Medium and Heavy-Duty Dispensing Overview

HFTO Workshop
Hydrogen Infrastructure Priorities to Enable Deployment in High-Impact Sectors

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National Renewable Energy Laboratory

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Overview – Medium & Heavy-Duty Dispensing

Current MD/HD vehicle deployments/demonstrations rely on LD fueling infrastructure, codes, and standards while new/revised 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 aren't 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)

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

Communications Note:

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			H70HF	

Dynamic - Control based on actual fueling conditions requiring

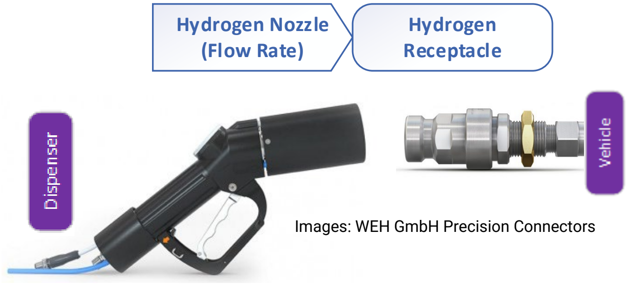
Static - Control based on tables and fueling temperature

Overview – MD/HD Dispensing Components

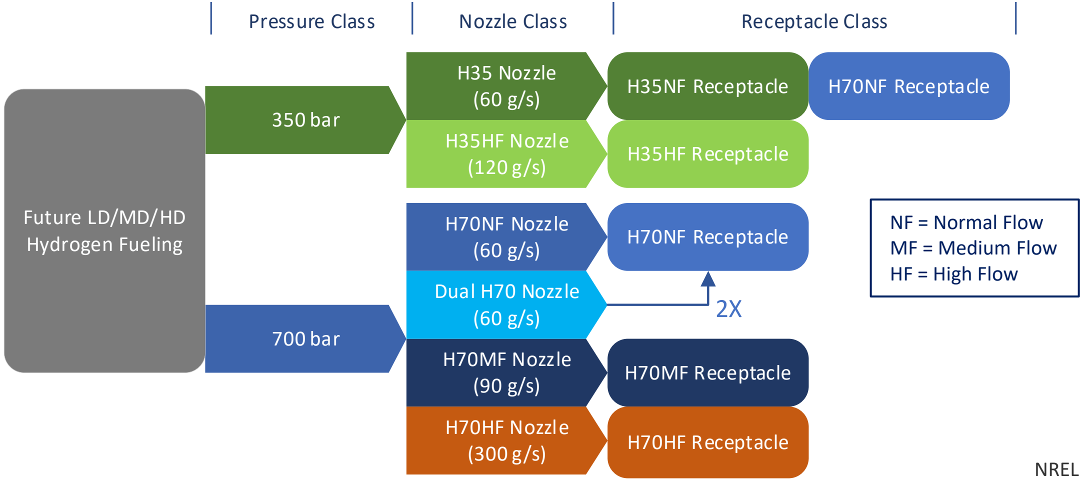
Dispensing components (nozzles, hoses, breakaways, and receptacles) are being developed in parallel to meet requirements of new MD/HD fueling protocols and stretch LD infrastructure usage.

- Codes and standards are lagging product development and deployment (ISO).
  - No current metrics for nozzle assembly geometry, pressure drop, flow coefficient, thermal mass, etc.
- Pre-production prototypes are currently being evaluated for performance and reliability.
  - Harmonization required with fueling protocols (ISO) and dispenser systems.
  - Designs are competing to set the standard.
  - Hoses are being upsized for HD applications, but usability remains 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 utilize light-duty based hardware.

