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The #H2IQ Hour

Today's Topic: Hydrogen Fuel Dispensing for Medium- and Heavy-Duty Vehicles

This presentation is part of the monthly H2IQ hour to highlight hydrogen and fuel cell research, development, and demonstration (RD&D) activities including projects funded by U.S. Department of Energy's Hydrogen and Fuel Cell Technologies Office (HFTO) within the Office of Energy Efficiency and Renewable Energy (EERE).

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The #H2IQ Hour Q&A

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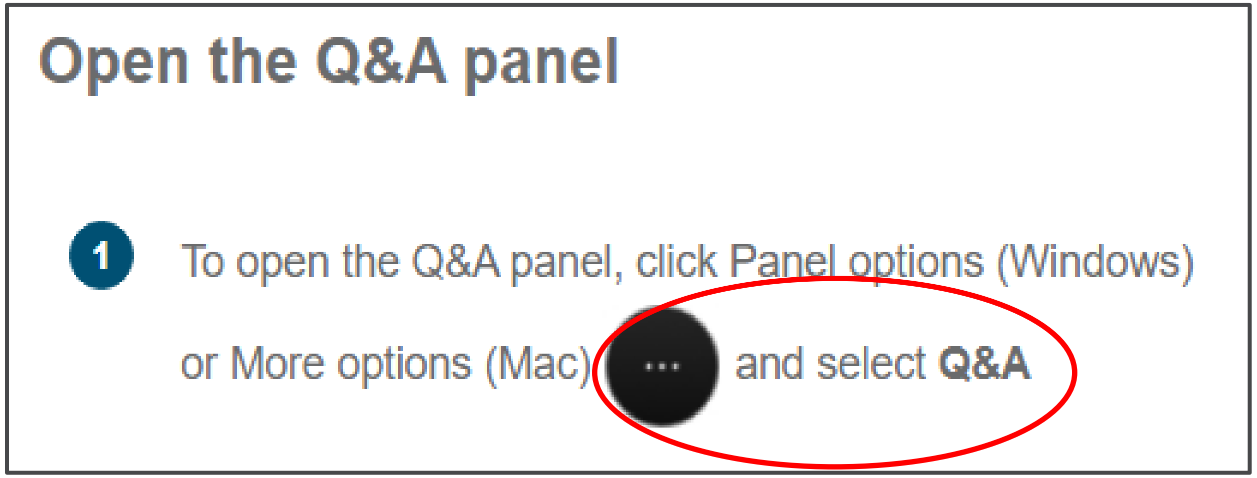

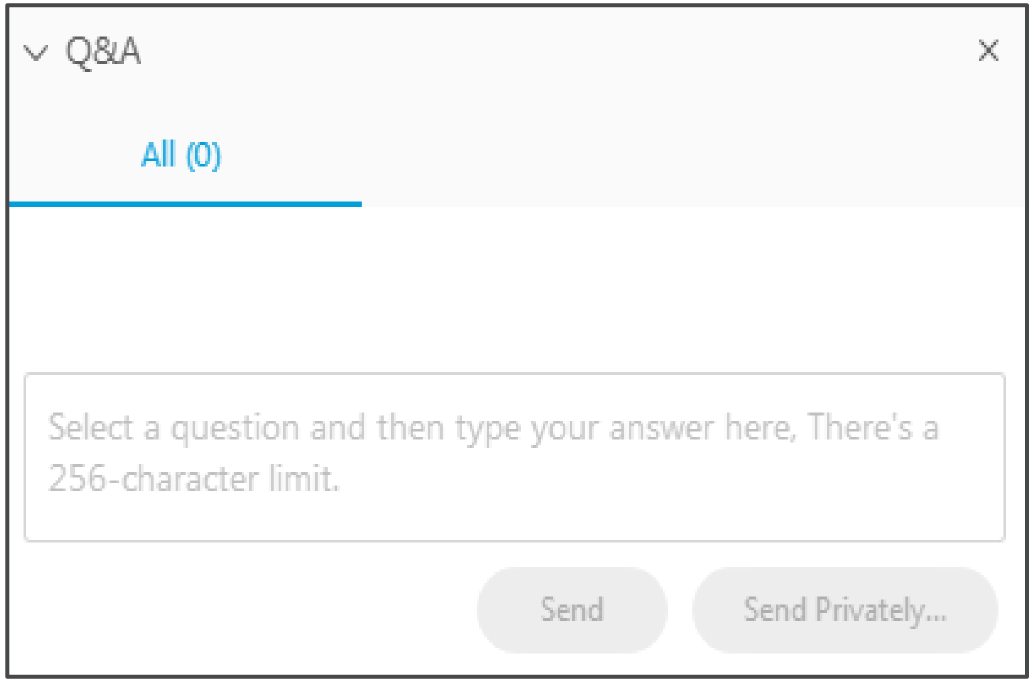

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NREL Transforming ENERGY

Hydrogen Fuel Dispensing for Medium- and Heavy-Duty Vehicles

DOE HFTO H2IQ Hour Webinar Series

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March 26, 2024
National Renewable Energy Laboratory

Contents

Overview – Medium & Heavy-Duty Dispensing

Current MD/HD vehicle deployments/demonstrations rely on LD fueling infrastructure, codes, and standards while new/revised faster-flow concepts are introduced, evaluated, and implemented.

- Results in slow/partial fueling events, strain on current infrastructure, and poor reliability/performance.
- Delays fleet deployments and hinders adoption potential.

Current MD/HD dispensing relies primarily on LD dispensing technology

Fueling Protocols

- **SAE J2601 (primarily, 350 bar and 700 bar)**
  - Category A-D table based fueling
  - MC Formula based fueling

Dispensing Hardware

- **Dispensers** (mass flow meters, flow control technology, various valve types, piping, pressure/temperature sensors, controls, etc.)
- **Nozzle assemblies** (nozzles, hoses, breakaways, and receptacles)

Communications

- **SAE J2799**
  - IR based communications
  - Non-communication fueling

Station Architecture

- **Compression, Bulk Hydrogen Storage, Gas Management, Precooling Systems, Controls, etc.**
- **Codes & Standards** (engineering, building, and fire)

Codes and Standards

Overview – MD/HD Fueling Protocols

New MD/HD fueling protocols are in development across various organizations internationally (SAE, EU PRHYDE, JPEC, South Korea, etc.) aimed at conforming with industry/Federal targets to support vehicle deployments.

- Protocol concepts require validation (beyond modeling and limited laboratory settings).
- Hardware is lacking (or not available) to support successful implementation:
    - Flow control, valves, high pressure components, and vehicle to dispenser communications.
  - Dispenser nozzle assemblies (nozzles, hoses, breakaways, and receptacles) are being developed in-parallel.
- Codes and standards are not aligned, being developed in-parallel/post protocol deployment.

