NREL
Transforming ENERGY

Assessment of Heavy-Duty Fueling Methods and Components

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DOE Hydrogen Program
2024 Annual Merit Review and Peer Evaluation Meeting

Project ID: SCS031

Project Goal

Develop a comprehensive assessment of heavy-duty (HD) fuel cell electric vehicle 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).

- 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 Energy Systems Integration Facility (ESIF) - 2023
Golden, Colorado, USA

Overview

Timeline and Budget

- Project start date: 2/2/2022
- Project end date: 2/1/2025
  - 3-year project (1 year extension)
  - Total project budget: $4.547M
  - Total recipient share: $916K
  - Total federal share: $3.631M
  - Total DOE funds spent*: $2.504M
  - Total Non-DOE Funds: $801K

    * As of 04/01/2024
- 2020 DOE HFTO H2@Scale CRADA Call AOI Topic 1: Fueling Components for HD Vehicles

Barriers

- Availability of heavy-duty hydrogen fueling infrastructure is limited (globally) to evaluate the performance of fueling protocol concepts and hardware.
- Lack of understating how heavy-duty fueling concepts will influence infrastructure and vehicle design, specification, and cost.
- Robust modeling tools for heavy-duty fueling concepts are underdeveloped or do not exist.

Partners

- PI: Shaun Onorato (NREL)
- Co-PI(s): Taichi Kuroki (NREL), Jamie Kee (NREL), Krishna Reddi (ANL), Lauren Mattar (NextEnergy), & Emily Moreyra (Chevron)
- Partner organization(s)
  - **NextEnergy** - Industry Group and Component Liaison
  - **Chevron** – Energy Company
  - **Argonne National Laboratory** - Modeling Partner

Potential Impact

Project relevance to DOE and Administration goals

Goal	Project relevance
Provide pathways to private sector uptake	Providing a pathway to commercial market though evaluation of HD hydrogen fueling components and HD fueling protocols under real-world conditions.
Build clean energy infrastructure	Provide support to industry, government, and codes and standards groups to build out new heavy-duty hydrogen infrastructure for hydrogen trucks and create jobs.
Lower greenhouse gas emissions and criteria pollutants	Enable infrastructure R&D to accelerate usage of hydrogen powered heavy-duty vehicles, which will help reduce emissions and pollution.
Support and improve energy, environmental, and/or social justice	Adoption of hydrogen powered heavy-duty vehicles has the potential to reduce emissions and pollution in areas of disadvantaged communities.

Approach: Project Level

The project structure utilizes 3 subgroups/teams that support execution of taskwork:

Project Subgroups

Hardware

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

- Generate performance, reliability, & characterization data with ID of technology gaps.
- Support codes and standards groups with data and feedback.

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 at NREL and ANL with industry supplied metrics.
- Develop a publicly available TEA/TCO analysis tool.

Coordination with industry partners

Project Partner Structure

Chevron
NEXTENERGY
Argonne National Laboratory
Air Liquide
nel
Hyundai
Toyota
Nikola
Industry Partner Group
Fueling Protocols
PRHYDE – Protocol for heavy-duty Hydrogen refueling
SAE International

Primary Deliverables

- ✓ **HD component and fueling protocol performance test data under fast-flow conditions.**
- ✓ **CFD modeling results for hydrogen storage tanks and HD components.**
- ✓ **TEA/TCO analysis results for industry supplied scenarios.**
- ✓ **Public version of upgraded HD-H2FillS.**
- ✓ **Public model structure to run TEA/TCO with NREL/ANL legacy models.**
- ✓ **Final comprehensive report.**

Hardware Subtask

Approach: Hardware (HD Fueling Hardware and Protocols)

Real world heavy-duty hydrogen component and fueling protocol evaluations at NREL's fast flow research facility.

Station Architecture

Leverage NREL's HD fast flow fueling facility to evaluate **new HD fueling concepts and hardware against DOE and industry metrics to accelerate technology development/deployment.**

Fueling Protocols

Validation of new HD fueling protocols with HD fueling hardware and HD vehicle tank system for performance, implementation challenges, technology gaps, and reliability.

Dispensing Hardware

Evaluation of industry supplied HD fueling components (i.e., nozzles, hoses, receptacles, and breakaway devices) for performance, usability, reliability, and characterization data.

Communications

Demonstration of advanced vehicle to dispenser communications beyond IrDA that comply with new fueling protocol concepts.

Codes and Standards Development

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

Industry Selected MD/HD Fueling Protocols for Validation

Protocols*	Status	Region
SAE J2601/5 TIR	Released	International
FCH 2 JU PRHYDE	Released	EU, UK, & US

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

Approach: Hardware (HD Fueling Hardware and Protocols)

Phased Test Plan for Evaluations of Fueling Hardware, Fueling Protocols, and Advanced Communications

Test Plan Phases

Year	2022	2023	2024												2025
Month	1 to 12	1 to 12	1	2	3	4	5	6	7	8	9	10	11	12	1
Preliminary Phase: NREL Station Benchmark/Commissioning	Complete														
Phase I – Refueling Hardware Commissioning		Complete													
Installation, phased pressurization, commissioning tests, and readiness reviews															
Phase II – SAE J2601/5 & Refueling Hardware Performance Evaluations															
Constant pressure ramp fast flow tests with refueling hardware		Complete													
SAE J2601-5 MCF-HF-G at 700 bar, 300 g/s, -40C Testing with HD refueling hardware															
Advanced communications testing (HyConnect)															
Phase III – Refueling Hardware Performance Evaluations for ISO - 3 nozzle sets (nozzle/receptacle)						New work									
Pressure drop tests with constant pressure ramp at 70 Mpa, +300 g/s, and -40C for each nozzle set															
Pressure drop tests SAE J2601-5 MCF-HF-G at 700 bar, 300 g/s, and -40C for each nozzle set															
Nozzle freeze lock tests (each nozzle set)															
Phase IV – PRHYDE Protocol Evaluations								Delayed for new work							
PRHYDE Static, Initial+, and Throttle fueling protocol fueling tests with refueling hardware															
Advanced communication testing (HyConnect)															
Phase V – Reporting															
Data dissemination, draft final reports, and retest as required for project completion															

DOE and Industry Target Metrics:

- **Mass Transfer** 60-100kg
- **Fill Time** <10 minutes
- **Mass Flow** Avg.: 10 kg/min Peak: 20 kg/min
- **H_2 Pressure** 70 MPa
- **H_2 Precooling** -40C
- **Vehicle CHSS** Within tank temperatures & pressure limits

Project Hardware Goal

Goal: Evaluate an industry selected HD fueling protocol with HD refueling hardware and advanced communications on the NREL HD dispenser with the largest configuration of the NREL HD vehicle tank system as possible (≥60 kgs).

Criteria: Meet protocol fueling table fill times (with associated fill time equation modifiers) for the ambient conditions of the test day within temperature and pressure limitations of the HD vehicle tank system.

Approach: Industry Hardware Development

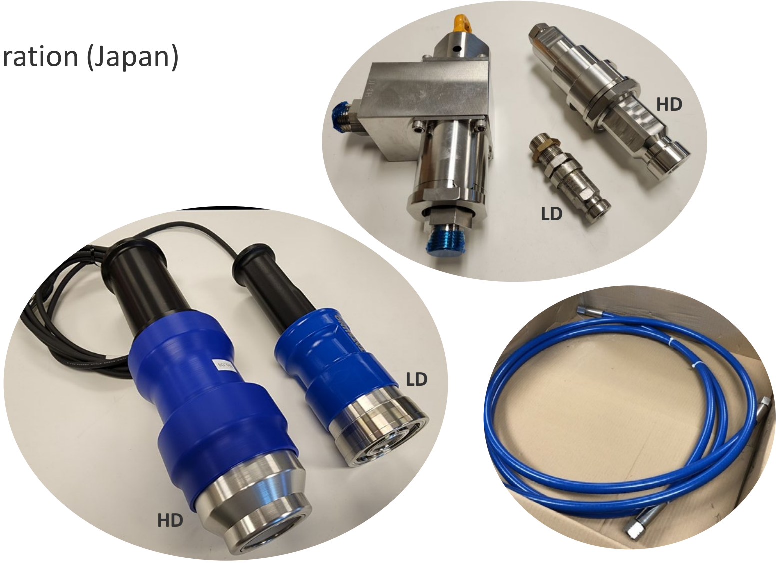
Heavy-Duty Hydrogen Component Development for Fast Flow Fueling

NEXTENERGY

- Industry group funded the development of 70 MPa hydrogen heavy-duty high-flow (H70HF) fueling hardware components against proposed global standards and industry specific metrics.
- NextEnergy, on behalf of the industry group, facilitated conversations, information sharing, and baseline component testing between the component manufacturers and NREL in support of the CRADA work.
- Original Component Suppliers:
    - **Nozzle, Receptacle, and Breakaway:** Tatsuno Corporation (Japan)
    - **Hose:** Parker (Germany)

Fueling Components Specification Targets

Nominal Working Pressure	70 MPa (H70)
Maximum Operating Pressure	87.5 MPa
Maximum Allowable Working Pressure	96.25 MPa
Operating Temperature	-50˚C to 95˚C
Maximum Average Flow Rate	180 g/s (10.8 kg/min)
Maximum Peak Flow Rate	300 g/s (18 kg/min)



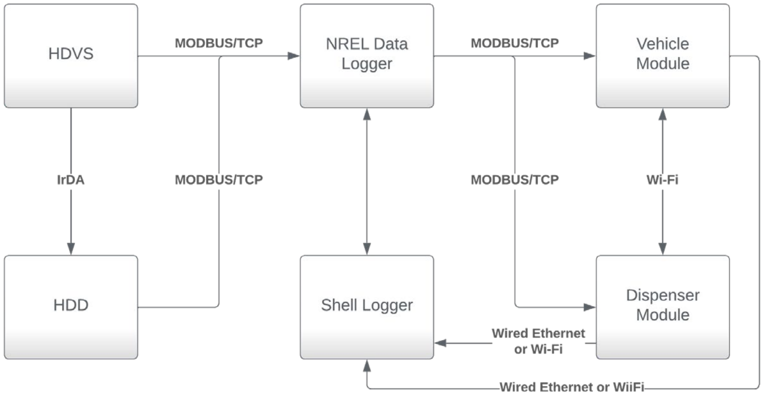
Tatsuno Fueling Hardware and Parker HD Hose

Approach: Hardware (Advanced Communications)

Shell Techworks HyConnect Advanced Communications Device

- Proof-of-concept communications system (beyond IrDA) for development and tests of advanced communication between a vehicle and dispenser during the hydrogen fueling process.
  - Conforms to SAE 2799 with modifications for SAE J2601/5 and bidirectional communications for PRHYDE fueling protocols.
- Incorporates custom embedded computing systems and two test nozzles for concept evaluation of NFC+Wi-Fi and Ethernet-APL solutions using black channel communications.
- **HyConnect Test System Includes**:
  - **Vehicle Module** – Simulated vehicle that transfers real-time data from NREL HDVS.
  - **Dispenser Module** - Simulated dispenser that receives/transfers real-time data from the vehicle.
  - **System Console and Ethernet Switch** - PC used to control, observe, and log communications with a standard commercial Ethernet switch.