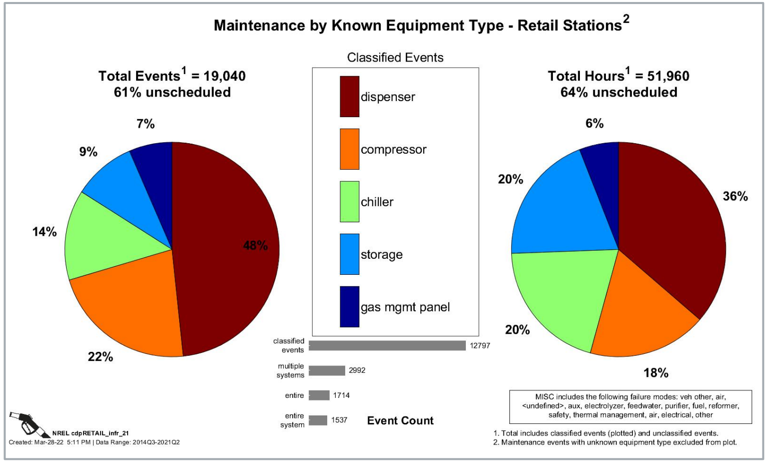
- Limited hardware available on the commercial market to construct HD dispensers and <u>reliability of components remains a major issue</u>.
    - Flow control technology gaps, mass flow meters, valves, filters, fittings, etc.
    - Significant lead times, cost, and reliability, reliability, reliability…
- Codes and standards are lagging product development and deployment.
- HD dispensers are being prepared for commercial deployment.
    - Lack of test facilities – designs need evaluation with nozzle assemblies, fueling protocols, and general reliability.
    - Advanced vehicle to dispenser communications will need to be retrofitted in the future.
- Dispenser designs remain constrained to number fueling positions (generally single) 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.

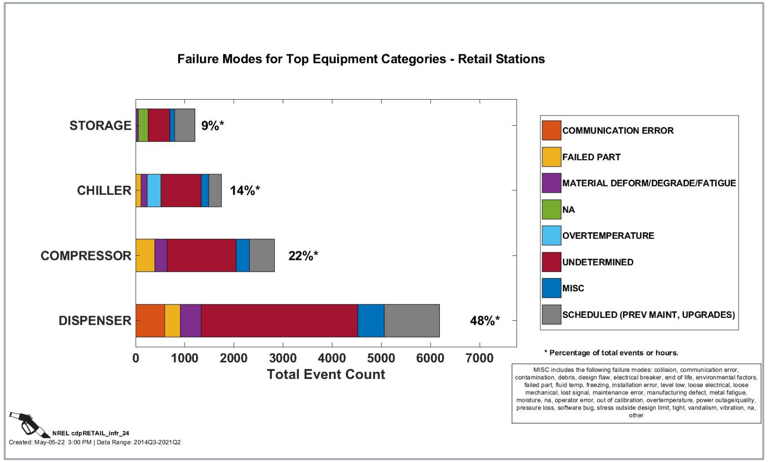
NREL and Bennett HD Dispensers

Notes – Medium & Heavy-Duty Stations

Many factors contribute to MD/HD station design, architecture is difficult to estimate while key factors are being fully developed and harmonization occurs across many technology areas.

- Codes, standards, and standardization 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.
- Capacity and throughput dictated by vehicle type(s) supported, fleet size, demand profile, fueling protocols, station layout, pressure class (700 bar vs 350 bar), 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 HITRF Station Expansion from 2020 to 2024

Heavy-Duty Hydrogen Fast Flow Facility

- **Fueling Capability (Gaseous):**

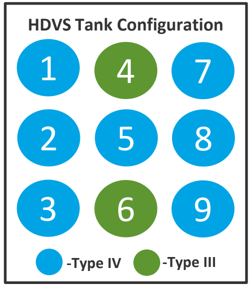
Pressure	H_2 Precooling Temp	Mass Flow
70 MPa	-40°C	Average: 10 kg/min Peak: 20 kg/min

- Comprised of:
  - **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)

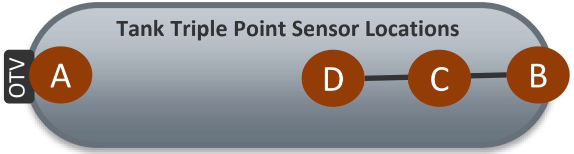
NREL's Heavy-Duty Hydrogen Fast-Flow Research Facility

Heavy-Duty Vehicle Simulator (HDVS)

- **Simulates one Class 8 semi-truck**
- 9x tanks (max 86 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.



- Additional pressure transducers (PTs) installed at rear of tanks.
- Tank manifold instrumented and built for consistent inlet conditions.

