, rather than 5 kg actually on-board a light-duty vehicle




Chris LaFleur et al. Hydrogen Fuel Cell Electric Vehicle Tunnel Safety Study. SAND2017-11157, October 2017.

# GOAL

Develop a **generalized framework** for assessing safety of alternate fuel 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 hydrogen vehicles in tunnels to be consistently and specifically assessed nationwide

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

Brian Ehrhart, Benjamin Schroeder, Dusty Brooks

Federal Highway Administration (FHWA) Webinar

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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

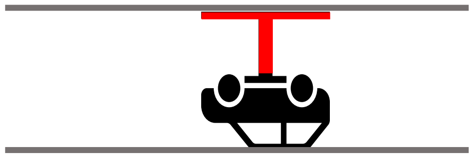
Similar to hydrocarbon vehicles, hydrogen vehicles pose **thermal hazards,** but with characteristics that differ:

- 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

# 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 used instead of pressure for LPG blowdown releases

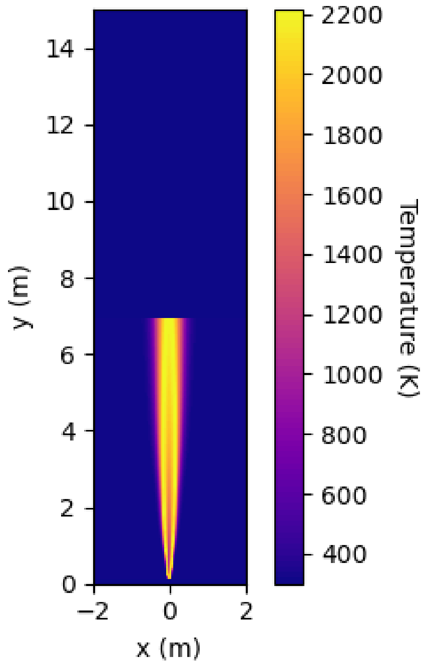
Steady state jet plume and jet flame models of gaseous releases based on pressures and mass flow rates for each blowdown time point