HyConnect System Block Diagram



HyConnect Dispenser and Vehicle Modules

Test Nozzles for Concept Evaluation NFC+Wi-Fi and Ethernet-APL Solutions

Accomplishment: Hardware (HD Fueling Hardware & Protocols)

Hardware and fueling concepts integrated at NREL's HD fast flow facility and validation activities underway.

Station Architecture: NREL fast flow facility upgraded and modified for integration of project hardware including mass flow meters, flow control valves, receptacle mounts, etc.

Refueling Hardware: Industry group successfully delivered 2 sets of each HD refueling component to NREL for integration and testing.

- Fueling hardware was evaluated for operational and safety aspects at a 3rd party test laboratory.
- Hardware installed and evaluated for pressure drop and usability under fast flow conditions on the NREL HD dispenser (at pressure and temperature).

Fueling Protocols: NREL programmed the SAE J2601-5 MCF-HF-G fueling protocol into the NREL HD dispenser and performed validation testing.

- Phased implementation approach of protocol algorithms and added complexity.
- Validation of fueling tables with test data to confirm assumptions made by SAE (pressure drop, Kv, etc.).

Advanced Communications: Collaboration with Shell Techworks for design and integration of the Shell HyConnect system for advanced vehicle to dispenser communications.

Codes and Standards Support: Results from initial testing shared with SAE and ISO Working Groups. Added project scope to evaluate two more nozzle/receptacle sets (WEH and Staubli).

Tatsuno, WEH GmbH, and Staubli Nozzle/Receptacle Assemblies

Industry Provided Hardware Installed at NREL's Heavy-Duty Hydrogen Fast-Flow Research Facility

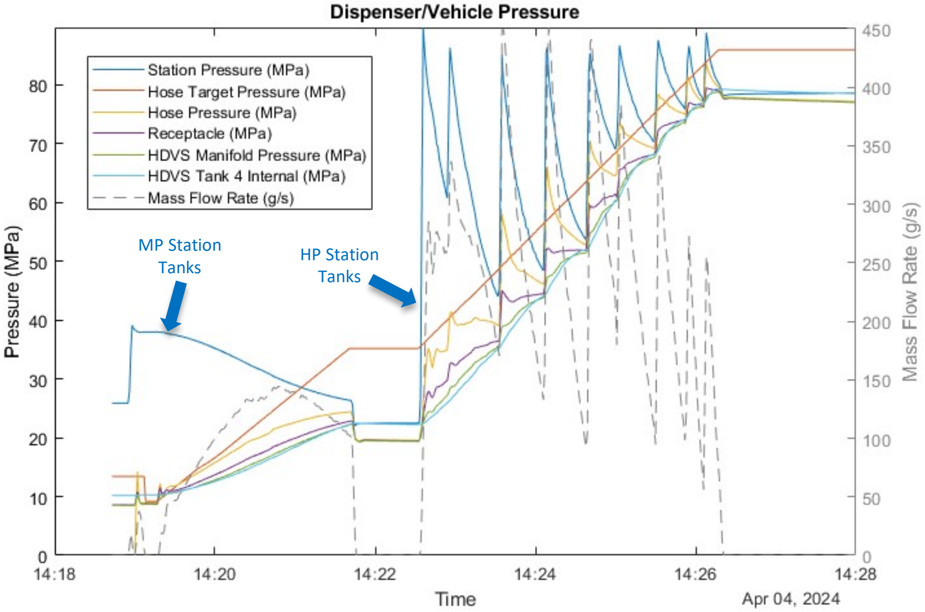
Accomplishment: Hardware (HD Fueling Hardware & Protocols)

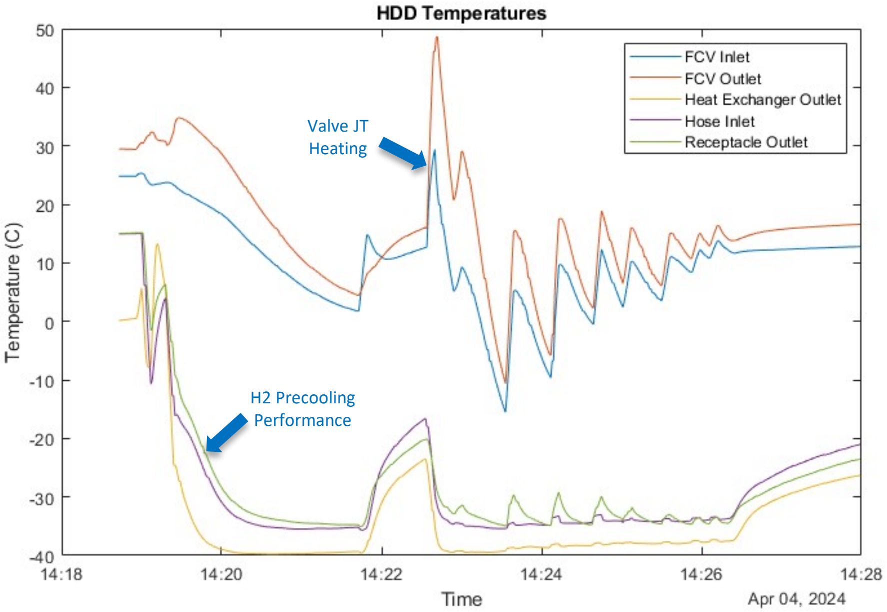
Milestone fueling event with SAE J2601/5 MCF-HF-G fueling hardware and advanced communications.

Milestone Fill Data:

Date: 4/4/2024
Mass Transfer: 70.5 kg
Total Fill Time: 420 Seconds (7 minutes)
Fueling Time: 368 seconds (Target 340 seconds per SAE-5)
Average Mass Flow Rate: 168 g/s (10 kg/min)
Peak Mass Flow Rate: 450 g/s (27 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 : 9 MPa/ 78.1 MPa
Fueling Time APRR: 11.2 MPa/min
Ending CHSS SOC: 95% Type IVs, ~102% Type IIIs
Ambient Temperature: 20.2°C





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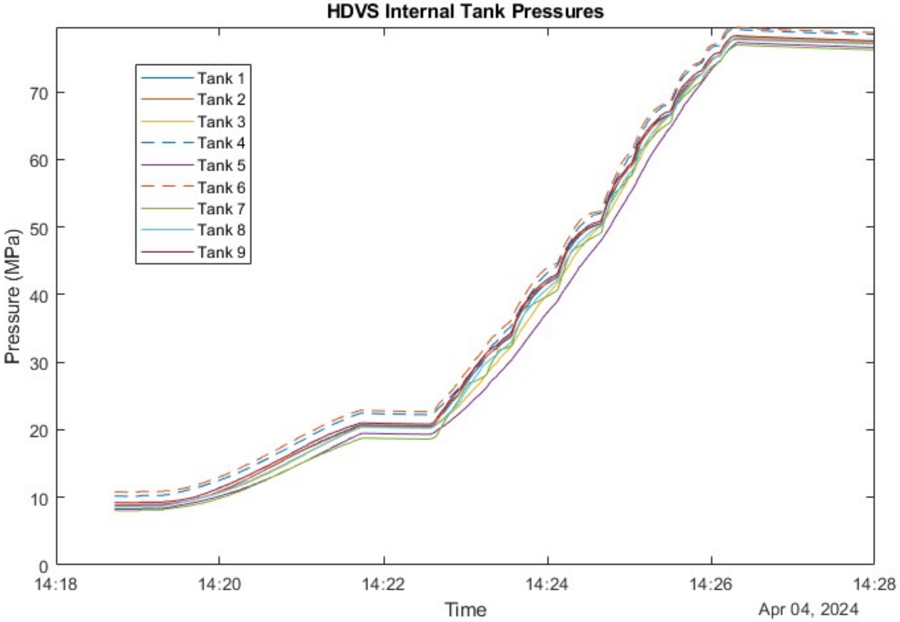
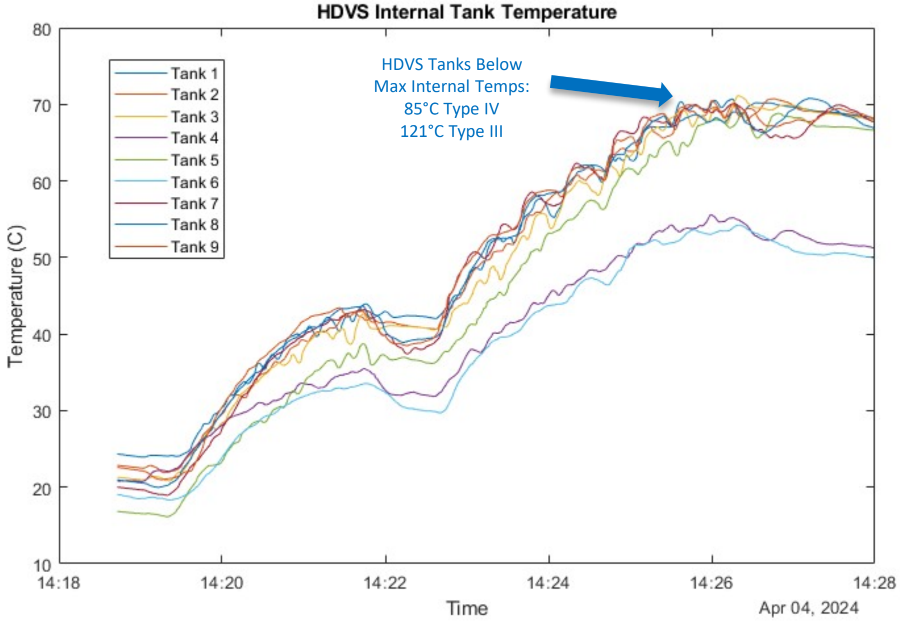
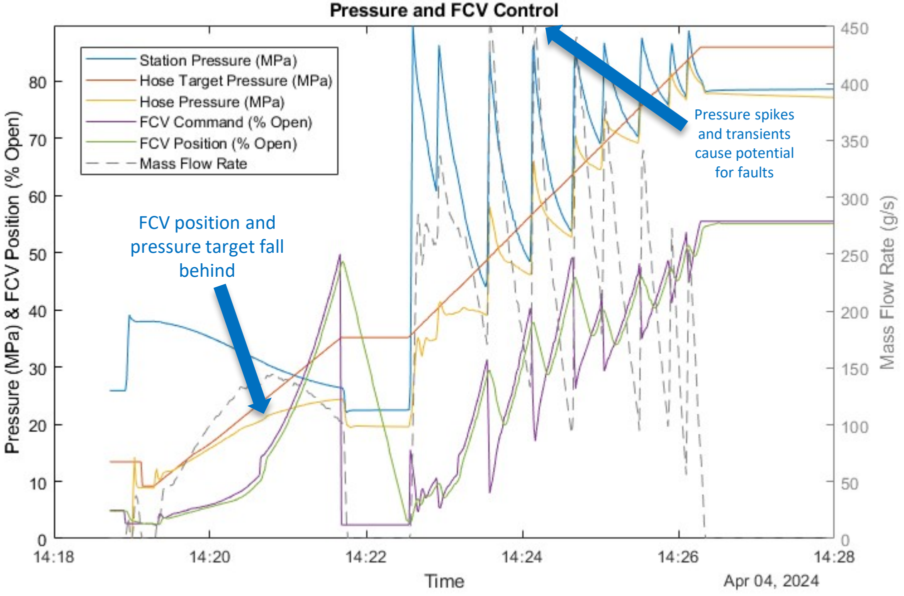