1 HD FCET

NREL Heavy-Duty Vehicle Simulator (HDVS)

HD Fast Flow Testing Achievements

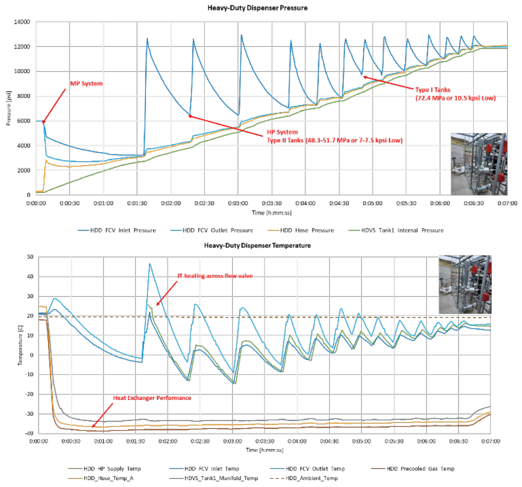
Heavy-Duty Fast Flow Testing - Major Achievements

- Multiple flow-tests completed leading up to two major benchmarks tests achieved in 2022 .
- Two major fills into HDVS system using all tanks and only Type IV tanks (for model validation).

Industry and DOE Target Metrics:

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

Heavy-Duty Test Data for NREL HD Dispenser



Major milestone fast flow tests completed:

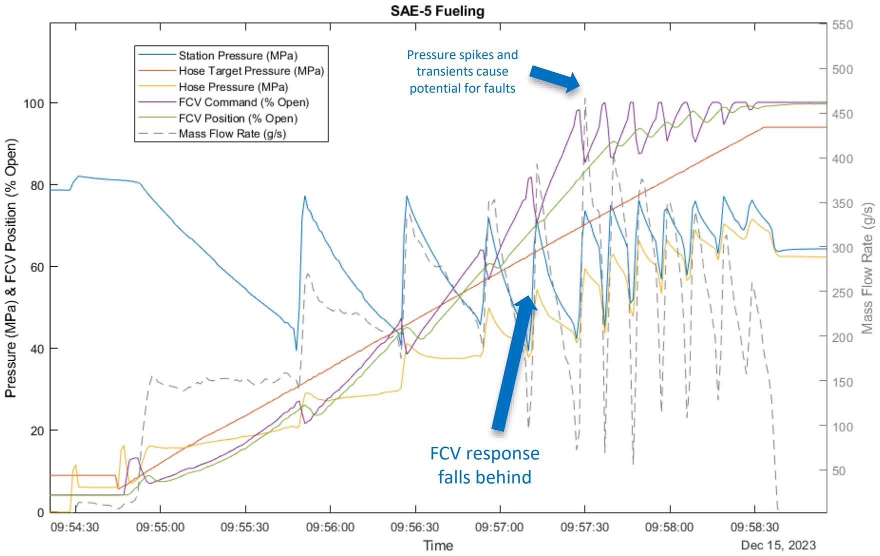
Date (mo./yr.)	Fill Mass (Kg)	Time (mins)	Average Mass Flow Rate (Kg/min)	Peak Mass Flow Rate (Kg/min)	SOC (%)	Notes
08/2022	61.5	4.7	13.2	18.7	94%	Type IV Only (60 Kgs)
10/2022	82.3	6.6	12.6	23	100%	Complete HDVS (>80 Kgs)

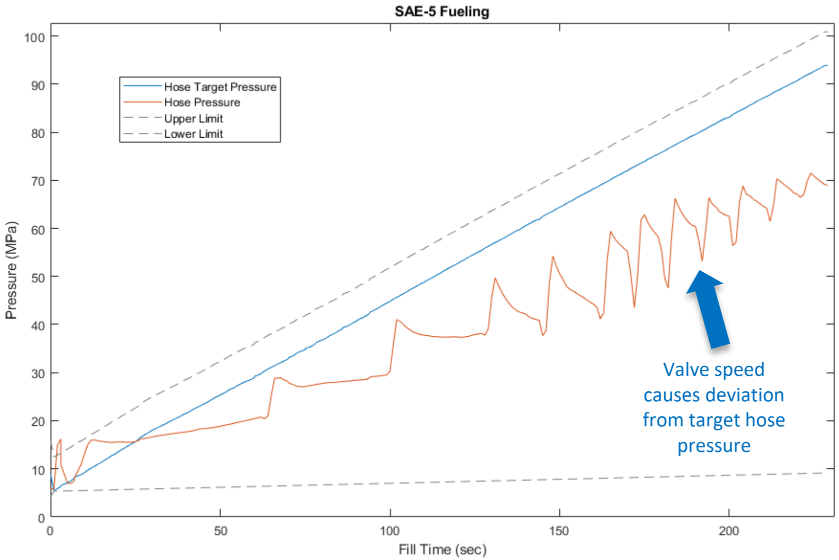
Met all industry and DOE target metrics for fast-fill tests into the HD vehicle simulator.