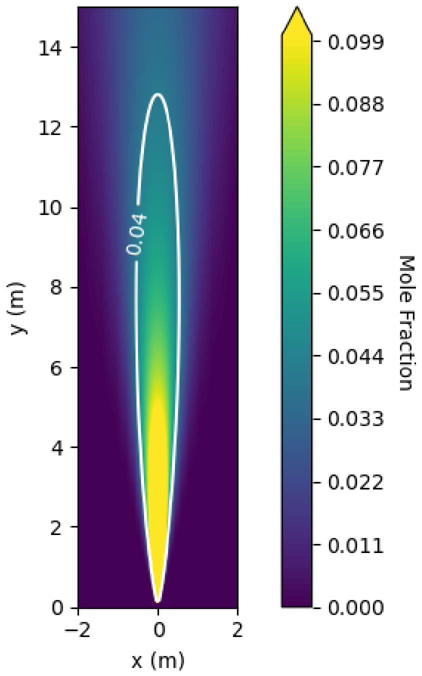
## Consequence Models

**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

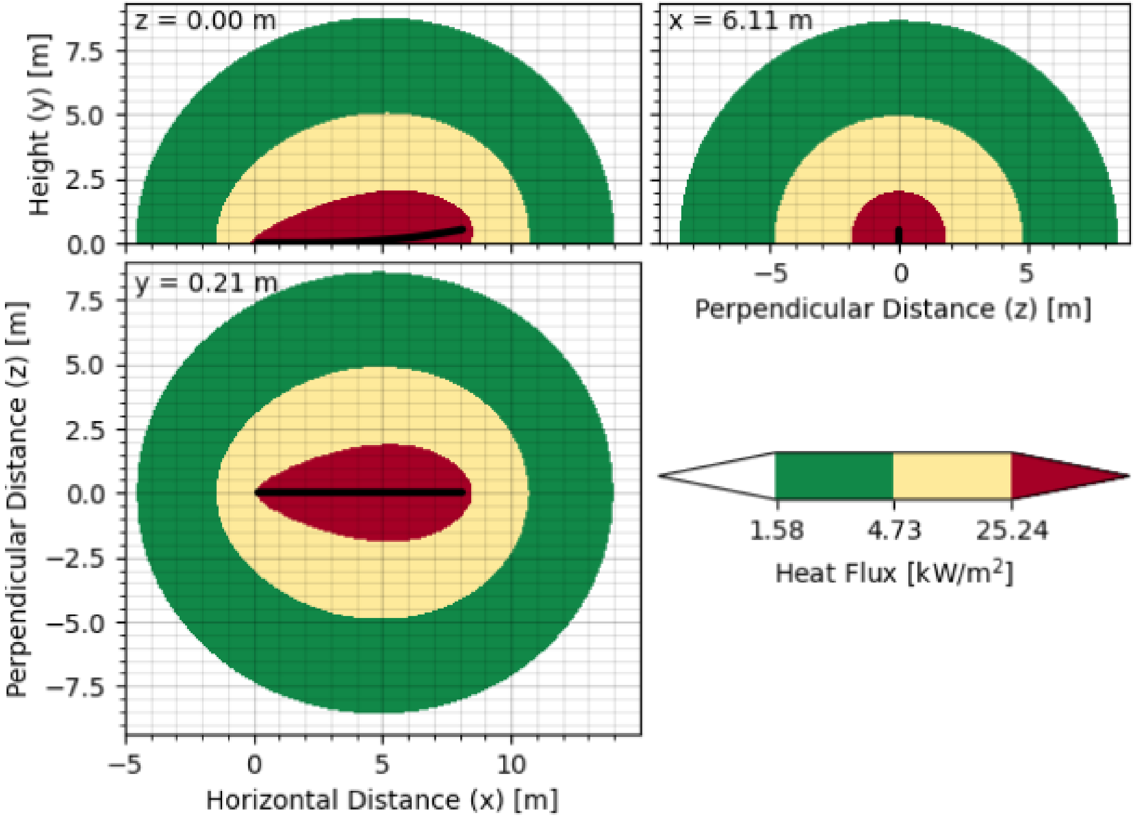


# CHARACTERISTICS OF A HYRDOGEN FLAME

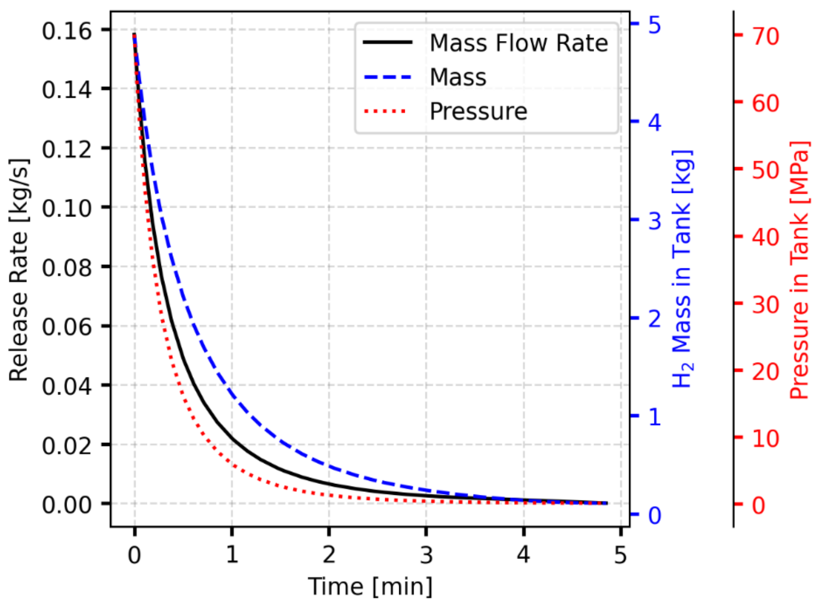
- Heat flux very high in or near the flame
  - Same with temperature
- Pure hydrogen has no carbon to burn, so no soot and much weaker thermal radiation
  - However, the rest of the vehicle burning will radiate much more strongly
- Buoyancy has an effect, but less so for high-pressure (high-momentum) releases
  - Direction of leak or TPRD release dictates direction of flame

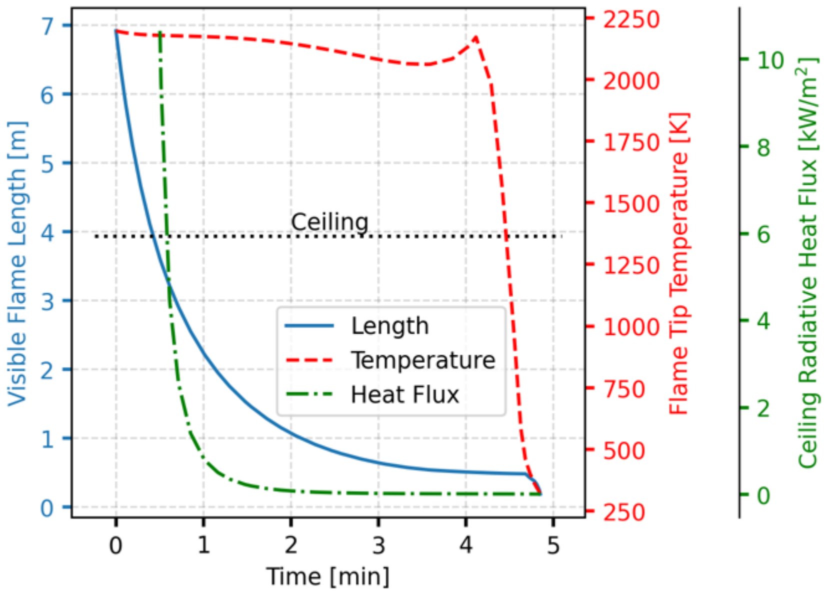

Image: https://h2tools.org/bestpractices/hydrogen-flames

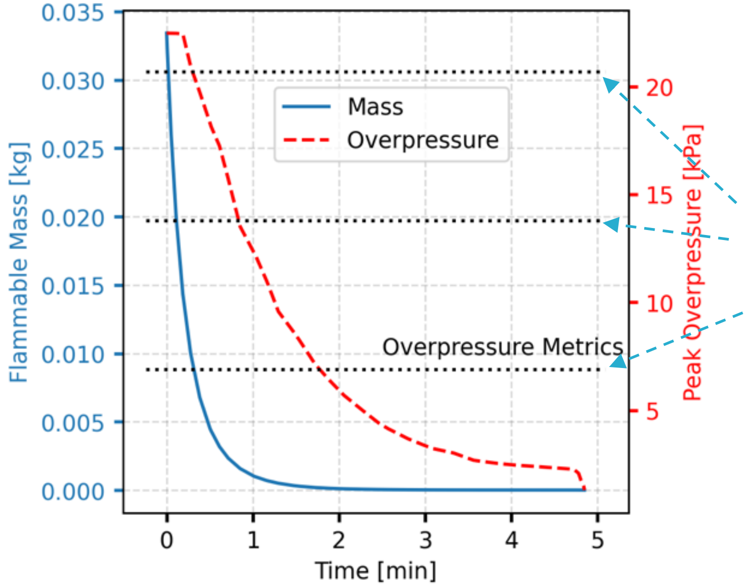



Example thermal heat flux estimation of 350 bar (~5,000 psi) hydrogen with 3.6 mm (0.14 in) leak diameter