General MD/HD Fueling Protocol Metrics:

Criteria	Metric
Pressure	**70 MPa (H70)** and 35 MPa (H35)
Mass Flow Rate (Nominal)	60 g/s (baseline), 90 g/s, 120 g/s, and **300 g/s (H70 target)**
Hydrogen Delivery Temperature	**-40°C** to 0°C (T40, T30, T20, T10, T0) and ambient (TA 30°C)
CHSS Capacity	>10 kgs up to 200 kgs **(100 kg target)**
Vehicle-Station Communications	Comm or Non-Comm (IrDA and/or advanced)
Fueling Calculation Method	Table-based and MC Formula
Fueling Time	**10 minutes** at 100 kg transfer

MD/HD Fueling Protocols:

Protocol*	Status	Region
★ **SAE J2601/5 TIR**	Released	International
FCH 2 JU PRHYDE	Released	EU, UK, & US
JPEC Dual Nozzle	In-Progress	Japan
RTR-HFP	In-Progress	South Korea
Others…		

*All to align with ISO TC/197 19885-2 WG24

Overview – MD/HD Fueling Protocols

SAE J2601-5 Technical Information Report (TIR)

- Released 2-23-2024 (https://www.sae.org/standards/content/j2601/5_202402/)
- Includes Category D High-Flow and MC Formula High-Flow General (MCF-HF-G)
- Pressure Classes: **H70 (70 MPa)** and H35 (35 MPa)
- Flow Rate Classes (Max in **g/s**): **60 (FM60), 90 (FM90), 120 (FM120), & 300 (FM300)**
- Coupling types are being defined in SAE, ISO, etc.
- Communications: Comm and Non-Comm (IrDA based) with optional data (OD)

Communications Notes:

Condition	Fueling Speed	Vehicle SOC
Non-Comm	Average	Low
Comm (SAE J2799)	Good	Good
Comm (SAE J799 w/ OD)	Best	Best

SAE J2601-5 Fueling Protocol Classifications:

Protocol Name	Pressure Class	Flow Rate Class Maximum (Comms)	Range of CHSS Capacity (liters)	Range of Tank Sizes within the CHSS (liters)	Coupling Type	Fuel Delivery Temperature Range
SAE Category D HF	H70	FM60 (w/o OD) FM90 (with OD)	248.6 to 5,000 (10kg to 201kg)	50 to 800	H70	-40°C to -17.5°C
SAE MCF-HF-G	H35	**FM120**	248.6 to 7,500 (6kg to 180kg)	50 to 1,000	H35HF	-40°C to +20°C
	H70	**FM60** (w/o OD) **FM90** (with OD)	248.6 to 5,000 (10kg to 201kg)	50 to 800	H70	-40°C to 0°C
		FM300 (with OD)			H70HF	

Dynamic - Control based on actual fueling conditions requiring

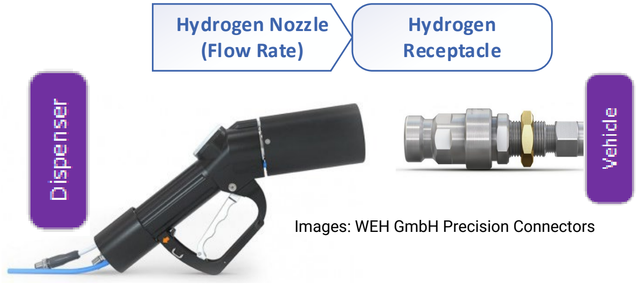
Static - Control based on tables and fueling temperature

Overview – MD/HD Dispensing Components

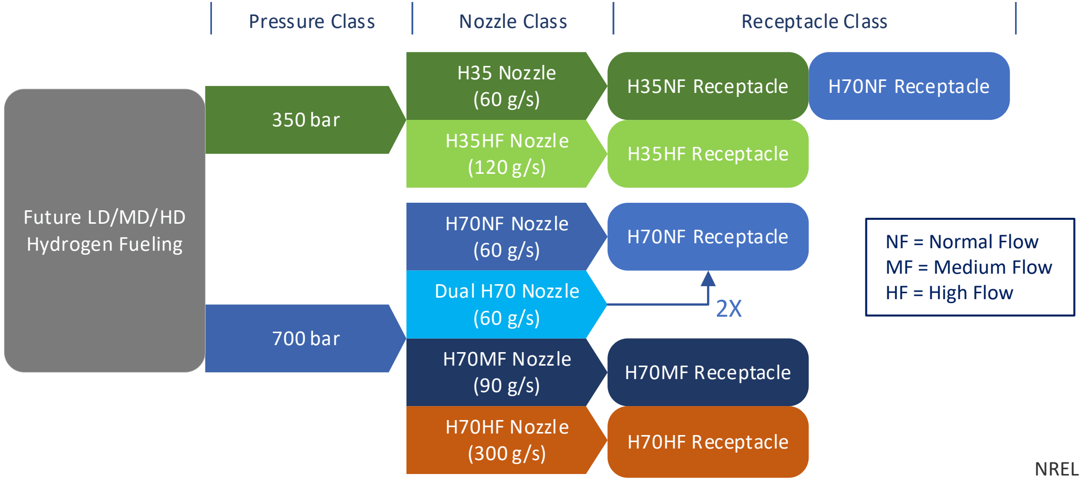
Dispensing components (nozzles, hoses, breakaways, and receptacles) are being developed in parallel to meet requirements of new MD/HD fueling protocols and stretch LD infrastructure usage.

- Codes and standards are lagging product development and deployment (ISO).
  - Metrics being defined for nozzle assembly geometry, pressure drop, flow coefficient, thermal mass, etc.
- Pre-production prototypes are under evaluation for performance and reliability.
  - Harmonization required with fueling protocols (ISO) and dispenser systems.
  - Designs are competing to set the standard.
  - Hoses are upsized for HD applications, but usability is a concern.

Hydrogen Fueling Connection Devices for MD/HD:



Images: WEH GmbH Precision Connectors



Overview – MD/HD Dispenser Components

Dispensers are being developed in parallel to meet requirements of new MD/HD fueling protocols and utilizing light-duty based hardware.

- Limited hardware on the commercial market to construct HD dispensers
  - Poor reliability/durability (major issue), long lead times, and high cost.
    - **Flow control technology gaps**, mass flow meters, valves, filters, fittings, etc.
  - Codes and standards are lagging product development/deployment.
- HD dispensers are being prepared for commercial deployment.
  - Lack of test facilities to evaluate with nozzle assemblies, fueling protocols, and assess general reliability/performance.
  - Advanced vehicle to dispenser communications not ready - will need to be retrofitted in the future (SAE-5 and SAE J2799).
- Dispenser designs remain constrained to number of fueling positions.
  - Generally single position due to pressure class, flow rate class, and internal component complexity/layout.
- Costumer usability concerns with large HD nozzle designs, poor hose ergonomics, and noise during the fueling process.