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 (from 3 manufacturers, 2 hoses).
  - Fueling table validation is needed based on modeling assumptions made by SAE on fueling hardware.
- Current flow control valve technology has major gaps for dynamic response and sufficient flow coefficients.
  - Lack of valve type/design options in the size, Cv, and speed required.
  - New valve designs needed with faster response and reliability.
- Preliminary tests show hose pressure slowly deviates from the target hose pressure due to valve actuation progressively falling behind.
  - Optimization of bank switching strategies, control algorithms, and valves position prediction are ongoing.

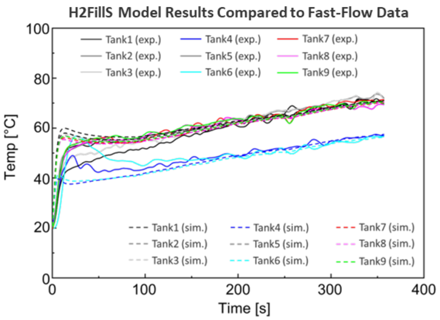


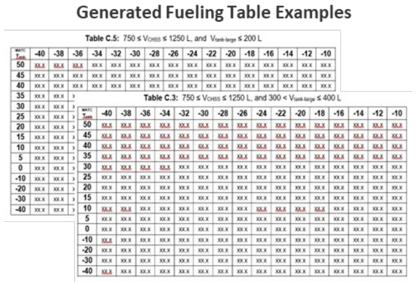


MD/HD Modeling Work and Capabilities

Hydrogen Filling Simulation (H2-FIllS)

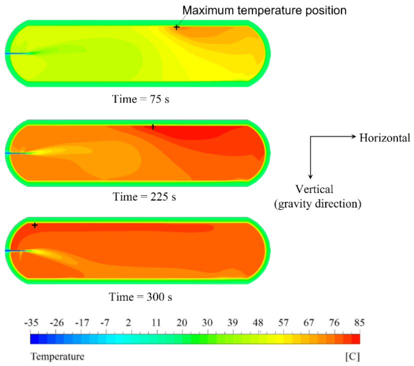
- 1D physics-based thermal fluid model simulating the real-world fueling process/interaction between station high-pressure storage system and vehicle CHSS.
- **HD version pending release Q2FY24**, LD version publicly available now: https://www.nrel.gov/hydrogen/h2fills.html
- NREL's HD systems were modeled 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).

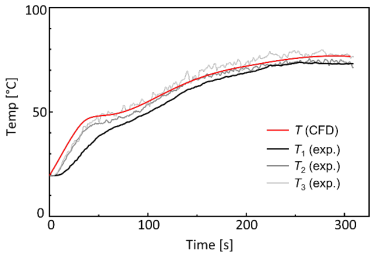




Computational Fluid Dynamics (CFD)

- 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.