# 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

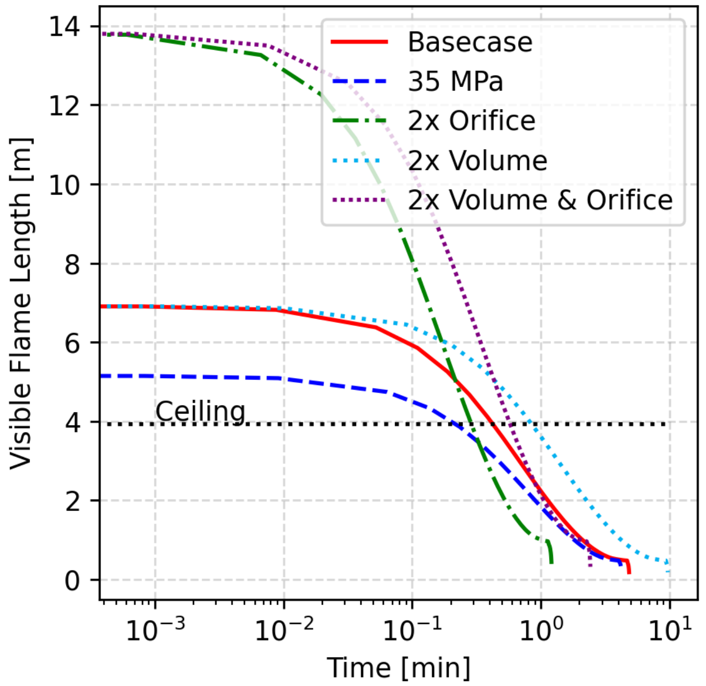
**Varying scenario parameters** that impact tank blowdown and resulting consequences

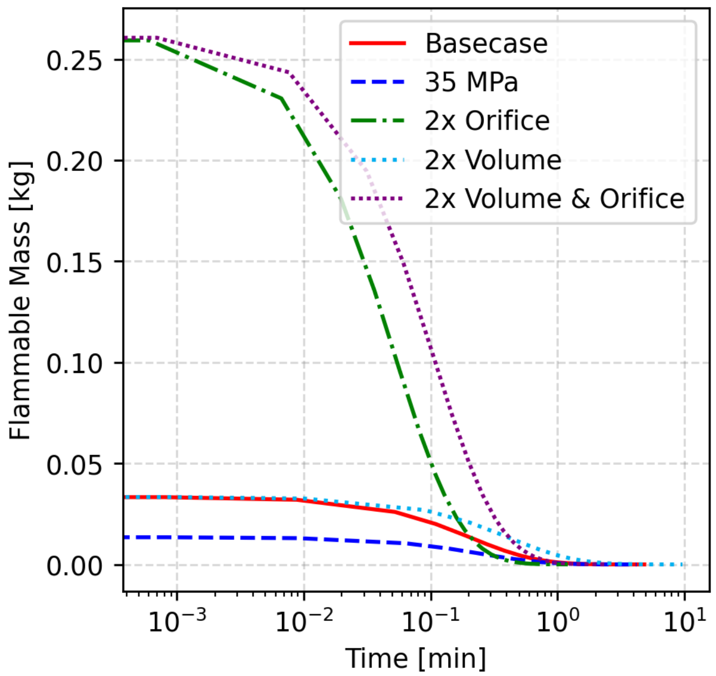
- Holding other parameters at nominal values

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

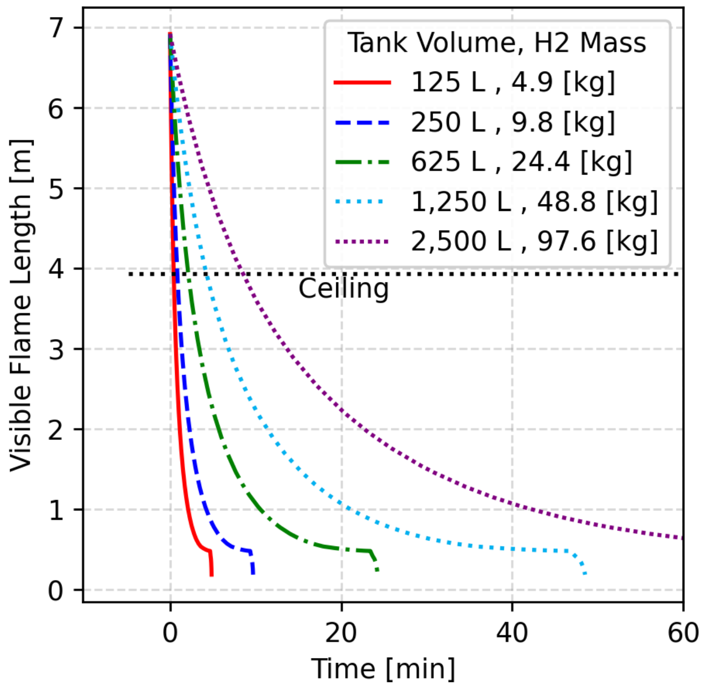
# TANK VOLUME STUDY

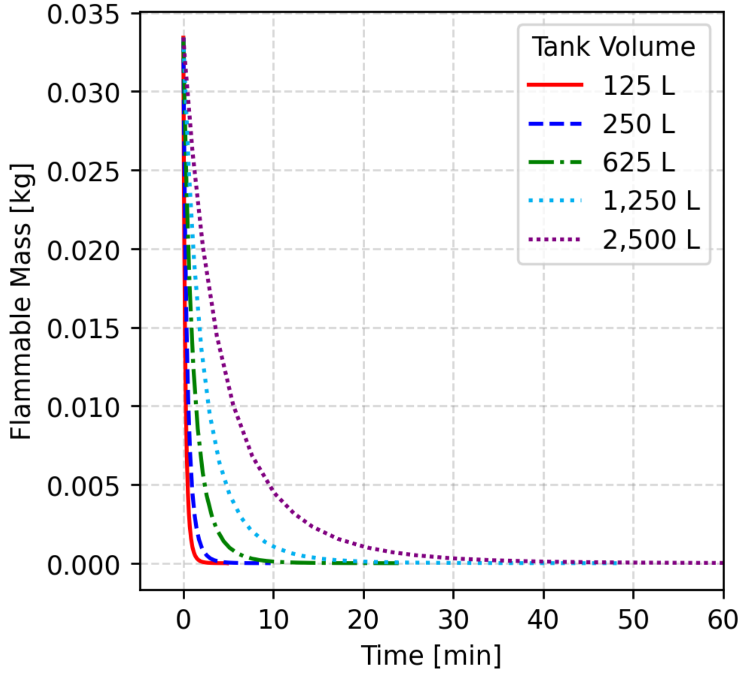
Varying tank volume provides insights into how different **vehicle classes** will impact the blowdown behavior