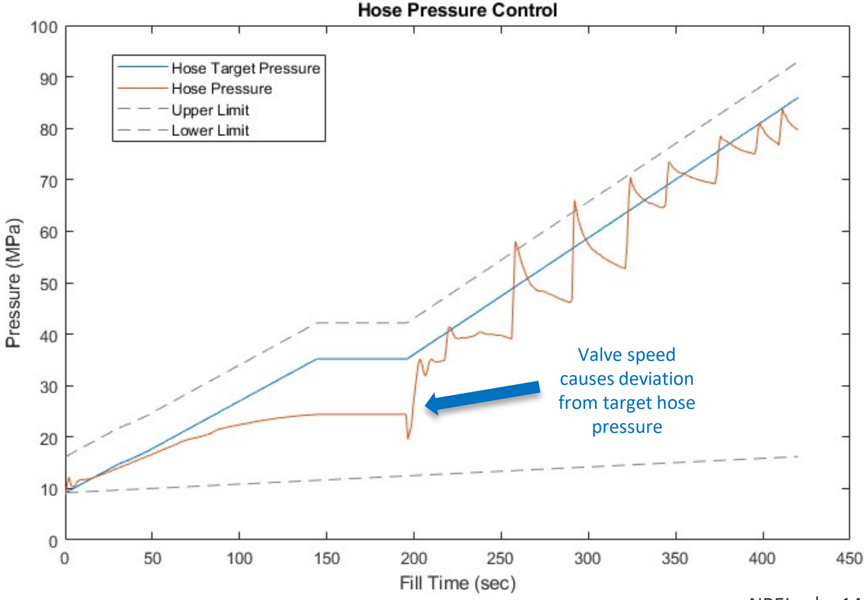


Accomplishment: Hardware (HD Fueling Hardware & Protocols)

NREL is one of the first to fully implement the SAE J2601/5 fueling protocol, a hardware & model validation challenge!

- Current flow control valve technology has major gaps for dynamic response at larger sizes required for HD fast flow.
  - New larger valve designs needed with significantly faster response, reliability, lower cost, and appropriate Cv.
- Validation testing shows that hose pressure slowly deviates from the hose target pressure due to several factors including valve actuation time. This results in the fill time lagging the predicted fill time in the fueling tables.
  - NREL is investigating optimization strategies involving station bank switching, control algorithms, valve position prediction, and pressure drop reduction.
- Pressure spikes observed during fills could cause faults, mitigating causes extended pauses during bank switches due to valve speed.



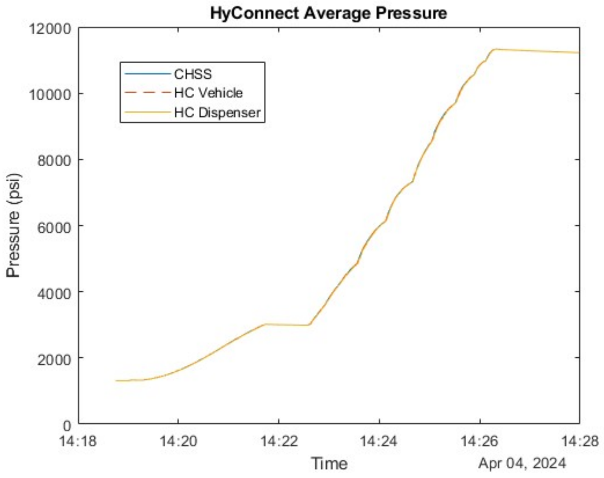


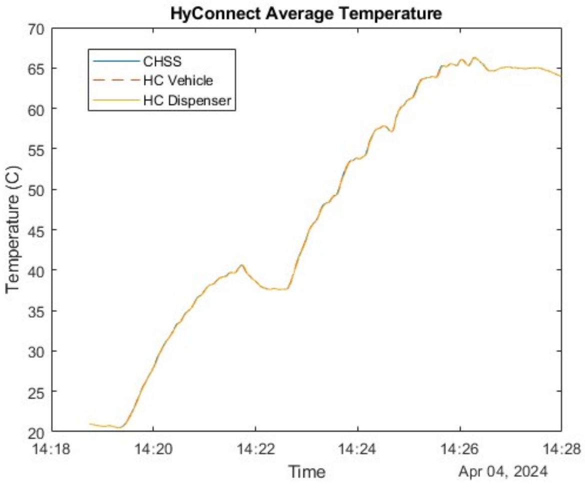
Accomplishment: Hardware (Advanced Communications)

Demonstration of the Shell Techworks HyConnect Advanced Communications Device during Fueling Events.

- HyConnect devices successfully integrated into the NREL HD fast flow fueling facility and established communications between devices.
- The HyConnect modules communicated with the NREL HD dispenser and HD vehicle system using MODBUS/TCP.
- Evaluated both NFC+Wi-Fi and Ethernet-APL solutions over a series of SAE J2601/5 fueling tests with added optional data fields to SAE J2799 (maximum tank volume, max tank temperature, minimum tank temperature, and maximum tank pressure)
- At the end of each fill, static and dynamic data captured by the HyConnect dispenser and vehicle modules were compared against the data transmitted by the NREL systems to confirm their consistency (data loss, lag, and accuracy) – data pending analysis.

HyConnect Test Results during 70 kg Fill (Demonstrating no data loss or lag)



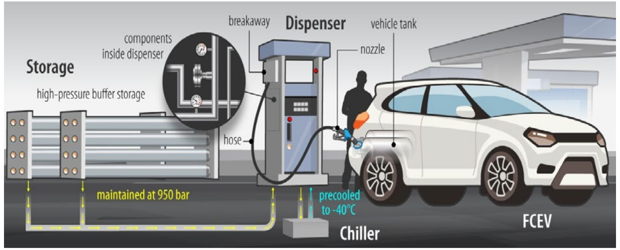


HyConnect Dispenser and Vehicle Modules Installed at the NREL HD Fast Flow Facility

Modeling Subtask

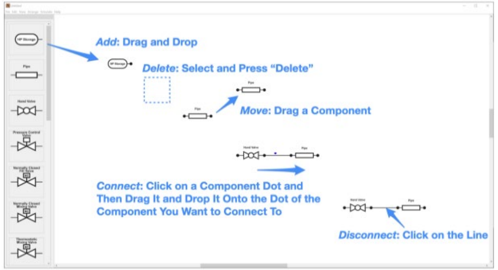
Approach: Fueling Model (H2FillS)

Hydrogen Filling Simulation (H2-FIllS)

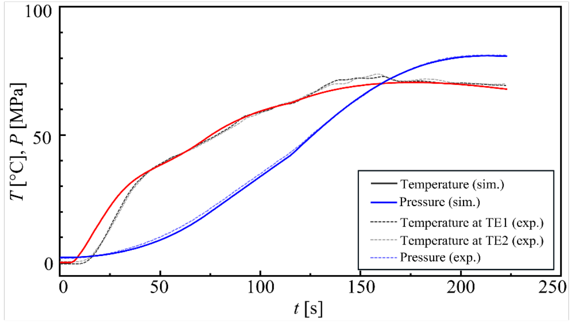


https://www.nrel.gov/hydrogen/h2fills.html

(1) Modeling of station fueling line



(2) Fueling simulation



Release of two versions of hydrogen filling simulation (H2FillS) models

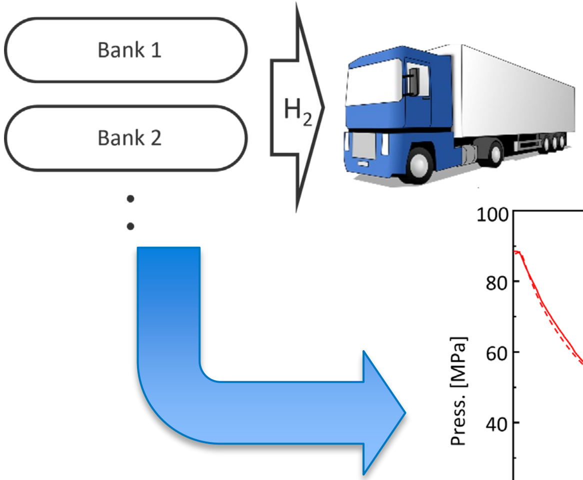
- Holistic model (target section: station high-pressure storage system → HD truck CHSS)
  - Enables the evaluation of the impact of individual station fueling components on the fueling performance.

    (e.g., Evaluation to see if station storage system capacity is sufficient to meet HD fueling protocol requirements)

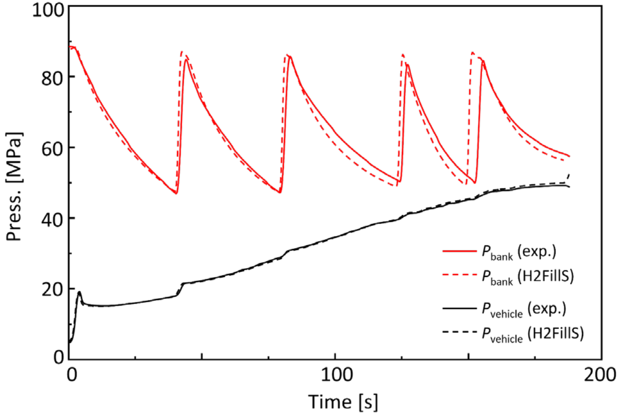
- Partial model (target section: dispenser → HD truck CHSS)
  - Enables the evaluation of interactions between the dispenser and truck

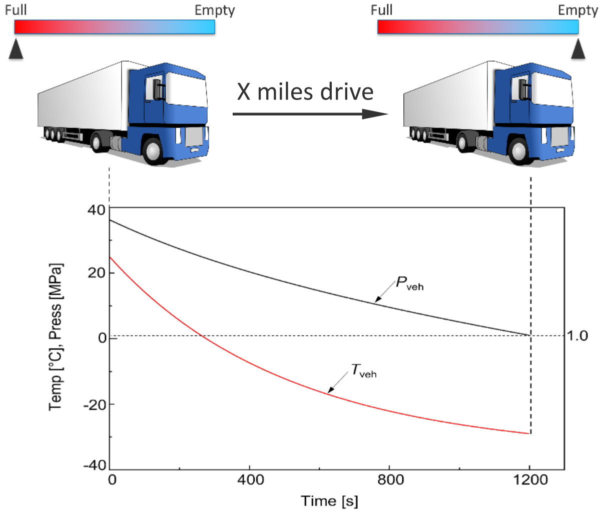
    (e.g., Evaluation how the precooling temperature impacts the temperature rise in the truck storage system).
  - Assist in the development of MD/HD fueling protocols (i.e., SAE J2601-5, PRHYDE, etc.).