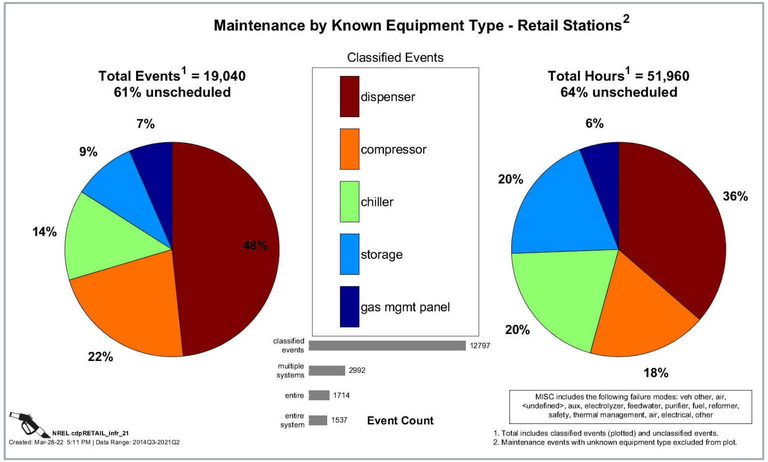
NREL and Bennett HD Dispensers

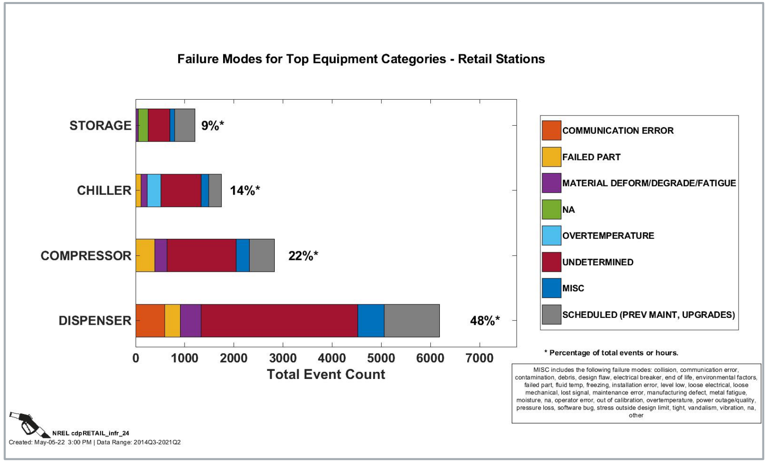
Heavy-Duty Dispenser Systems Installed at NREL's HD R&D Station (2023)

Medium & Heavy-Duty Stations Notes

Many factors contribute to MD/HD station design. Architecture is difficult to estimate while key factors are under development and harmonization occurs across many technology areas.

- Codes, standards, and other gaps lagging rapid development and deployment schedules for vehicle demos.
- Availability of major subsystems, components, and parts (**compressors**, hydrogen precooling systems, storage, etc.)
  - Some components/subsystems do not exist yet (large high throughput compressors).
- Capacity and throughput dictated by many factors:
  - Vehicle type(s) supported, fleet size, demand profile, fueling protocols, station layout, pressure class, etc.
- Subsystem and component reliability remain a major issue and reason for station down time (see NREL NFCTEC data).





https://www.nrel.gov/hydrogen/nfctec.html

Hydrogen Infrastructure Testing and Research Facility (HITRF)

First-of-its-kind experimental research capability, modeling, and analysis tools in support of medium and heavy-duty fueling R&D.

Located: Energy Systems Integration Facility (ESIF)
Golden, Colorado, USA

Assessment of new HD fueling protocols, components, and systems in a real-world environment.

Thermo-physical R&D with computational fluid dynamics and advanced fueling models (HD-H2FillS).

Techno-economic assessments and cost of ownership studies with updated modeling tools.

Provide industry stakeholders with validation data and publicly available HD modeling tools.

NREL HD R&D Station Expansion (Fall 2023)

Heavy-Duty Hydrogen Fast Flow Facility

- **Fueling Capability (Gaseous):**

Pressure	H_2 Precooling Temp	Mass Flow
70 MPa	-40°C	Average: 10 kg/min Peak: 20 kg/min

- **Heavy-Duty Dispenser** (HDD)
  - Configurable flow path (nozzle assembly or hard piped)
- **Heavy-Duty Vehicle Simulator** (HDVS)
  - +80 kg fill mass (equivalent to one Class 8 truck)
  - Configurable volume(s) & heavily instrumented with sensors (PT, TT, & safety).
- **Bulk Gas Storage**
  - ~650 kg (Low, Medium, High Pressure)
  - Limited back-to-back fueling capability
- **Precooling System**
  - Brine based with R404a chiller circuit
  - Custom micro-channel heat exchanger
- **HD Gas Management Panel**
  - Configurable for cascade fueling
  - Gas recirculation (to save on cost)

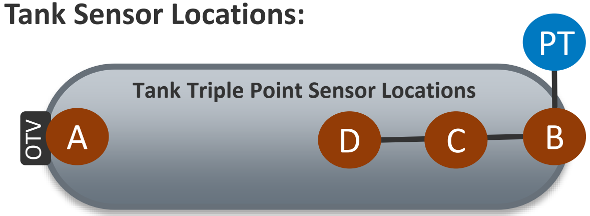
NREL's Heavy-Duty Hydrogen Fast-Flow Research Facility

Heavy-Duty Vehicle Simulator (HDVS)

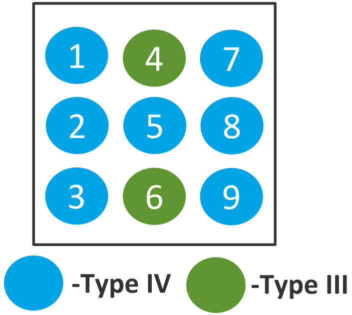
- **HDVS System simulates one Class 8 semi-truck.**
- 9x tanks (max 83 kg fill) - Configurable.
  - 7x Type IV tanks (68+ kg fill, 85°C rated)
  - 2x Type III tanks (20+ kg fill, 121°C rated)
- Utilizes automotive on-tank-valves (OTVs) with integrated bulk gas temp sensors and thermal pressure relief devices (TPRDs).
- Triple point sensors (2x) installed within one Type IV & III tank.
- Pressure transducers (PTs) installed at rear of tanks.
- Tank manifold instrumented and built for consistent inlet conditions.