- 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

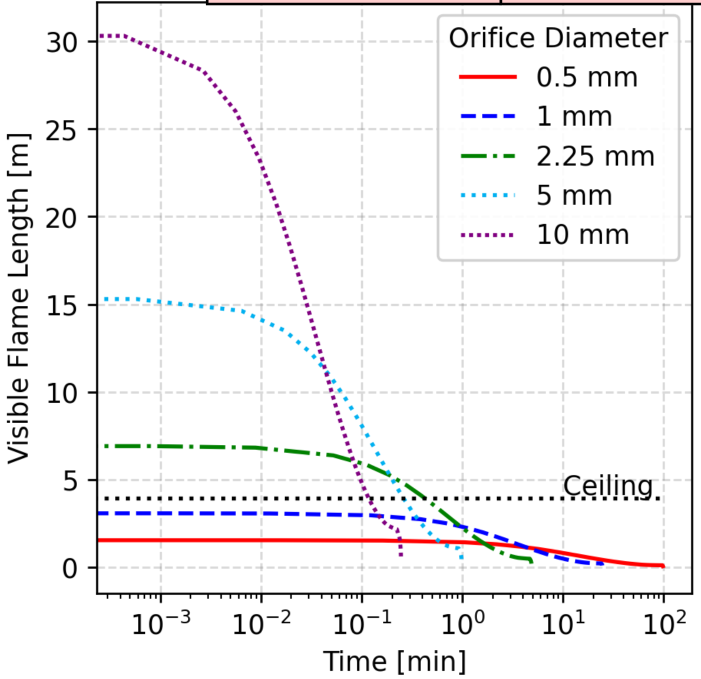
# TANK ORIFICE SIZE STUDY

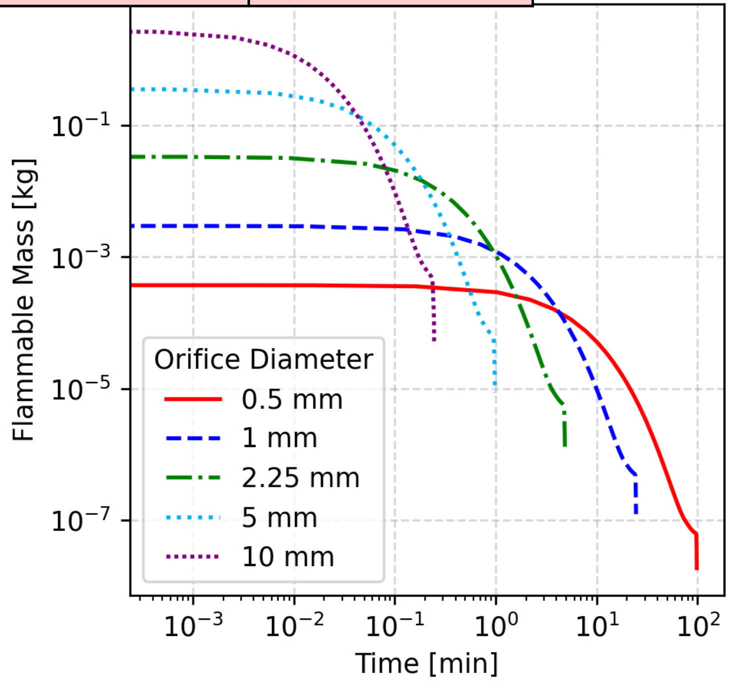
Varying orifice diameter through which fuel is released (**TPRD**) between 0.5 mm and 10 mm