Approach: Fueling Model (H2FillS)

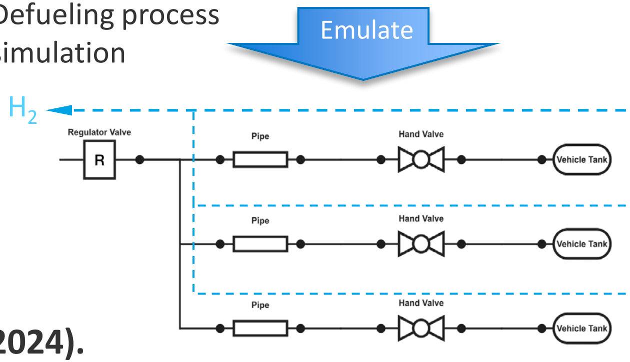


High-pressure bank utilization process simulation





Defueling process simulation



Holistic version: Under development (expected release: Spring 2024).

- The station storage bank utilization process can be simulated, which provides:
  - How quickly the temperature and pressure decrease.
  - How often bank switching needs to be taken place.

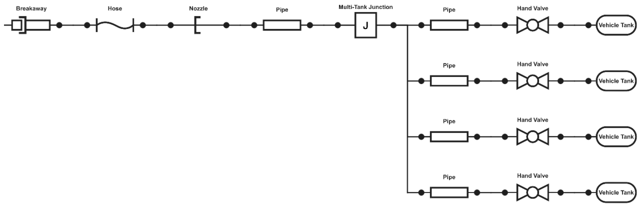
Partial version: Completed beta testing with partners (expected release: Spring 2024).

- The defueling process of an HD truck storage system can be simulated.

Accomplishment (1): Fueling Model (H2FillS)

SAE J2601-5

(1)



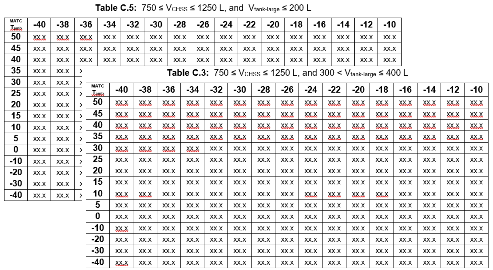
Worst-case fueling system

(2)

NATIONAL RENEWABLE ENERGY LABORATORY

&

(3)



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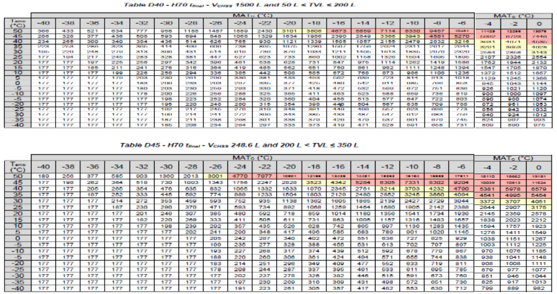
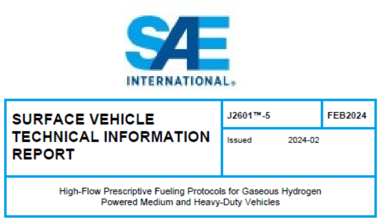




The fueling table generation capability successfully helped SAE J2601-5 publish MD/HD HF fueling protocols.

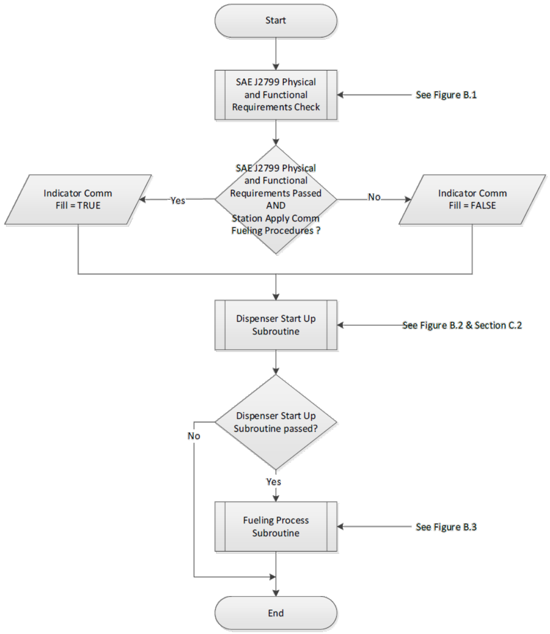
(1) SAE J2601-5 developed worst-case fueling systems (e.g. large pressure drop and thermal mass).

(2) The fueling systems were incorporated into H2FillS integrated with NREL's high-performance computing system (HPC).

(3) The NREL team generated the t-final fueling tables on the HPC.

(4) The tables were reflected in the SAE J2601-5 fueling protocol document published on Feb 24, 2024.

Approach & Accomplishment: Fueling Protocol Modeling and Validation



Overview of MC Formula method (SAE J2601-5 fueling protocol)

(1)

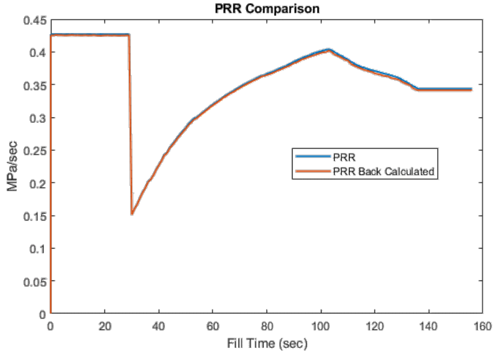
```
double MCFormula(int PressCategory, double CHSS, double TVL, double Time, double Tamb, double Pinitial, double MFRdisp,
    double Tdisp, double Pdisp, double MATexpected, double PRRmax, double PRRmin, double PRRprev)
{
    get_tfinal_table(PressCategory, Tamb, CHSS, TVL);
    tfinal_a = 1.0;
    tfinal_b = (Pfinal - Pmin) / (Pfinal - Pmin - 7.0);
    Ptrans = 0.5 * (Pfinal + Pinitial);
    MAT_a = MFRdisp;
    MAT_b = MAT_a * Tdisp;
    if (Time > 1)
    {
        MAT0_a_summation = MAT0_a_summation;
        MAT0_b_summation = MAT0_b_summation;
        if (Time >= 30)
        {
            MAT30_a_summation = MAT30_a_summation;
            MAT30_b_summation = MAT30_b_summation;
        }
    }
    else
    {
        MAT0 = MAT30 = MATexpected;
    }

    if (Time <= 30) {
        MAT = MATexpected;
    }
    else if (Time > 30 && Ptrans > Pdisp)   {
        MAT = MAT30;
    }

    //*************************************************************
    //        Validtion of MC Formula pressure ctonrol logic
    //*************************************************************
    get_tfinal(Tmat:MAT - 273.15 + 1.0E-4);
    if (tfinal_sec * (Pfinal - Pinitial) / (Pfinal - Pmin) - Time > 10.0 && Pdisp < 0.99 * Pfinal)  {
        PRR = (Pfinal - Pdisp) / (Time * (Pfinal - Pmin) / (Pfinal - Pmin) - Time);
    }
    else {
        PRR = PRRprev;
    }
    tfinal_a = (100.0 + 18.5 * (PRRmax - PRRmin)) / 100.0;
    return PRR;
}

int main(int argc, char* argv[])
{
    //getPRR(0:H35 1: H70, CHSS [L], Maximum tank volume among CHSS [L], ,
    //Initial HDVS pressure [MPa], Mass flow rate [g/s], Hose temperature [K], Hose pressure [MPa],
    //Minimum pressure ramp rate [MPa/s], Prevous pressure ramp rate);
    //All the parameters after the initial HDVS pressure needs to be updated every time this function is executed.
    MCFormula(PressCategory:1, CHSS:244.0*4, TVL:244.0, Time:13.0, Tamb:20.0, Pinitial:3.6, MFRdisp:60.0, Tdisp:15.0 + 273.15,
        Pdisp:15.0, MATexpected:-20.0 + 273.15, PRRmax:0.0, PRRmin:100.0, PRRprev:0.1);
    return 0;
```

(2)



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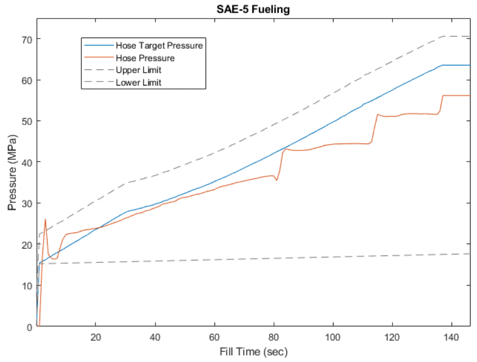


SAE J2601-5 protocol implementation for protocol validation at NREL's HD station

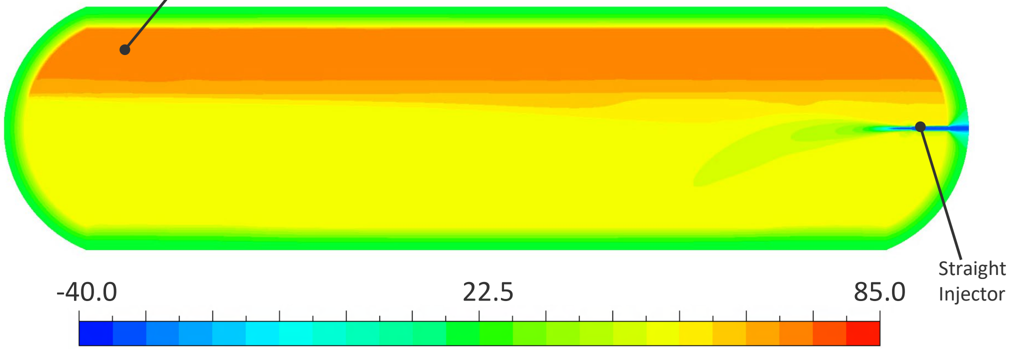
(1) The HD version of the MC Formula method was incorporated into a C++ code.