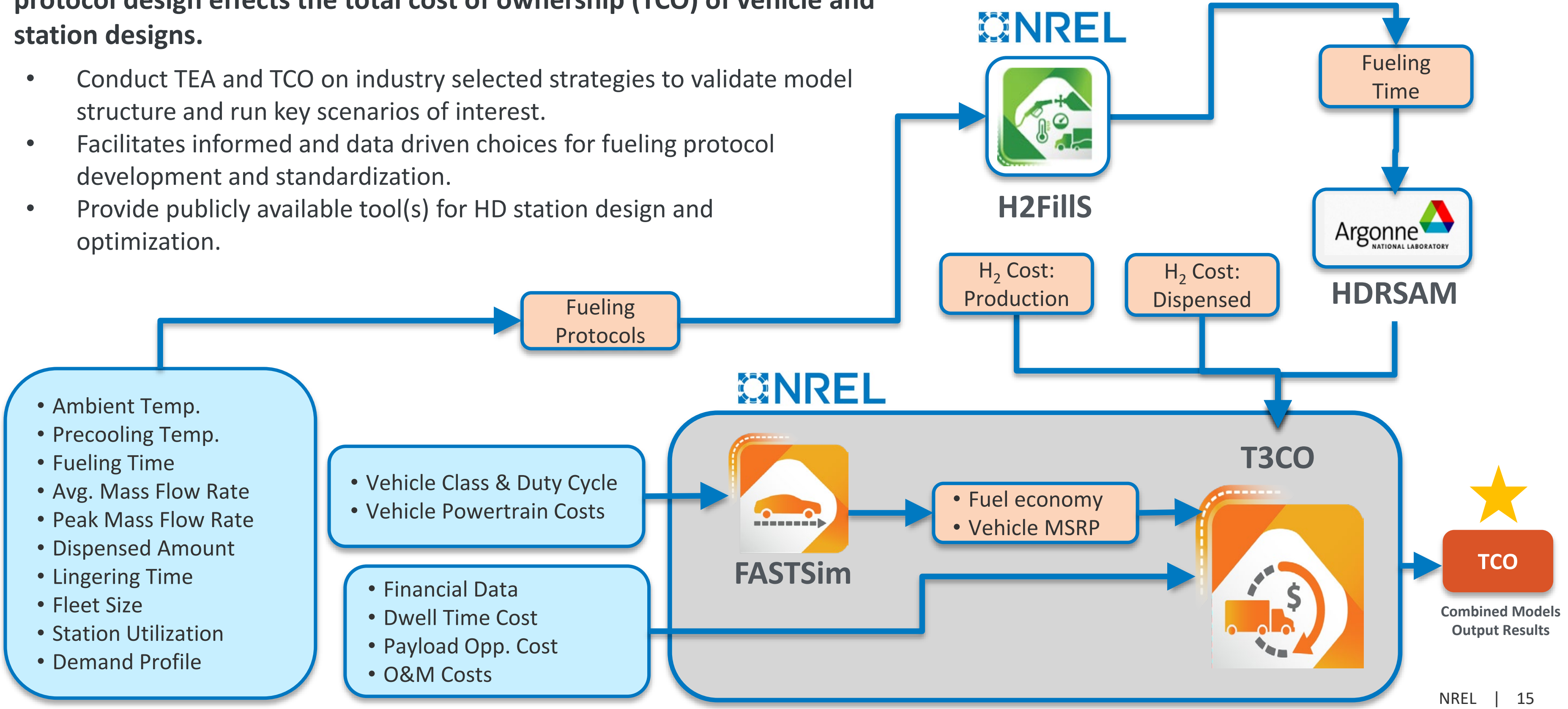




MD/HD Analysis - TEA/TCO

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.

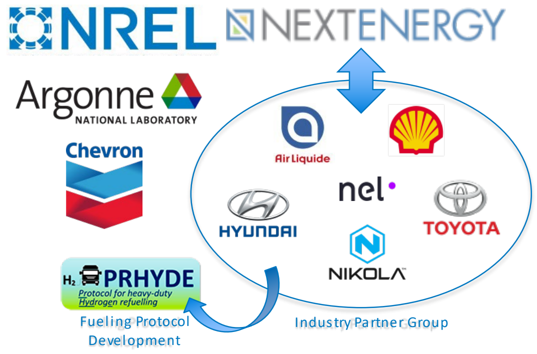
- Conduct TEA and TCO on industry selected strategies to validate model structure and run key scenarios of interest.
- Facilitates informed and data driven choices for fueling protocol development and standardization.
- Provide publicly available tool(s) for HD station design and optimization.