1 HD FCET

Tank Sensor Locations:



Tank Configuration:



NREL Heavy-Duty Vehicle Simulator (HDVS)

HD Fast Flow Testing Achievements

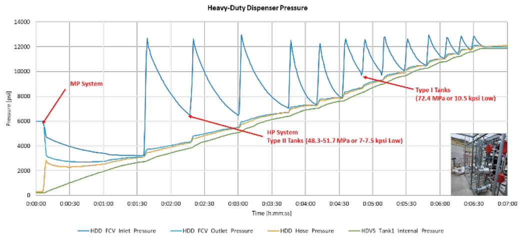
Heavy-Duty Fast Flow Testing - Major Achievements

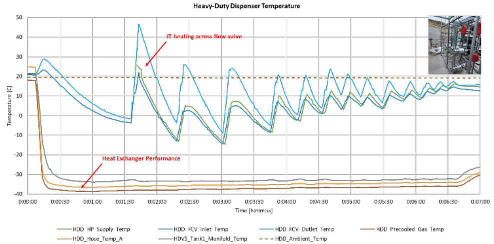
- Research completed under the Innovating Hydrogen Stations CRADA Project (Completed 2022).
- Goal: Construct HD fast flow R&D facility and demonstrate feasibility of meeting DOE/industry metrics for HD fast flow fueling.

Industry and DOE Target Metrics:

Mass	Time	Mass Flow	Vehicle
60-100Kg	<10 minutes	Average: 10 kg/min Peak: 20 kg/min	Within tank temp & pressure limits
Temperature	**Pressure**		
-40 C	70 MPa		

Heavy-Duty Test Data for NREL HD Dispenser





Major milestone fast flow tests completed:

Date (mo./yr.)	Fill Mass (Kg)	Time (mins)	Average Mass Flow Rate (Kg/min)	Peak Mass Flow Rate (Kg/min)	SOC (%)	Notes
08/2022	61.5	4.7	13.2	18.7	94%	Type IV Only (60 Kgs)
10/2022	82.3	6.6	12.6	23	100%	Complete HDVS (>80 Kgs)

✅ **Met all industry and DOE target metrics for fast-fill tests into the HD vehicle simulator.**

Assessment of HD Fueling Methods and Components CRADA

H2@Scale Cooperative Research and Development Agreement for HD Fueling R&D

- Develop a comprehensive assessment of HD hydrogen fueling protocols and fueling hardware to understand the effects of fueling protocol architectures on station design, vehicle design, functional safety requirements, and the implications on the total cost of ownership (TCO).

Project Subgroups

Hardware

Evaluations of real-world HD fueling components (nozzle, receptacle, breakaway, & hose) with fueling protocols (SAE & EU PRHYDE) at NREL's fast flow R&D station.

- Generate reliability, performance, and usability data.
- Assist Codes and standards groups with standardization activities.

Modeling

Modeling and validation of HD components & fueling protocols with experimental results and updating fueling models for public release.

- Perform computational fluid dynamics (CFD).
- Upgrade the NREL H2FillS model for HD fueling and protocols validation.

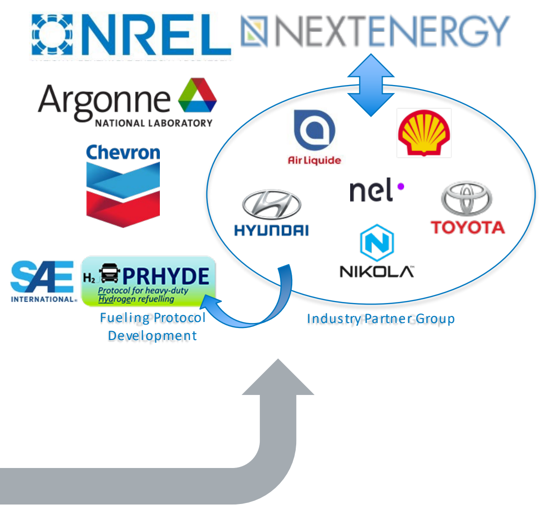
Analysis

Perform comprehensive techno-economic assessments (TEA) to determine total cost of ownership (TCO) of HD station concepts and vehicle architectures.

- Leverage existing modeling tools developed at NREL and ANL with industry supplied metrics.

Coordination with industry partners

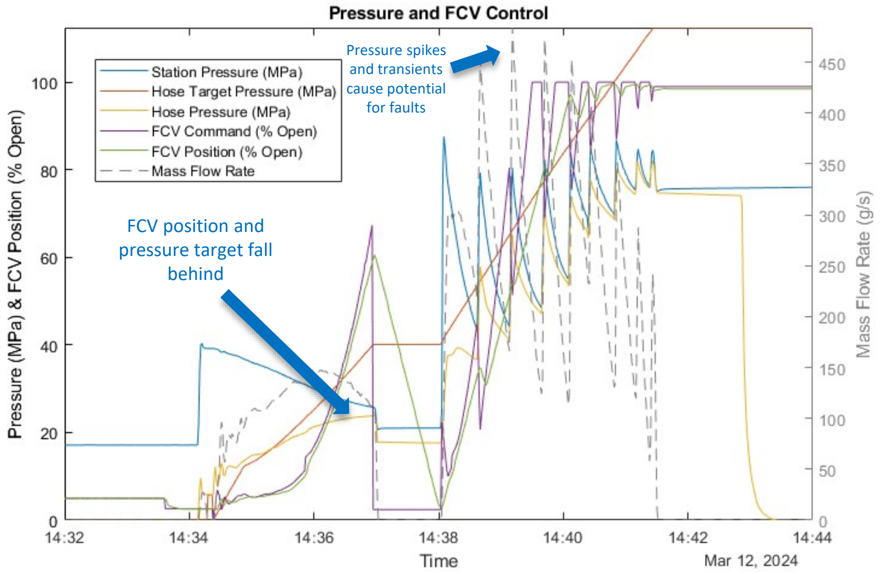
Project Partner Structure:

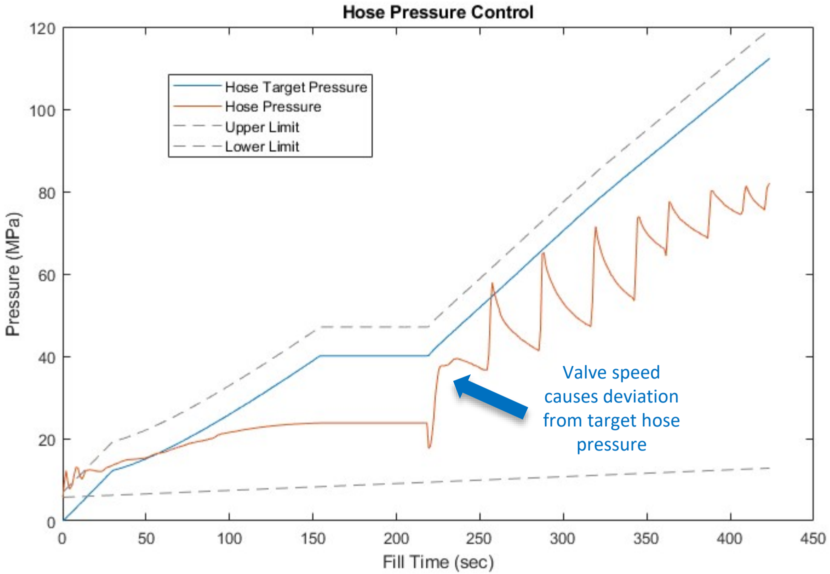


HD Fast Flow Protocol Evaluation & Flow Control

Moving beyond HD fast flow fundamentals to evaluate next generation fueling protocols with fast flow fueling hardware.