(2) The MC Formula code was integrated with the NREL HD dispenser and SAE J2601-5 fueling was performed.

(3) Verified that the SAE J2601-5 fueling was controlled based on the MC Formula control logic.

Approach & Accomplishment: CHSS CFD Simulations

CFD Conditions	Values
T_{amb}	20°C
Initial P_{tank}	5 MPa
1st half PRR (if P_{tank} < 40 MPa) 2nd half PRR (if $P_{tank} \geq$ 40 MPa)	15 MPa/min 3 MPa/min
Ending P_{tank}	80 MPa
Ending SOC	98%



<u>Slow-fill CFD simulation (Approach)</u>

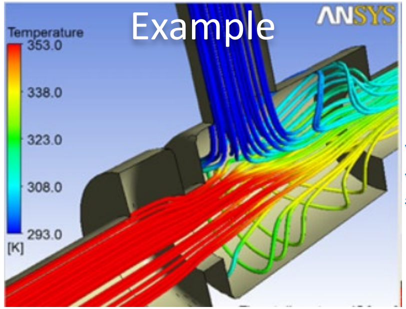
- Reasons the slow-fill CFD simulation is required:
  - NREL limited the minimum pressure ramp rate (PRR) to 7.6 MPa/min for safety reasons (thermal stratification).
  - Fueling protocols cannot be fully validated without slow-fill conditions (i.e., high ambient temperatures).

<u>Slow-fill CFD simulation (Accomplishment)</u>

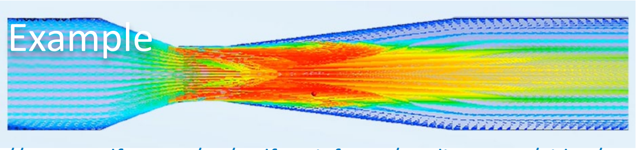
- The slow fill simulation was performed with a Type IV tank and straight injector (see conditions listed in table above).
- Conclusions:
  - Although thermal stratification occurs, the peak hydrogen temperature does not exceed the 85°C limit.
  - If Type IV tanks are initially pressurized under fast-fill conditions, the PRR can be reduced to 3 MPa/min.

Approach & Accomplishment: CFD Modeling with HD Fueling Hardware

Ansys
FLUENT



https://ntu-open-source-20.fandom.com/wiki/MAE-Aerospace_Eng-Ansys_Fluent



https://www.cadfem.net/en/cadfem-informs/media-center/video/no-37-fluid-mechanical-simulation-of-a-venturi-tube-with-ansys-fluent.html

HD fueling hardware CFD modeling (Approach)

- 3D CFD models will be built based on the geometry information provide by the manufacturer.
- The HD fueling hardware CFD models are run to evaluate its pressure drop and heat transfer characteristics.

HD fueling hardware CFD modeling (Accomplishment)

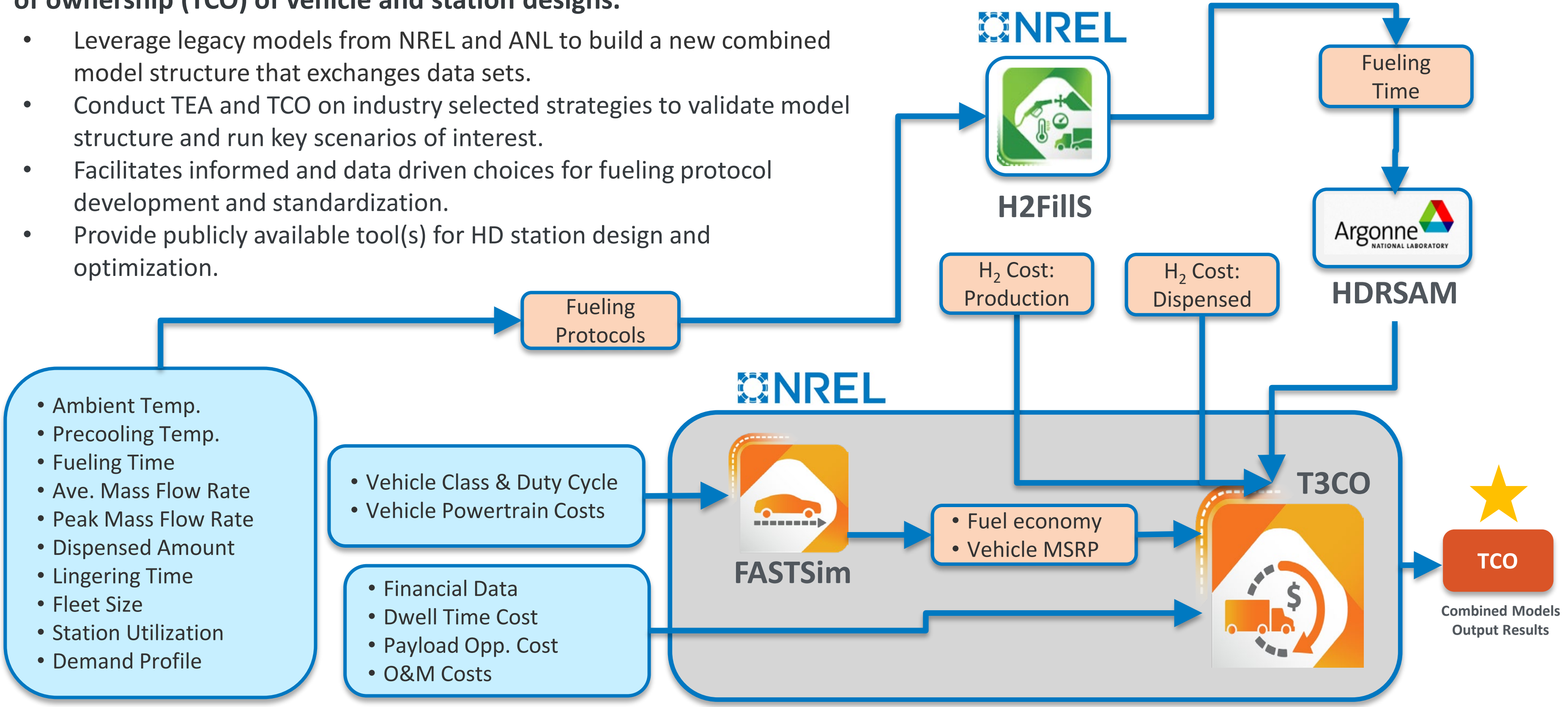
- 3D CFD models will be built and then run on NREL's HPC system when geometry information is received.
- Agreements pending on information sharing between NREL and manufacturer.

Analysis Subtask

Approach: Analysis (TEA/TCO)

Develop a suite of modeling tools to inform how fueling protocol design effects the total cost of ownership (TCO) of vehicle and station designs.

- Leverage legacy models from NREL and ANL to build a new combined model structure that exchanges data sets.
- 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.



Approach: Analysis (TEA - HDRSAM)

Technoeconomic Analysis for the Effects of Fueling Protocols on HD Stations Cost

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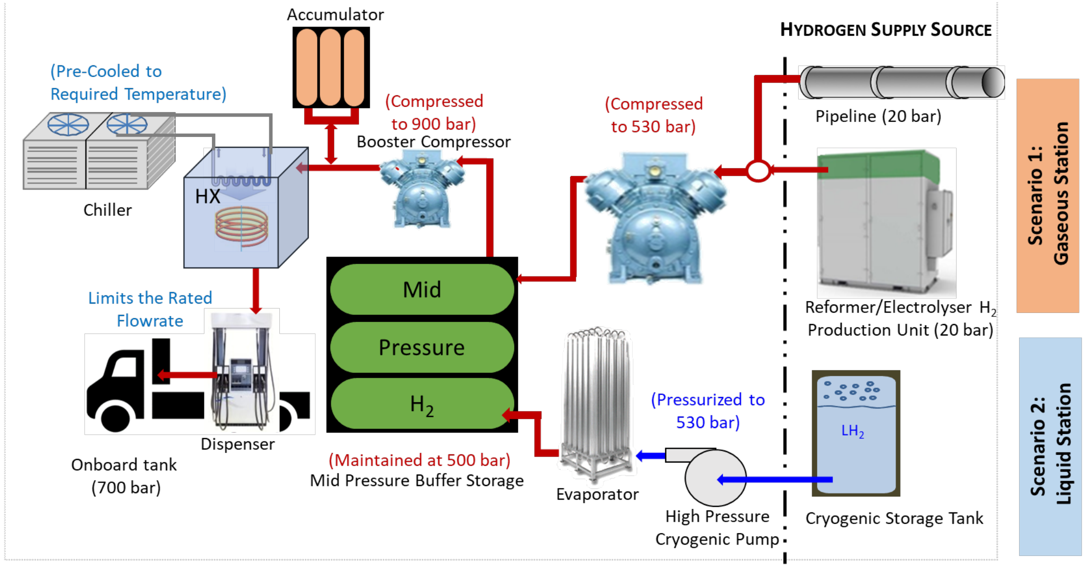
- Heavy-Duty Refueling Station Analysis Model (HDRSAM) is an MS Excel based techno-economic assessment model for estimating the refueling cost of a fleet of heavy-duty hydrogen vehicles for various fueling station configurations and demand profiles.
    - https://hdsam.es.anl.gov/index.php?content=hdrsam
- Cost data is broken down by station component (Compressor, Storage, Dispenser, Refrigeration, Electrical, and Controls/Other).
- HD fueling protocols used as inputs (fueling time, mass flow rate, etc.) from HD-H2FillS:
    - SAE J2601/5
    - EU PRHYDE
- Industry partners identified key metrics for station configurations to perform analysis:
    - Liquid and gaseous bulk gas storage hydrogen stations dispensing at 700 bar gaseous.
    - Fill amount, fleet size, demand profile, ambient temperature, precooling temperature, lingering time, etc.



HDRSAM Station Configurations (Liquid and Gaseous Hydrogen Supply)

Approach: Analysis (TEA - HDRSAM)

HDRSAM Model Assumptions - Station Parameters & Configuration

Argonne NATIONAL LABORATORY

- Industry supplied metrics and assumptions:

Fill Amount	Fueling Pressure	Station Supply Pressure	Station Utilization	Fleet Size	Demand Profile	Station and Fueling Parameters	Ambient Temp (°C)	Precooling Temp (°C)	Lingering Time (min)	Station Type
60 kg	700 bar	20 bar	100%	20 40 100	Single 10hr Double 5hr	T-static T-initial T-throttle SAE J2601-5	40 °C 10 °C	- 40 °C - 20 °C	5 min 10 min	Gaseous Liquid

- A sample set of fueling protocol parameters for 40°C ambient and -40°C precooling used as inputs to HDRSAM model.