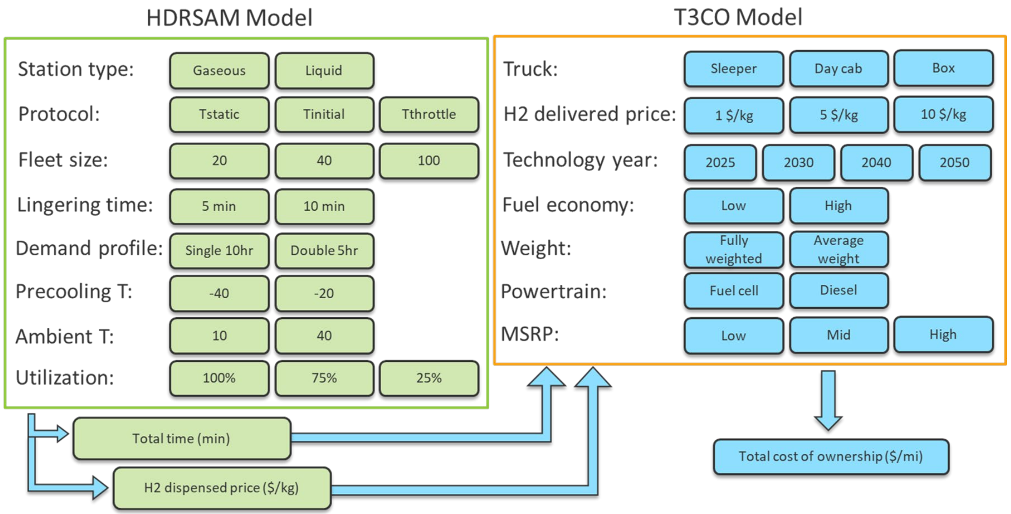
MD/HD Analysis - TEA/TCO

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.



Industry Supplied Metrics and Variables

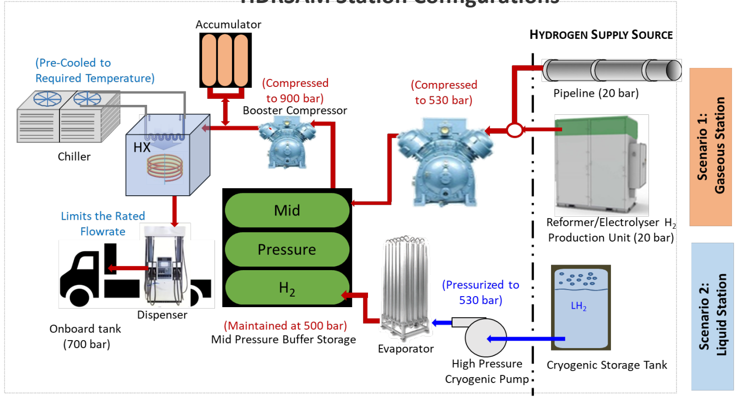


MD/HD Analysis - TEA/TCO

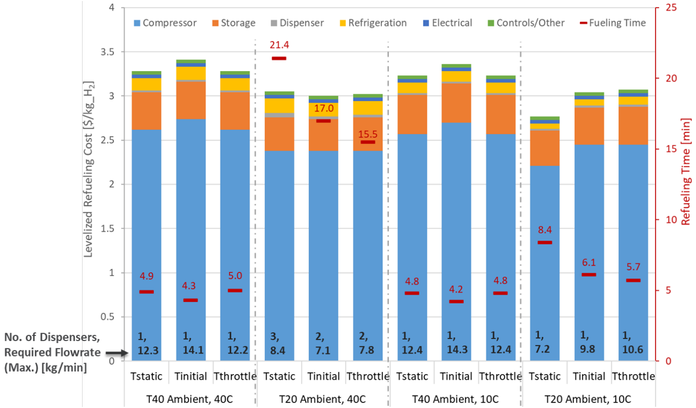
HDRSAM Analysis:

- HDRSAM evaluates the cost of heavy-duty fuel cell electric vehicles fleets over various fueling station configurations and demand profiles.
- **Compressors and cryo-pumps remain the largest source of station cost,** followed by bulk hydrogen storage and gas precooling cost (for gaseous stations)**.**
- Faster fueling rates and hydrogen precooling temperature (-40°C) contribute to higher levelized refueling costs.
- Slow fueling rates require more dispensers to fuel large fleets, which increases the maximum fueling rate due to the possibility of simultaneous fueling at all dispensers.