- 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 |



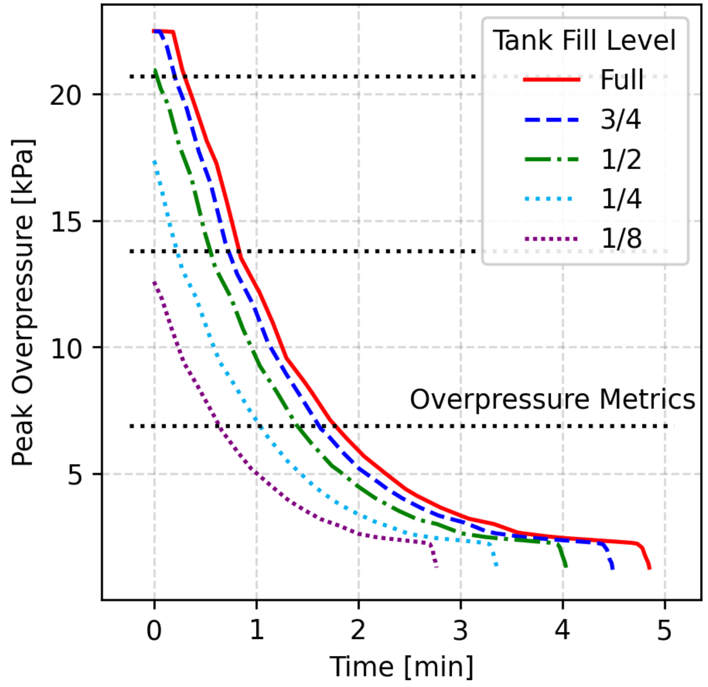



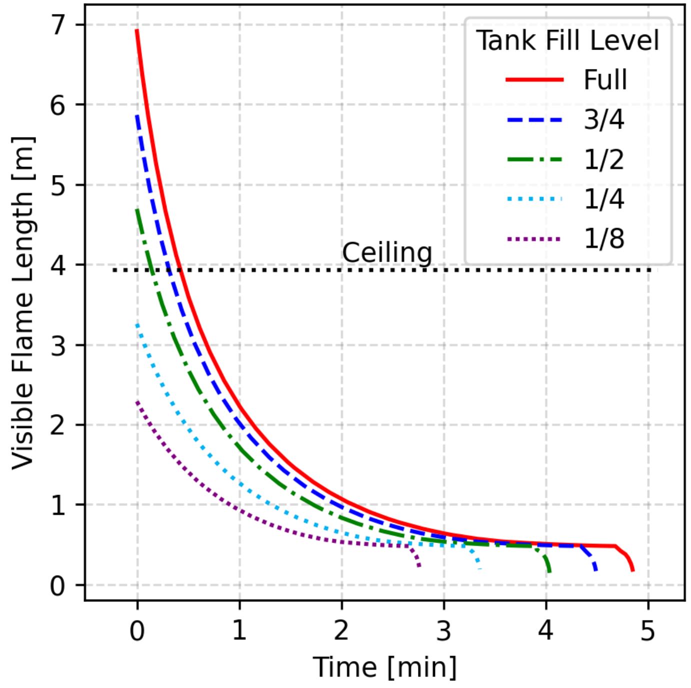
# TANK FULLNESS STUDY

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

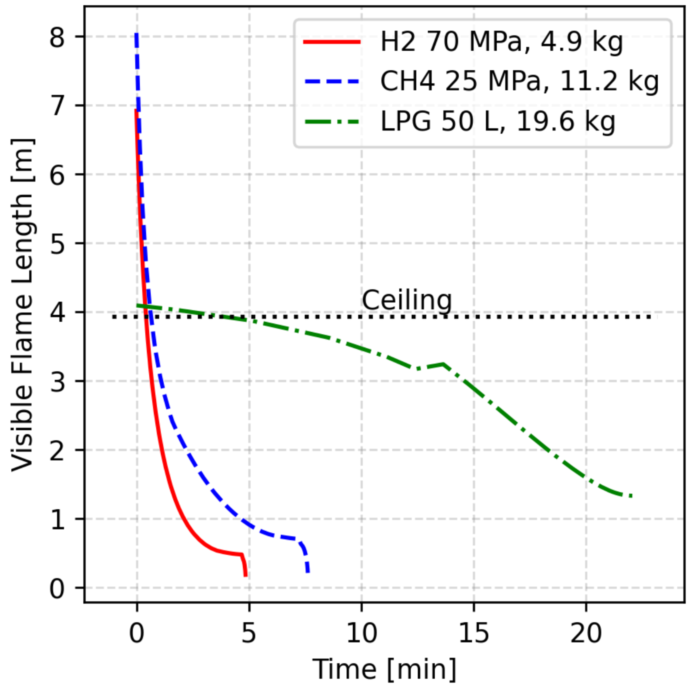
# FUEL TYPE STUDY

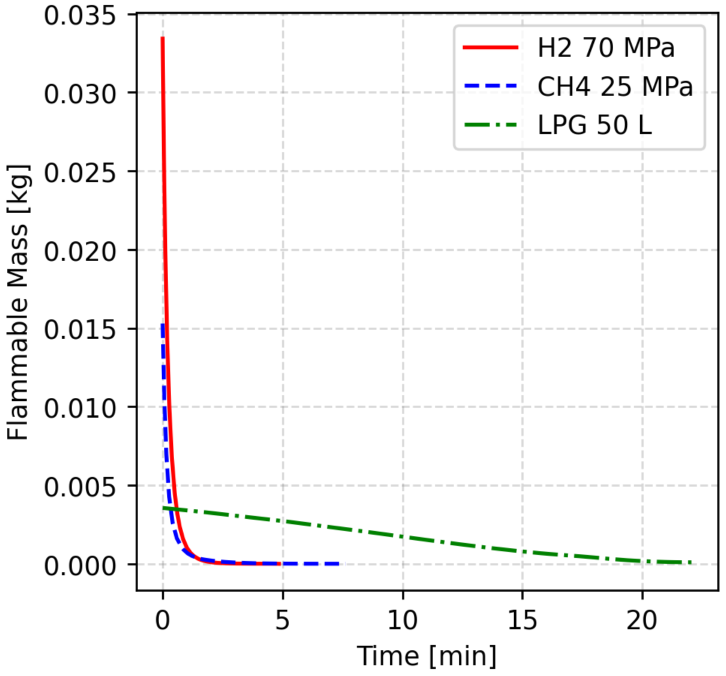
**Comparisons against other fuels provides perspective for $H_2$ predictions**

- 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



# TUNNEL GEOMETRY CHARACTERIZATION

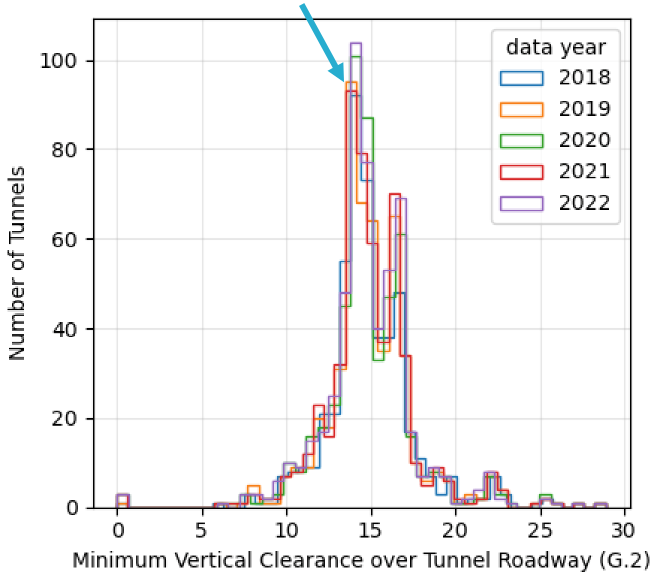
Extracted tunnel characteristic data from U.S. Federal Highway Administration **National Tunnel Inventory**

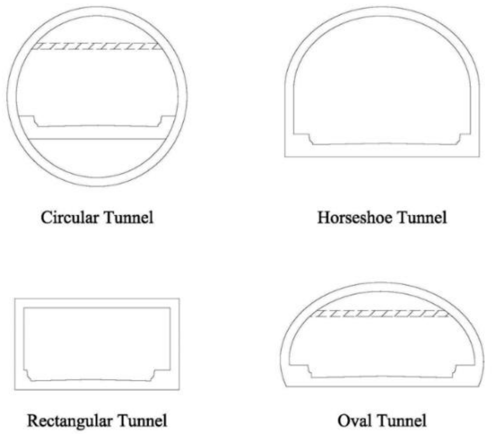
Annual data on tunnel characteristics and inspection results