- NREL one of the first to attempt full implementation of the SAE J2601-5 fueling protocol - A hardware and model validation challenge.
  - Evaluating the fueling protocol in a phased approach with new pre-production nozzle assemblies (3 nozzles & 2 hoses).
  - Validation of fueling tables is needed with test data to confirm assumptions made by SAE (pressure drop, Cv, etc.).
- Current flow control valve technology has major gaps for dynamic response and sufficient flow coefficients.
  - New larger valve designs needed with significantly faster response, reliability, lower cost, and improved Cv.
- Preliminary tests show hose pressure slowly deviates from the hose target pressure due to valve actuation progressively falling behind.
  - NREL investigating optimization of bank switching strategies, control algorithms, valve position prediction, and pressure drop reduction.

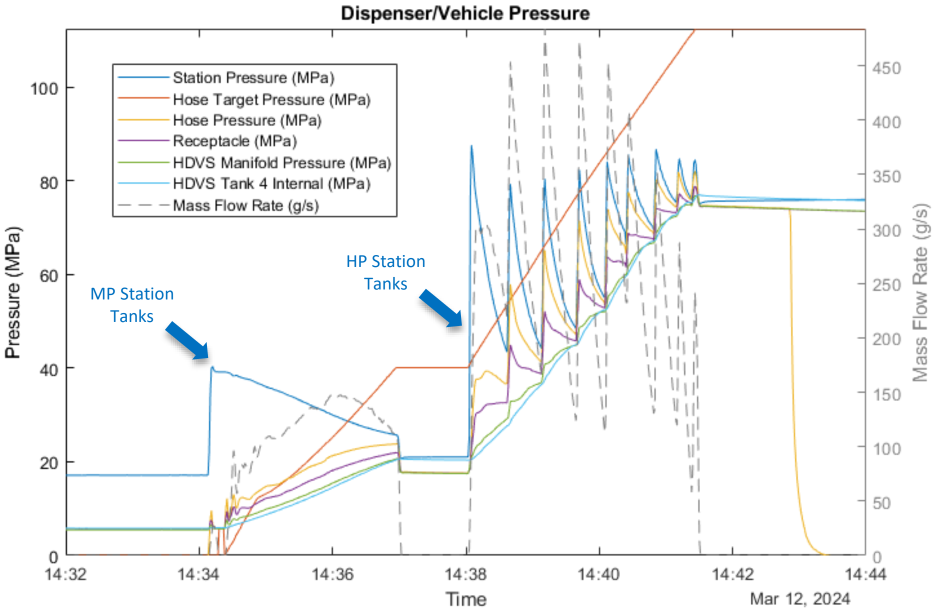


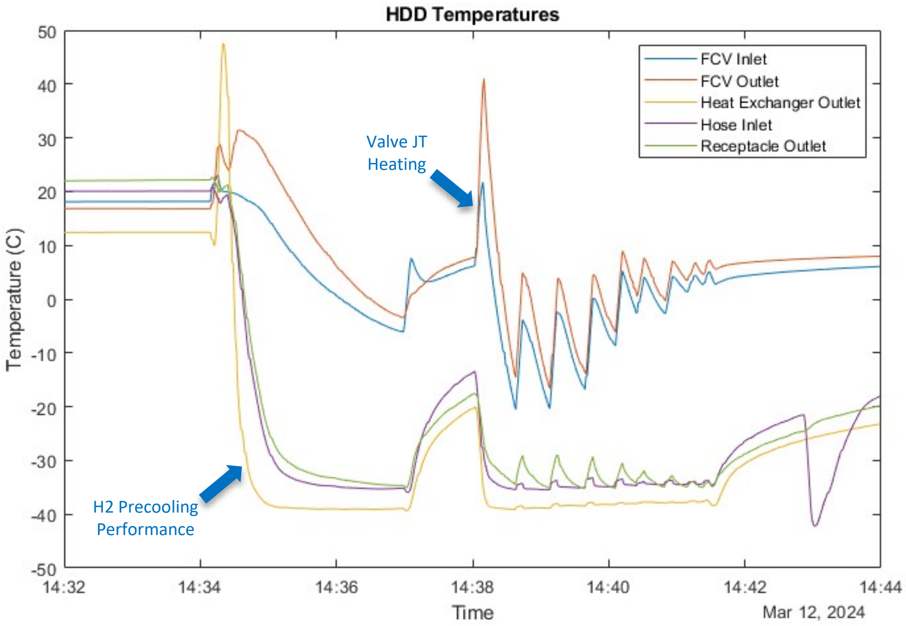


HD Fueling Protocol Experimental Results

Date: 3/12/2024
Mass Transfer: 73 kg
Total Fill Time: 423.5 Seconds (7.06 minutes)
Fueling Time: 358.9 seconds (Target 330 seconds per SAE-5)
Average Mass Flow Rate: 172.3 g/s (10.3 kg/min)
Peak Mass Flow Rate: 483.33g/s (29 kg/min)

Fueling Protocol: SAE J2601-5 MCF-HF-G H70 FM300 T40
Configuration: 9 tanks – 7 Type IV and 2 Type III
Starting/Ending Pressure : 5.5 MPa/ 74.6 MPa
APRR: 9.9 MPa/min
Ending CHSS SOC: 92% Type IVs, ~100% Type IIIs
Ambient Temperature: 13°C