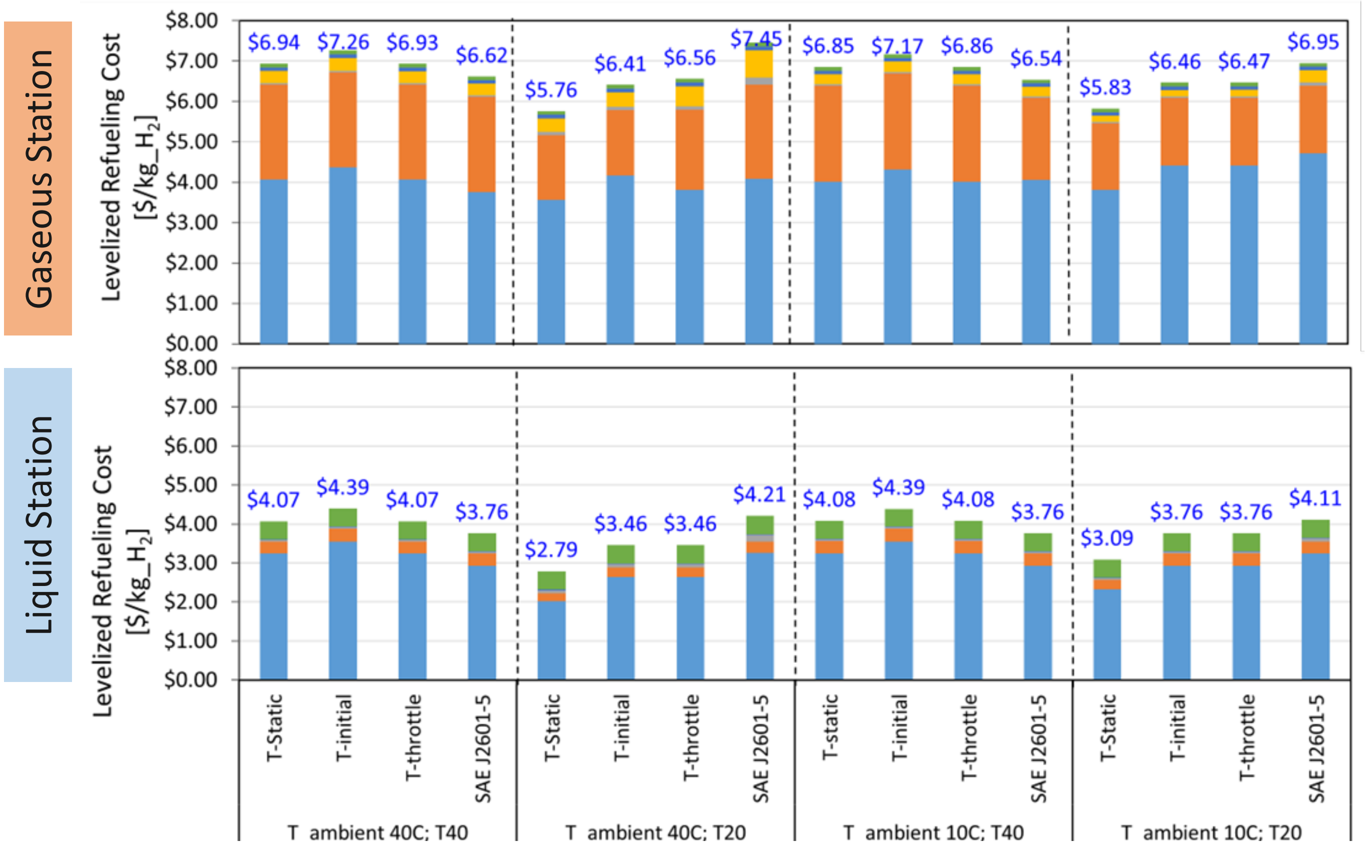
Ambient Temp (°C)	Max Dispensing Temp (°C)	Fueling Protocol	Average Flow (kg/min)	Peak Flow (kg/min)	Fueling Time (min)	Lingering Time (min)	# of Hoses		
							20 Fleet	40 Fleet	100 Fleet
40	-40	T-Static	12.3	16.8	4.9	5.0	1	1	2
		T-initial	14.1	19.2	4.3	5.0	1	1	2
		T-throttle	12.2	15.9	5.0	5.0	1	1	2
		SAE J2601-5	11.0	15.7	5.5	5.0	1	1	2

- Two hourly fueling profiles, (i) One 10-hour fueling window and (ii) Two 5-hour fueling windows.

Hour of day		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Single 10 hour window	20 Fleet	2	2	2	2	2	2	2	2	2	2	0	0	0	0	0	0	0	0
	40 Fleet	4	4	4	4	4	4	4	4	4	4	0	0	0	0	0	0	0	0
	100 Fleet	10	10	10	10	10	10	10	10	10	10	0	0	0	0	0	0	0	0
Double 5-hour windows	20 Fleet	2	2	2	2	2	0	0	0	0	0	0	0	2	2	2	2	2	0
	40 Fleet	4	4	4	4	4	0	0	0	0	0	0	0	4	4	4	4	4	0
	100 Fleet	10	10	10	10	10	0	0	0	0	0	0	0	10	10	10	10	10	0

Accomplishment: Analysis (TEA - HDRSAM)

HDRSAM Model Results – Effect of Fueling Protocol on Station Cost



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Parameter	Value
Fleet Size	40
Fueling Profile	Single 10hr
Lingering Time	5 min

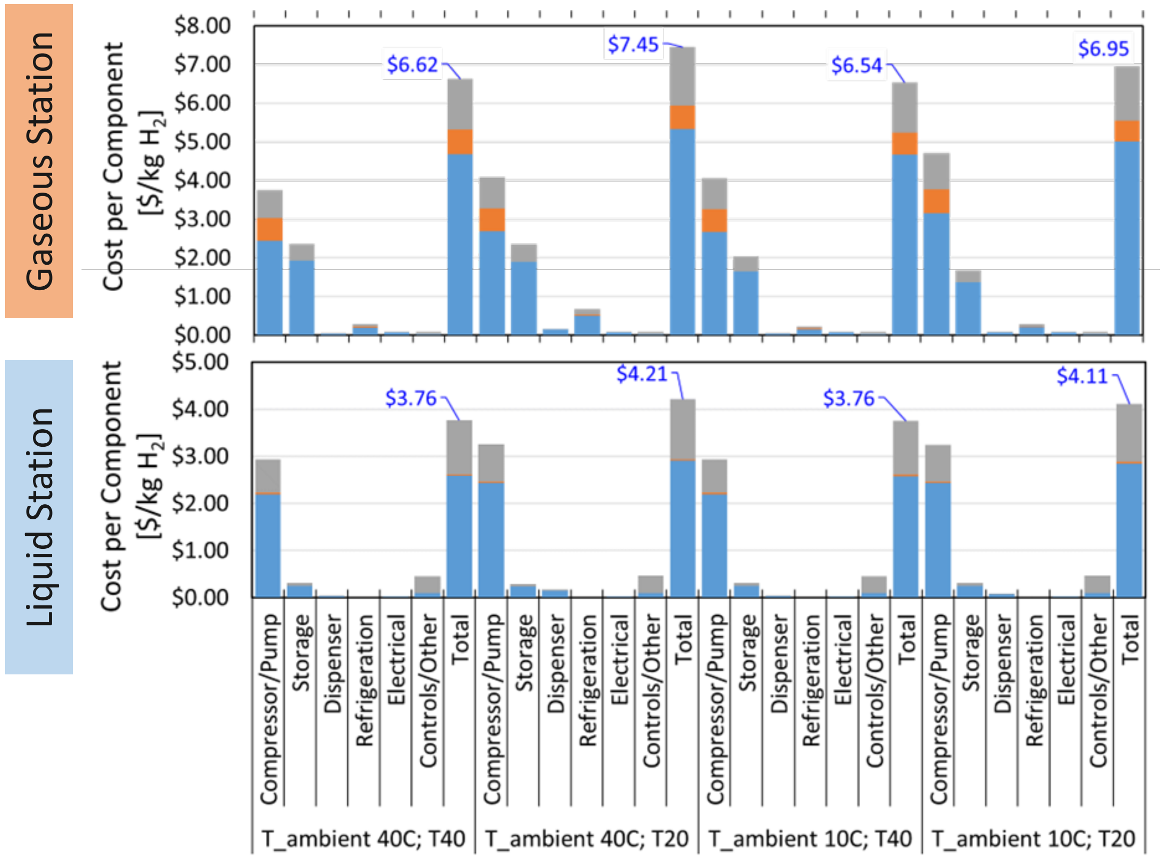
Legend

- Controls/Other
- Electrical
- Refrigeration
- Dispenser
- Storage
- Compressor/Pump

Levelized refueling cost is influenced by the fueling protocols.

Accomplishment: Analysis (TEA - HDRSAM)

HDRSAM Model Results – Cost Contribution of Station Components (SAE J2601-5 Example)



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Parameter	Value
Fueling Protocol	SAE J2601-5
Fleet Size	40
Fueling Profile	Single 10hr
Lingering Time	5 min