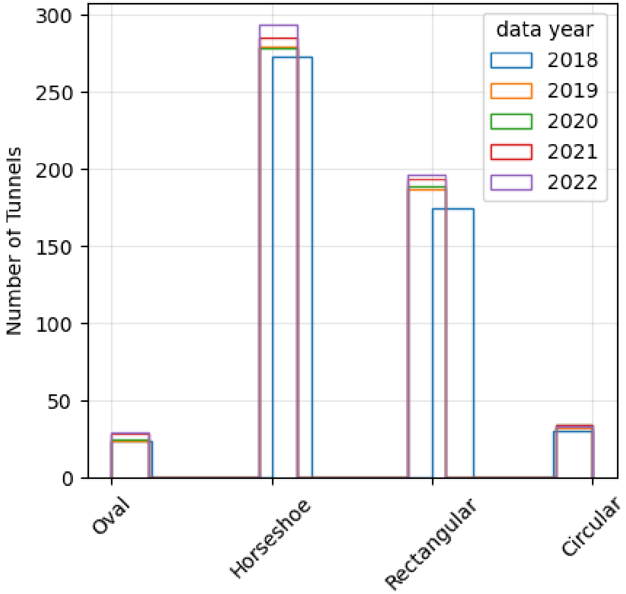
- **Characteristics**: location, year built, average traffic load, length, ...
- Inspected **elements**: tunnel liner, roof girders, ceiling slab, ceiling panels, ...

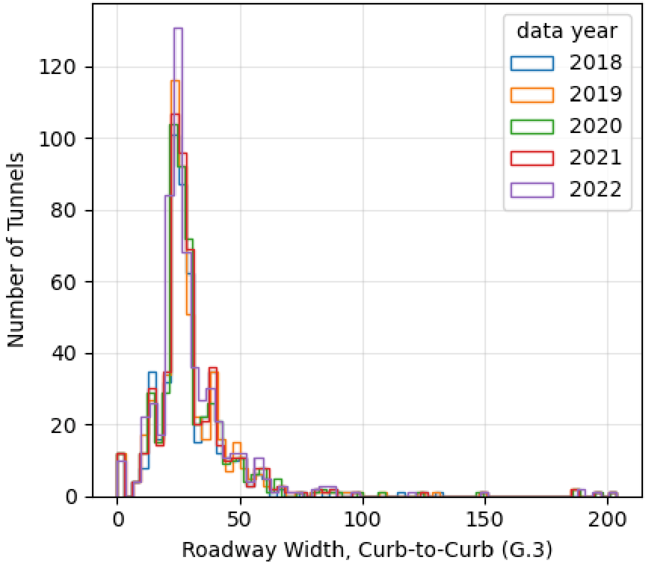
Use **tunnel characteristic/element statistics** to inform safety analyses

Release height in simulations corresponds to most common tunnel heights



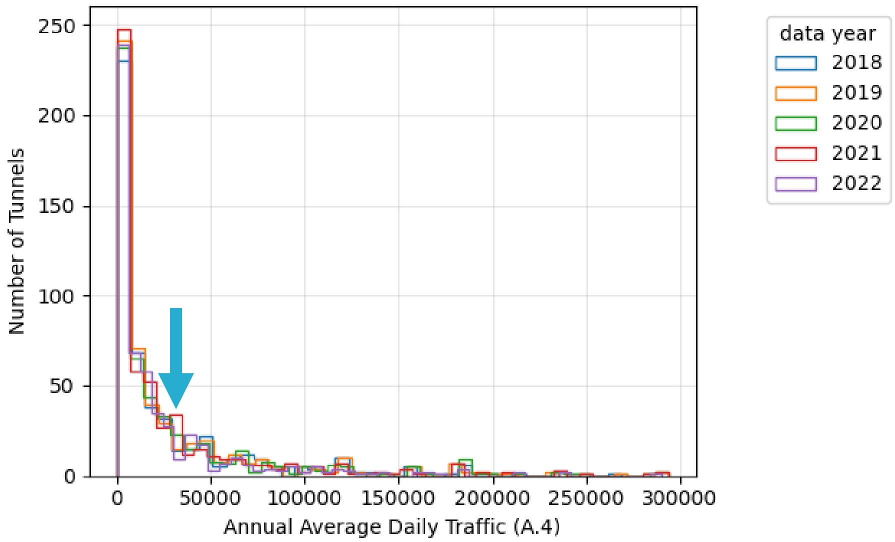

https://www.fhwa.dot.gov/bridge/inspection/tunnel/inventory.cfm

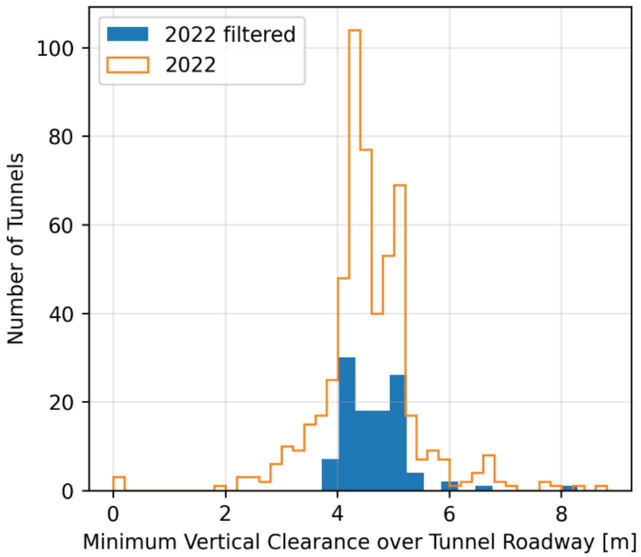
# FOCUS ON HIGH-TRAFFIC TUNNEL CHARACTERISTICS