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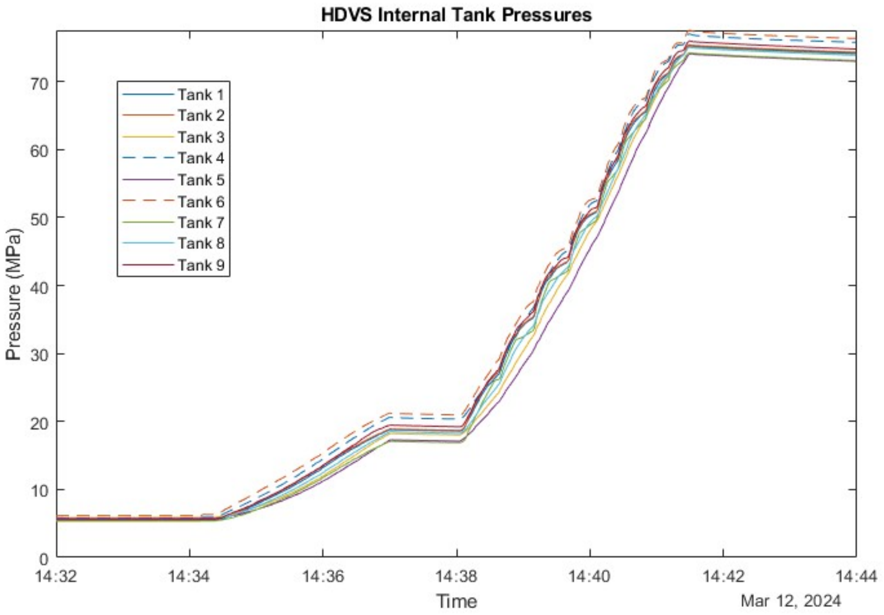
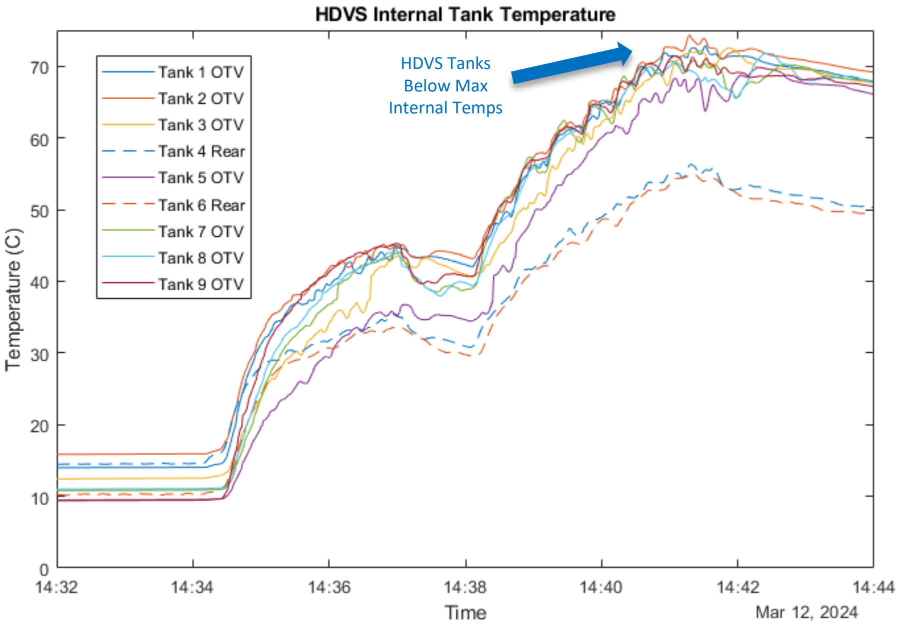
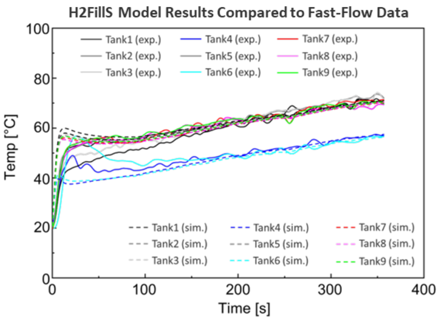


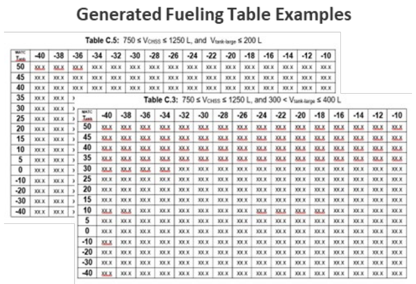


MD/HD Modeling Work and Capabilities

Hydrogen Filling Simulation (H2-FIllS)

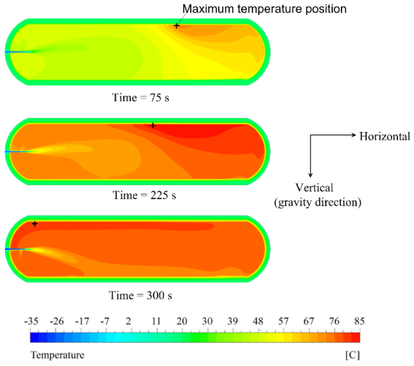
- 1D physics-based thermal fluid model simulating the real-world fueling process/interaction between station high-pressure storage system and vehicle CHSS.
- **HD version pending release Q2FY24**, LD version publicly available now: https://www.nrel.gov/hydrogen/h2fills.html
- NREL's HD systems were modeled and simulated in H2FillS. Results were compared with the real-world testing data to validate the model.
- H2FillS was modified to run fueling protocol concepts and generate fueling tables (provided to SAE-5 and EU PRHYDE).

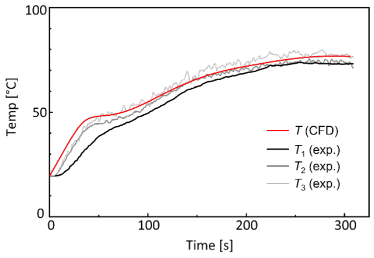




Computational Fluid Dynamics (CFD)

- Leverages NREL's high performance computing system (supercomputer) to run 3D CFD with Ansys Fluent.
- Validating 1D model results, investigate the influence of injector geometry (straight and angled) and various pressure ramp rate to develop hot spots and thermal stratification inside tanks.
    - Results influence fueling protocol development.
    - Angled injectors mix gas well, straight injectors lead to hot spots and thermal stratification.