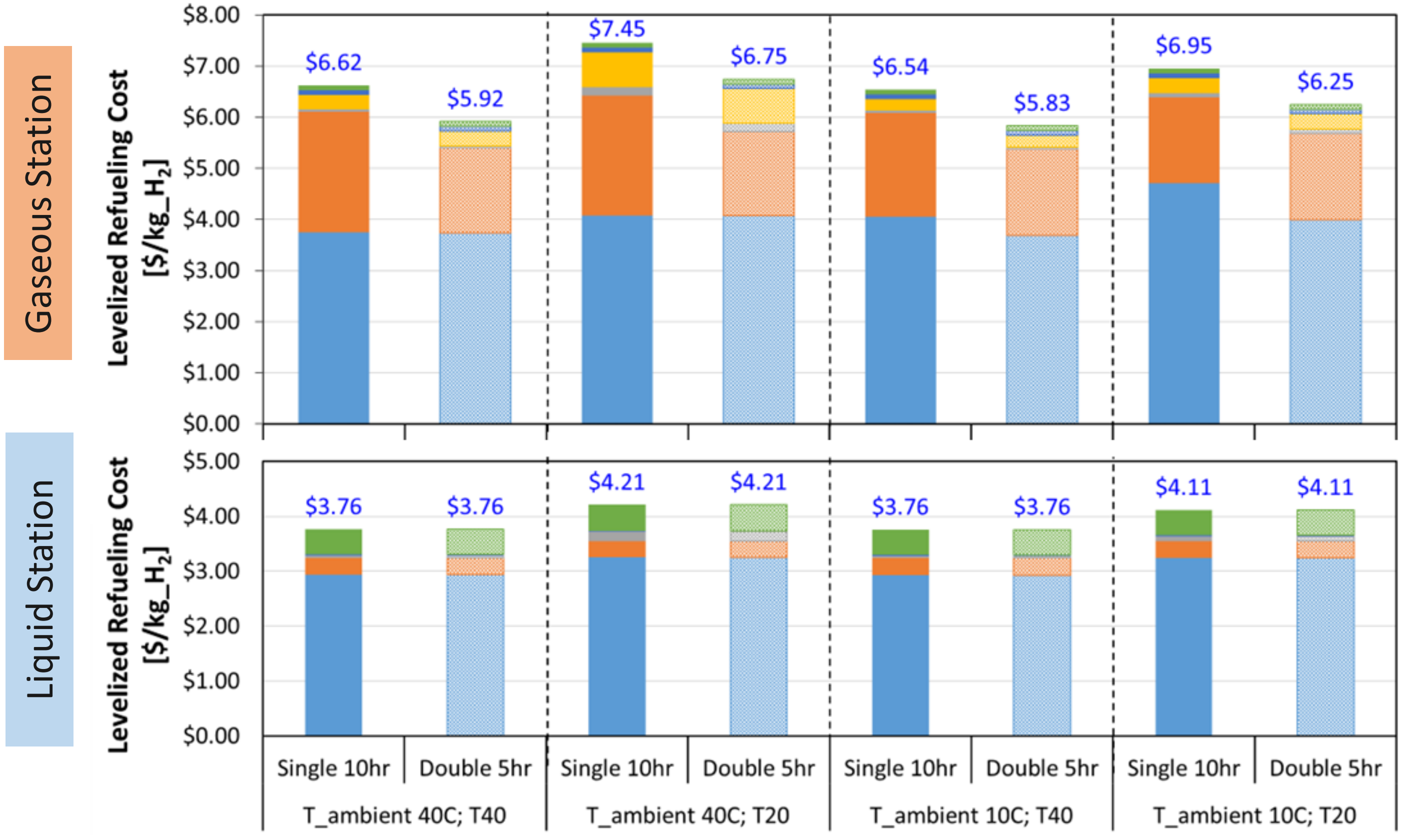
Legend

- Other O&M [$/kg_H2]
- Energy/Fuel [$/kg_H2]
- Capital [$/kg_H2]

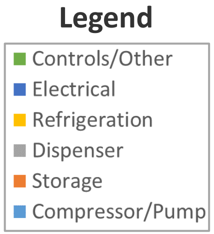
The refueling cost depends on the individual contributions of different station components.

Accomplishment: Analysis (TEA - HDRSAM)

HDRSAM Model Results – Effect of Station Demand Profile (SAE J2601-5 Example)



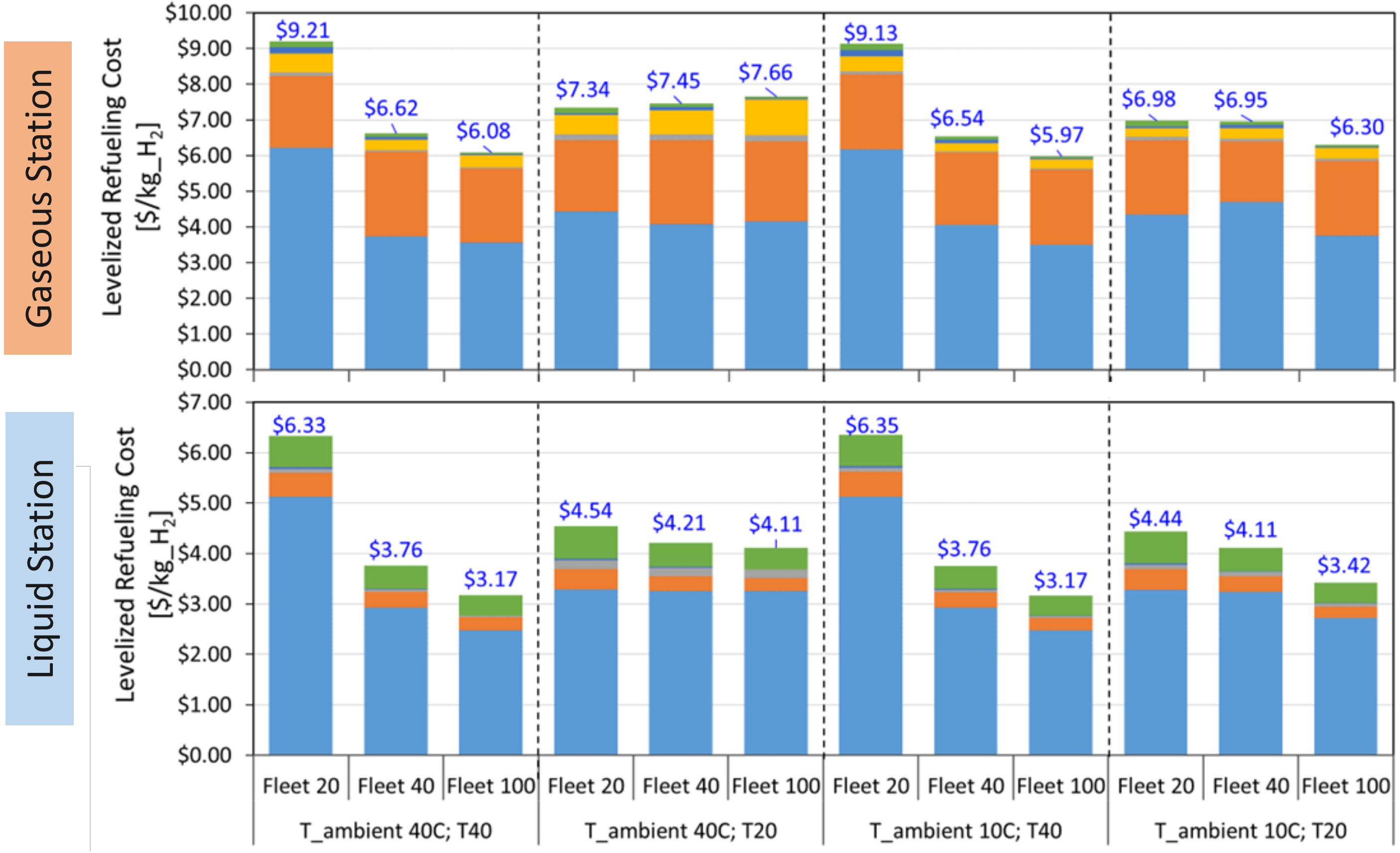
Parameter	Value
Fueling Protocol	SAE J2601-5
Fleet Size	40
Lingering Time	5 min



Distributed station usage has significant effect on gaseous station.

Accomplishment: Analysis (TEA - HDRSAM)

HDRSAM Model Results – Effect of Fueling Protocol on Station Cost (SAE J2601-5 Example)



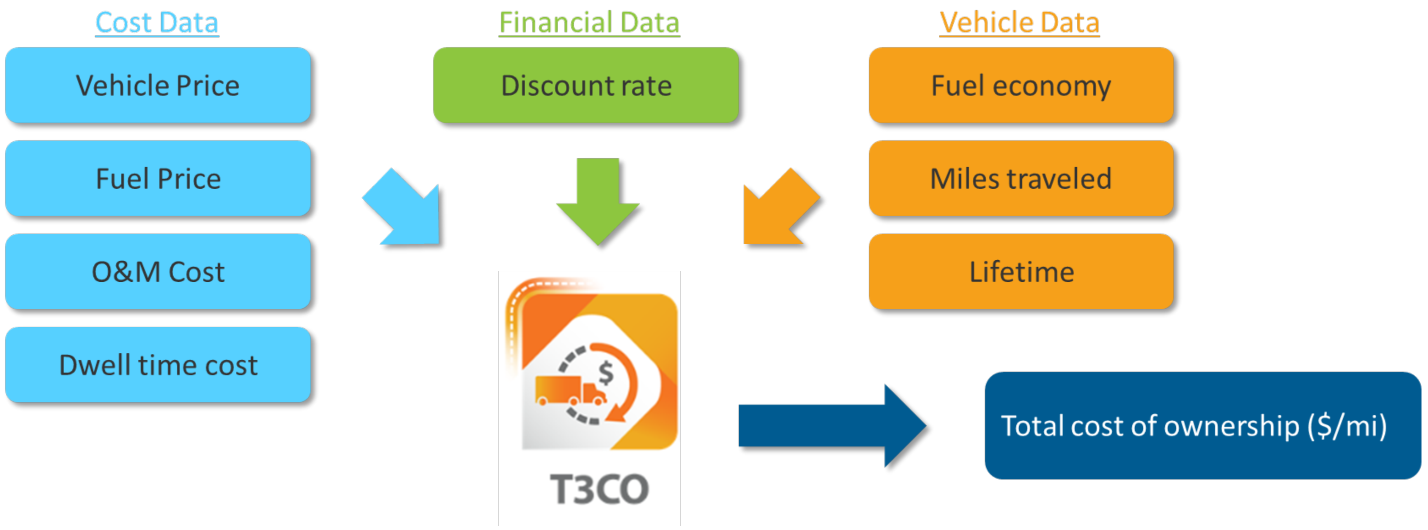
Parameter	Value
Fueling Protocol	SAE J2601-5
Fueling Profile	Single 10hr
Lingering Time	5 min

Levelized refueling cost decreases exponentially with the increase in the fleet size.