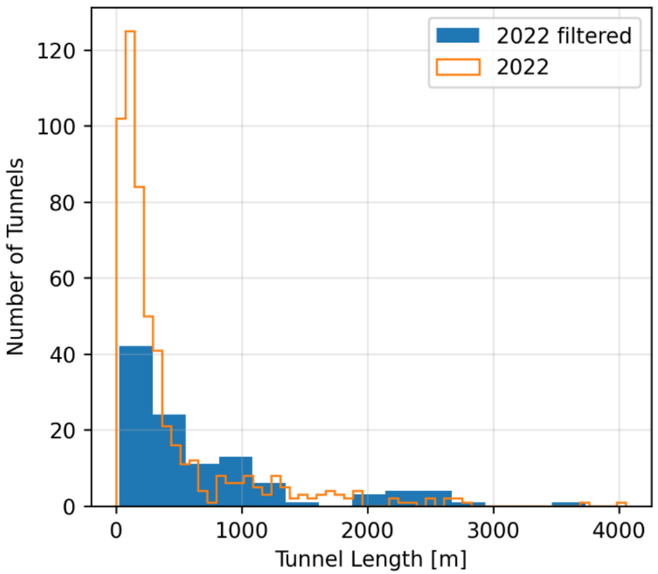
Determine prevalence and relevance based on **prioritization** such as high daily traffic loads

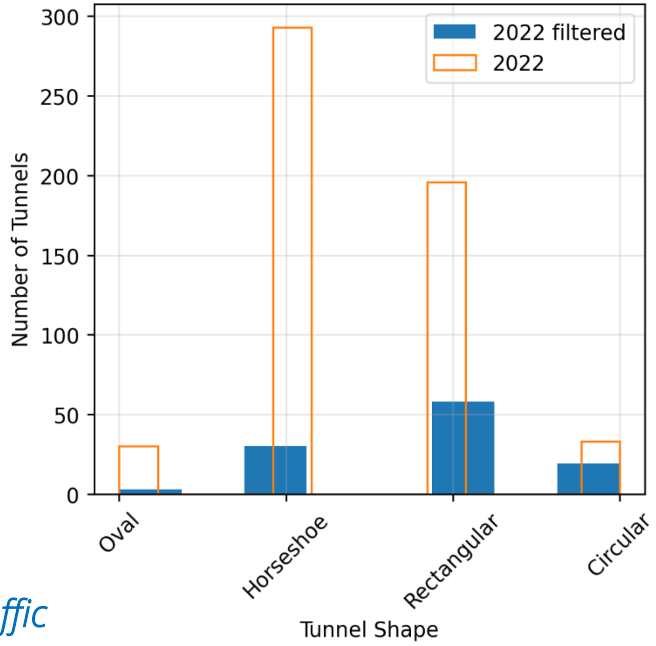
Tunnels with average daily vehicle traffic > 37,000 represent the top 20% of tunnels

Focus on those tunnels due to higher crash risk



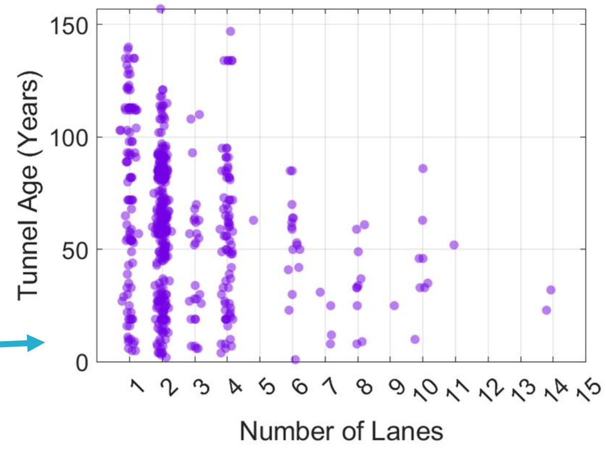



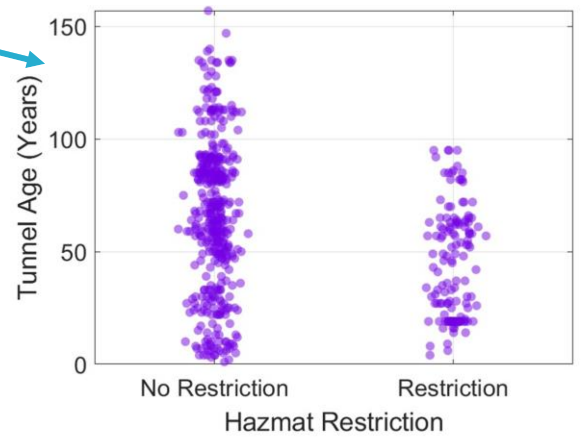

*filter based on being in the top 20% of daily traffic*

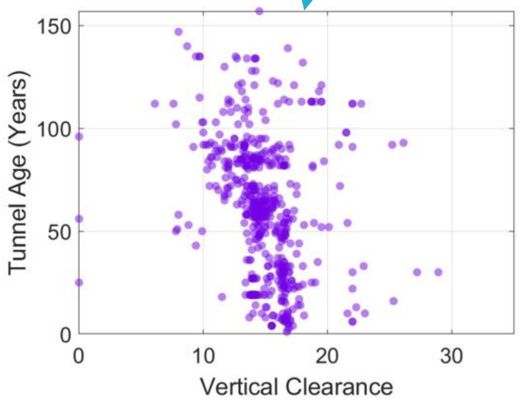
1. https://www.fhwa.dot.gov/bridge/inspection/tunnel/inventory.cfm

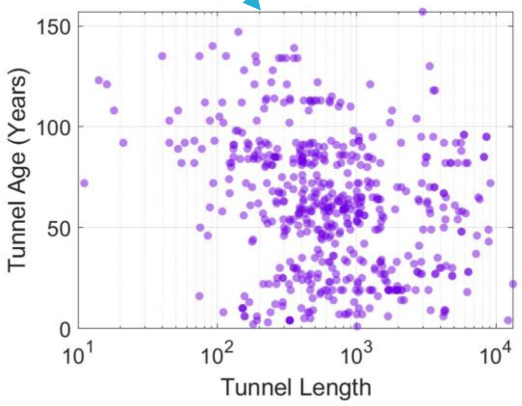
# TUNNEL AGE MAY NOT DETERMINE TUNNEL CHARACTERISTICS