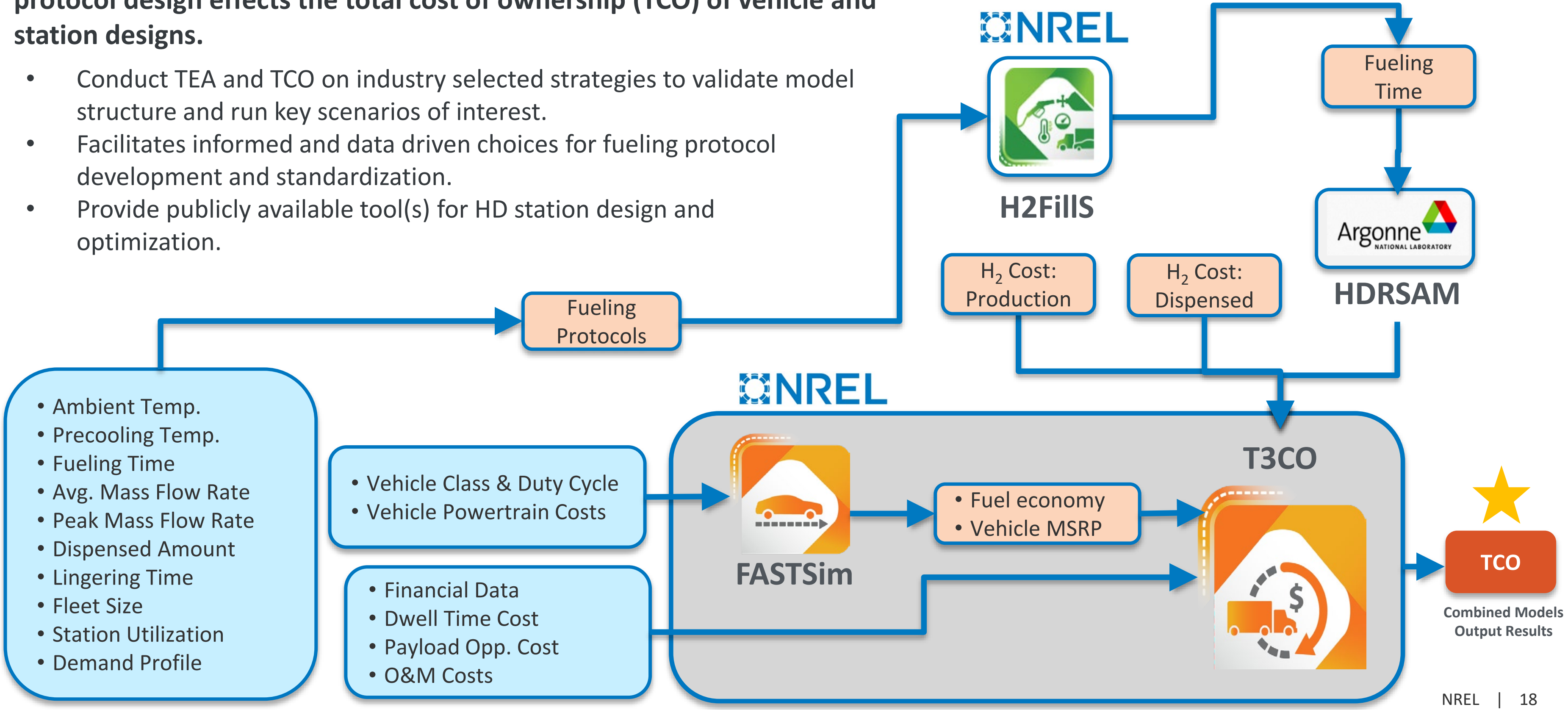




MD/HD Analysis - TEA/TCO

NREL and ANL combined legacy modeling tools to inform how fueling protocol design effects the total cost of ownership (TCO) of vehicle and station designs.

- Conduct TEA and TCO on industry selected strategies to validate model structure and run key scenarios of interest.
- Facilitates informed and data driven choices for fueling protocol development and standardization.
- Provide publicly available tool(s) for HD station design and optimization.

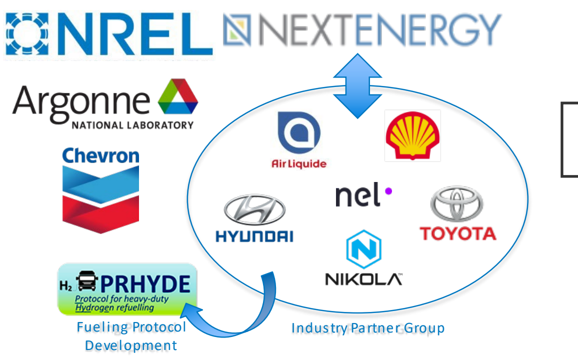


MD/HD Analysis - TEA/TCO

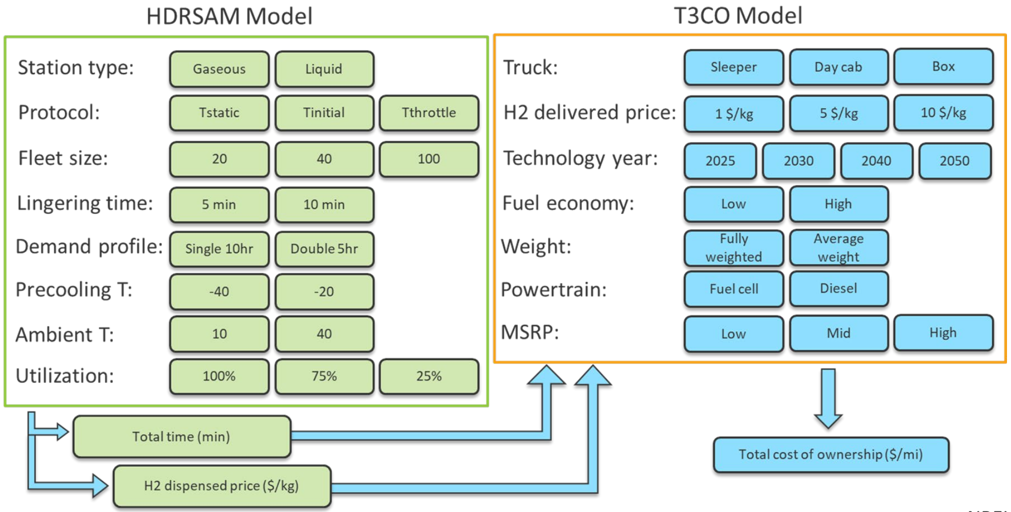
Industry supplied key metrics to validate the combine model structure and run key scenarios of interest.

- Gaseous fueling at 70 MPa , -40°C precooling, and utilize SAE J2601-5/EU PRHYDE fueling protocols.
- Class 8 trucks are priority followed by Classes 6 and 4 vehicles.
- Demand profile is critical, but profiles are based on wide variety of vehicles and use cases.
    - Data is lacking for MD/HD applications or non-existent.
- Station environmental conditions are an area of concern for deployment in cold/hot regions.
- Updated costs for components and subsystems are needed to improve model accuracy.