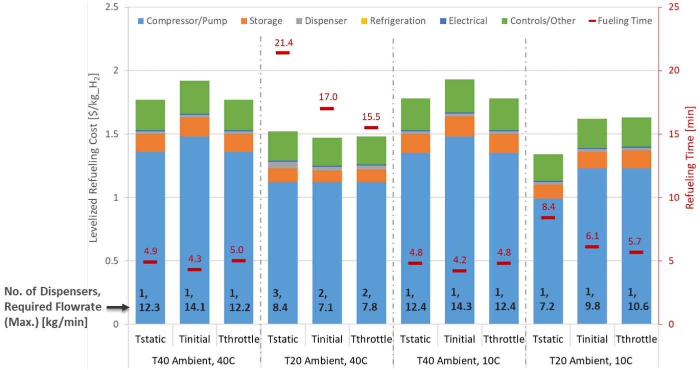
HDRSAM Station Configurations



Cost Contribution of Gaseous Station Components (100 Fleet Size)



Cost Contribution of Liquid Station Components (100 Fleet Size)



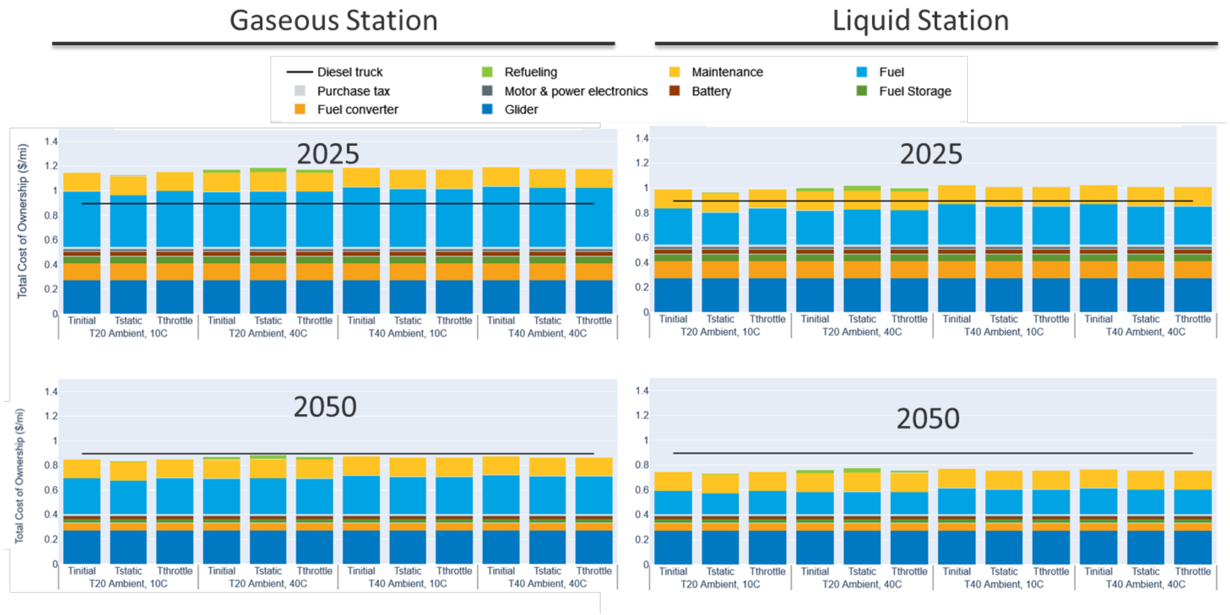
MD/HD Analysis - TEA/TCO

Total Cost of Ownership Analysis using NREL FASTSim and T3CO:

- Calculated using inputs from HD-H2FillS and HDRSAM. Analysis methodology incorporates station design and vehicle performance to determine total cost of ownership.
- Affect of fueling protocol choice on TCO appears minor, but scenarios with longer fueling times incur largest fueling cost.
    - **Fuel price is the largest cost driver.**
- Liquid refueling 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



Summary and Workshop Notes

Summary and Workshop Notes:

- 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.
  - Model validation is required to update fueling protocols, fueling tables, and 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, subsystems, and systems as required by codes and standards groups.
- 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.
- Target innovation and development in critical areas where gaps in MD/HD have been identified.
  - Compressors, flow control technology (valves), nozzle assemblies, advanced communications, etc.

Thank You

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