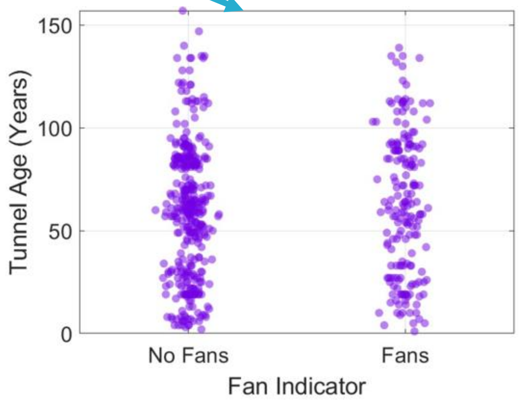
- Many different ways to categorize and sort tunnel characteristics
  - Tunnel age may be an easy way to broadly categorize multiple tunnels at once
- Some characteristics do vary somewhat with tunnel age
  - Wider tunnels tend to be newer
  - Some of the oldest tunnels have no hazmat restrictions
- Other factors tend not to vary with age
  - Vertical clearance, length, presence of fan



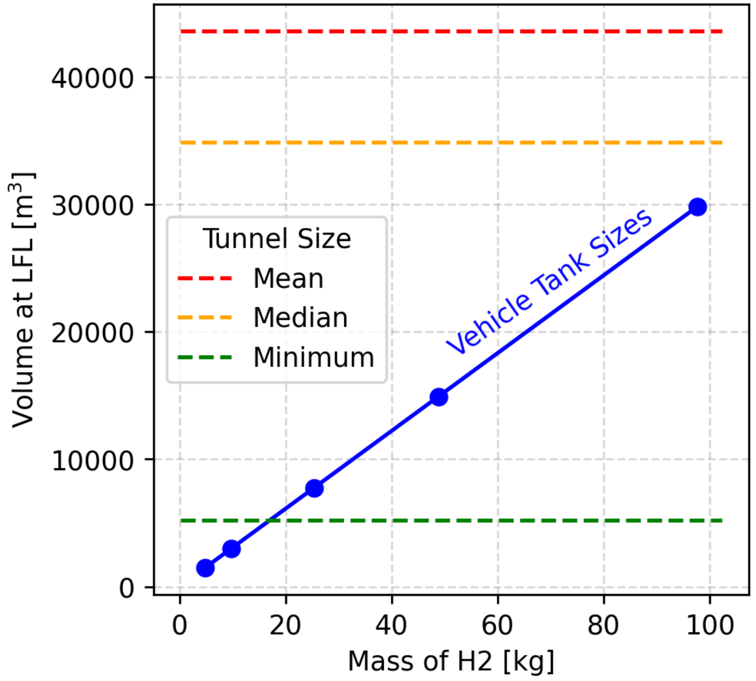



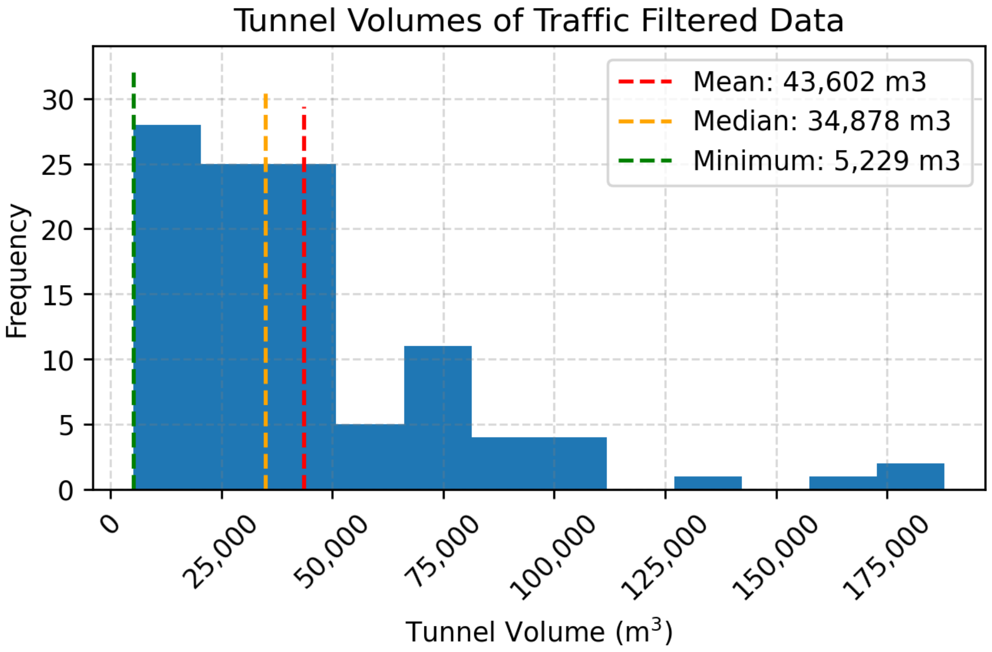
# FUEL DISPERSION

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**

# HOW TO COMPARE VEHICLE FUEL TYPES?

- What is similar and what is different between two vehicle fires with different fuels?
- **Similar**:
  - Non-fuel fire: tires, seats, interior
  - Broadly similar amounts of energy in stored fuel
  - Toxic smoke from combustion products
- **Different**:
  - Timing of fuel fire: rapid release vs longer duration
  - Direction of fuel fire: compressed gases can cause the fire to be more pronounced in a single direction
  - Overpressure: fuel accumulation and confinement makes overpressure possible
    - Specifics can be difficult to predict
  - Some differences in smoke/fume composition

# CONCLUSIONS

Progress towards 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

## Acknowledgements

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# FUTURE WORK AND NEXT STEPS

Integrate information from tunnel design codes and standards

Material response characterization to determine potential damage extents

Compare high-fidelity simulations to reduced-order models to enable easier scenario assessments

Get additional feedback!

# Thank You for Your Attention

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Questions?

# Reference Slides

# 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*