NREL HD Fueling Methods Project CRADA Partners



Industry Supplied Metrics and Variables

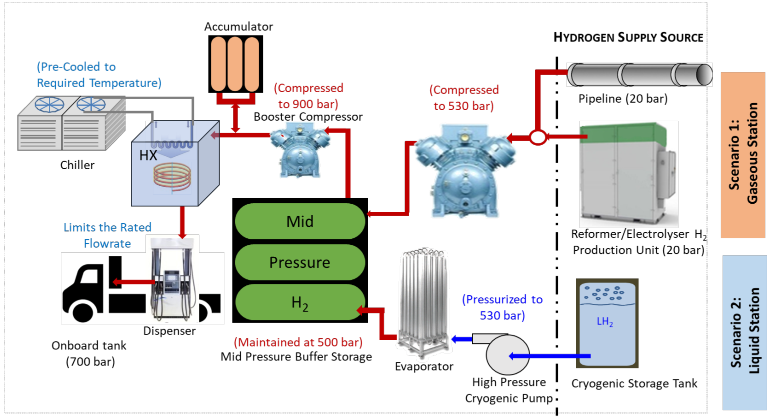


MD/HD Analysis - TEA/TCO

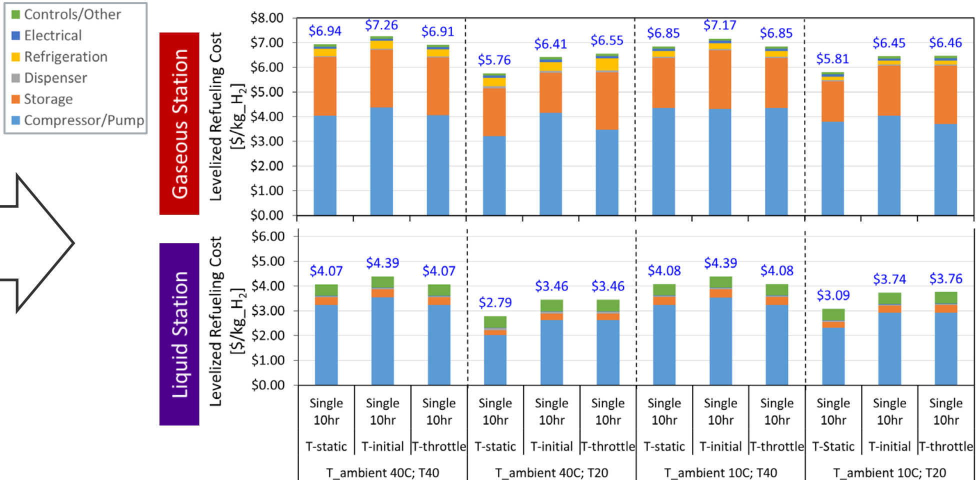
HDRSAM Analysis investigates the influence of fueling protocols selection on station design and cost.

- HDRSAM evaluates the cost of HD fuel cell electric vehicles fleets over various fueling station configurations and demand profiles.
- **Compressors and cryo-pumps remain the largest source of station cost** (for gaseous stations), followed by bulk hydrogen storage, and then gas precooling cost**.**
- Individual protocols do not have a large effect on the fueling time, thus **station cost difference is not significant between protocols**.
- Levelized refueling cost cheaper for liquid hydrogen stations vs. gaseous stations.
- Refueling cost depends on the individual contributions of different station components. *Cost data needed for HD station components!*

HDRSAM Station Configurations



Cost Contribution Station Components (Fleet Size 40)



MD/HD Analysis - TEA/TCO

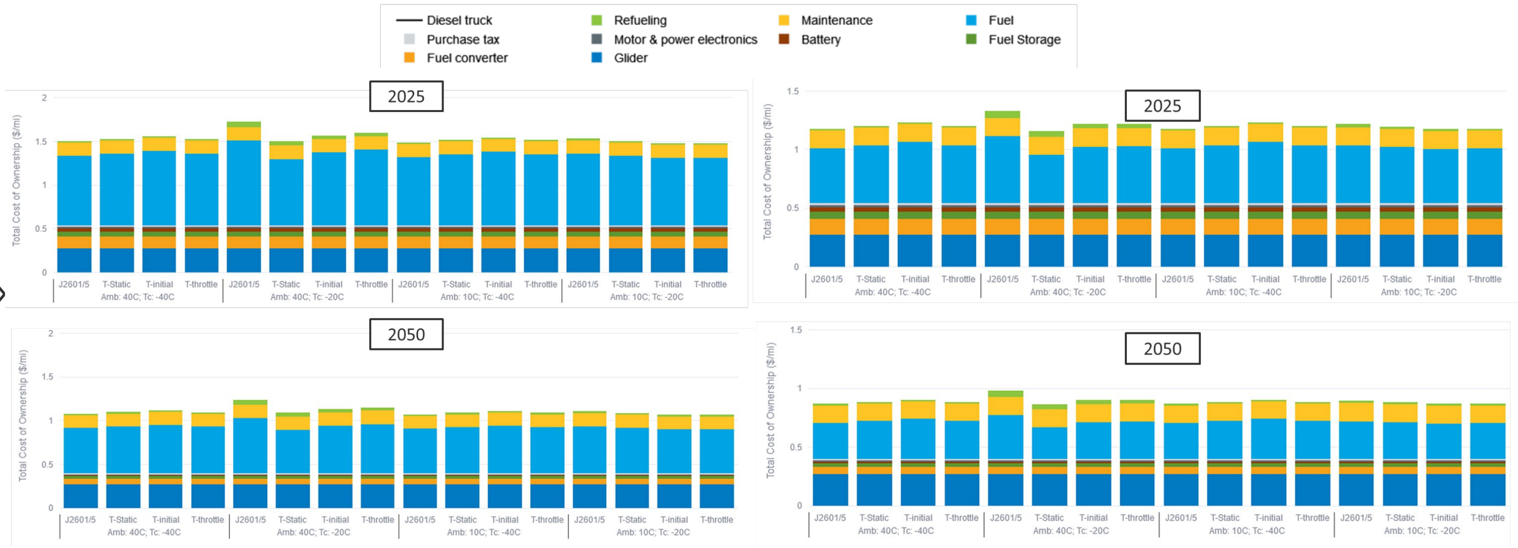
Total Cost of Ownership analysis investigates the influence of fueling protocols selection on vehicle configuration and station design.

- Calculated using inputs from HD-H2FillS and HDRSAM into NREL's FASTSim and T3CO.
- Analysis methodology incorporates vehicle performance from NREL's current and legacy HD truck data.
- Affect of fueling protocol choice on TCO appears minor, but scenarios with longer fueling times incur modestly higher fueling cost.
    - **Fuel price is the largest cost driver.**
- Liquid fueling stations lead to lower dispensed cost and lower TCO.
- As technology and fuel efficiency improve, hydrogen trucks become competitive with diesel (under key assumptions).

FASTSim

T3CO

Gaseous Station | Liquid Station



Summary

Validation of fueling protocols and fueling components are critical for successful deployment of MD/HD vehicles.

- Further real-world test data is required to identify technology gaps, and assess risk.
- Validation of models required to update fueling protocols, fueling tables, & revisit key assumptions.

Support necessary codes and standards activities to drive/accelerate decision making processes and harmonize efforts across technology areas.

- Conduct necessary validation of components, assemblies, and subsystems.
- Supply decision making entities with supporting data.

Address component/system poor reliability, high cost, availability, and long lead times.

- Investment in existing/new test facilities to evaluate components with hydrogen at temperature and pressure (industry lacks facilities with these capabilities).
- Manufacturing and materials R&D to improve durability and reliability.

Target innovation and development in critical areas where gaps in MD/HD are identified.

- Compressors, flow control technology (valves), nozzle assemblies, advanced communications, etc.

Thank You

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