Approach: Analysis (TCO - NREL)

Total Cost of Ownership Analysis using T3CO

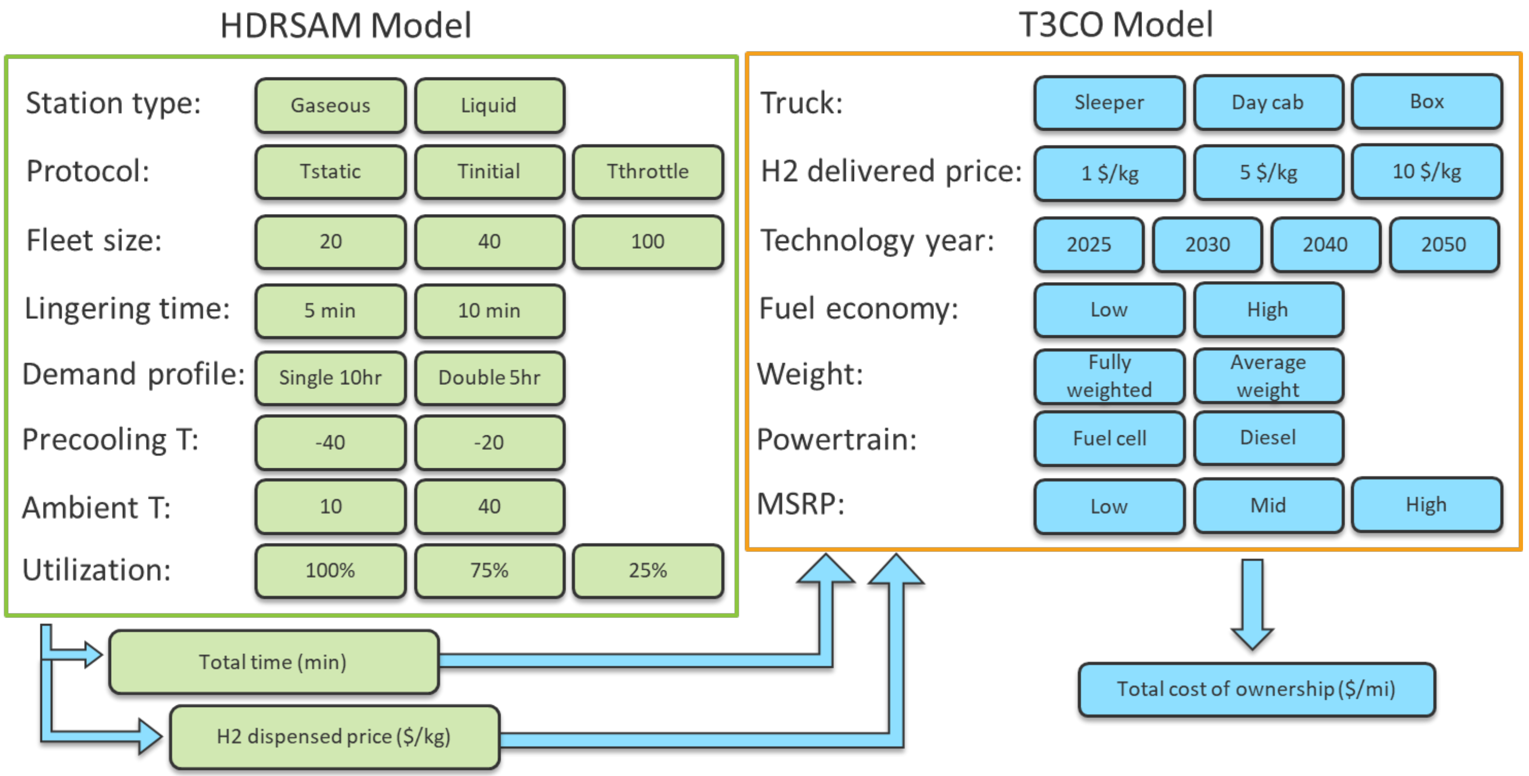
- Transportation Technology Total Cost of Ownership (T3CO) is a Python based techno-economic assessment model for estimating the total cost of ownership (TCO) of vehicles.
    - https://www.nrel.gov/transportation/t3co.html
- T3CO evaluates the total cost of ownership for various vehicle classes and technology improvement trajectories.
- The T3CO model includes the station refueling cost from HDRSAM to determine the fuel cost.
- Class 8 sleeper, day cab, and box truck were primarily considered based on project scope and industry partner feedback.



Approach: Analysis (TCO - NREL)

Model Variables Supplied from HDRSAM and Industry

- The HDRSAM model feeds into T3CO to understand both station and vehicle sensitivities



Approach: Analysis (TCO - NREL)

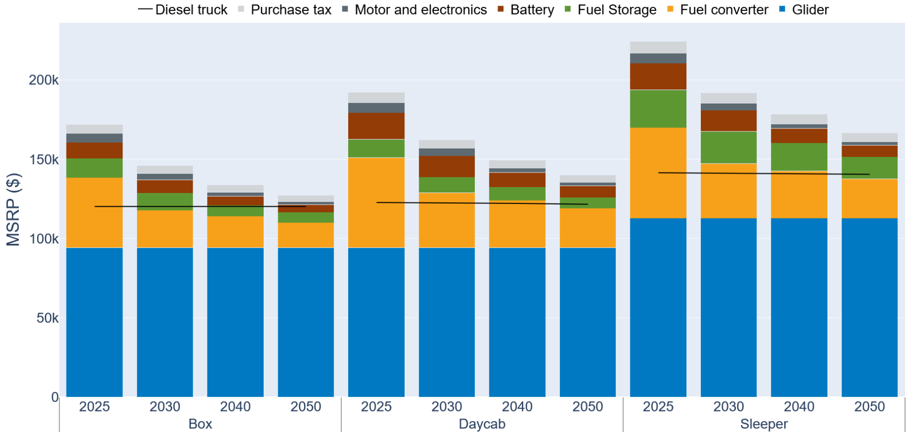
Total cost of ownership incorporates forecasted HD hydrogen truck cost data from multiple sources.

- Forecasts for vehicle costs is informed by models, literature, surveys, and DOE MYRD&D.
- Includes cost and performance targets for technology specific components from 2025 to 2050.
  - Fuel cell power, cost, and efficiency
  - Storage cost
- **MSRP:** Manufacturer's Suggested Retail Price
- **GVWR:** Gross Vehicle Weight Rating

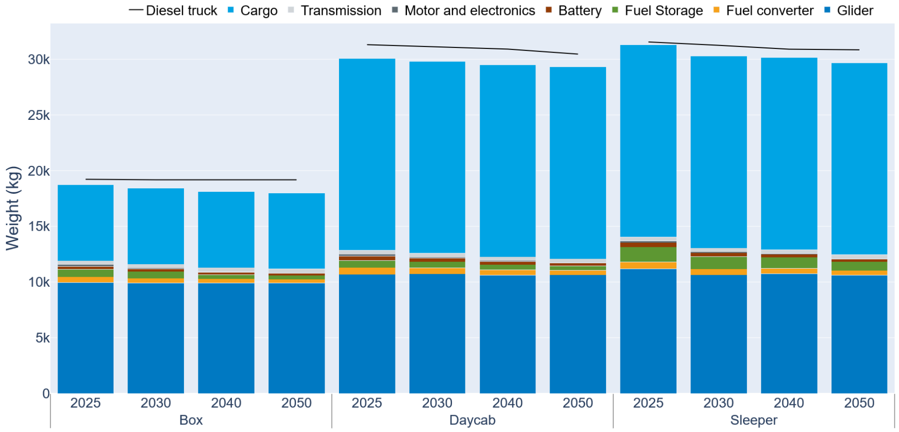
Cost Targets For Class 8 Sleeper Truck

Technology Year	2025	2030	2040	2050
Fuel Cell Power (kWh/kg)	0.7	0.8	0.9	1.0
Fuel Cell Cost ($/kW)	130	80	70	60
Fuel Cell Peak Efficiency	0.64	0.68	0.70	0.72
H_2 Storage Cost ($/kWh)	10	9	8.5	8

MSRP Forecast of Fuel Cell Electric Truck by Cab Type and Technology Year

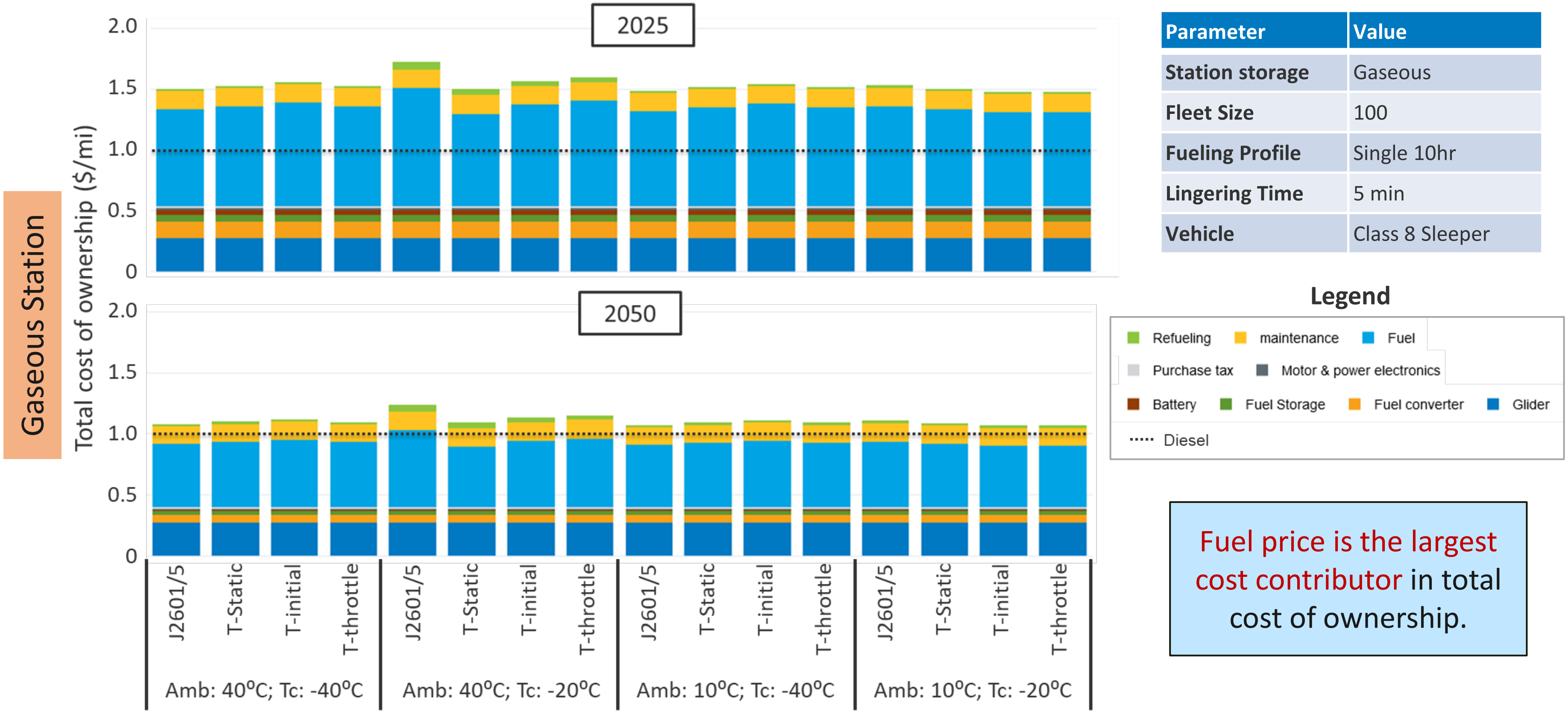


Fuel Cell Electric Truck GVWR by Cab Type and Technology Year



Accomplishment: Analysis (TCO - NREL)

Total Cost of Ownership Results for Class 8 Trucks at Gaseous Storage Fueling Stations (700 bar gaseous dispensed)

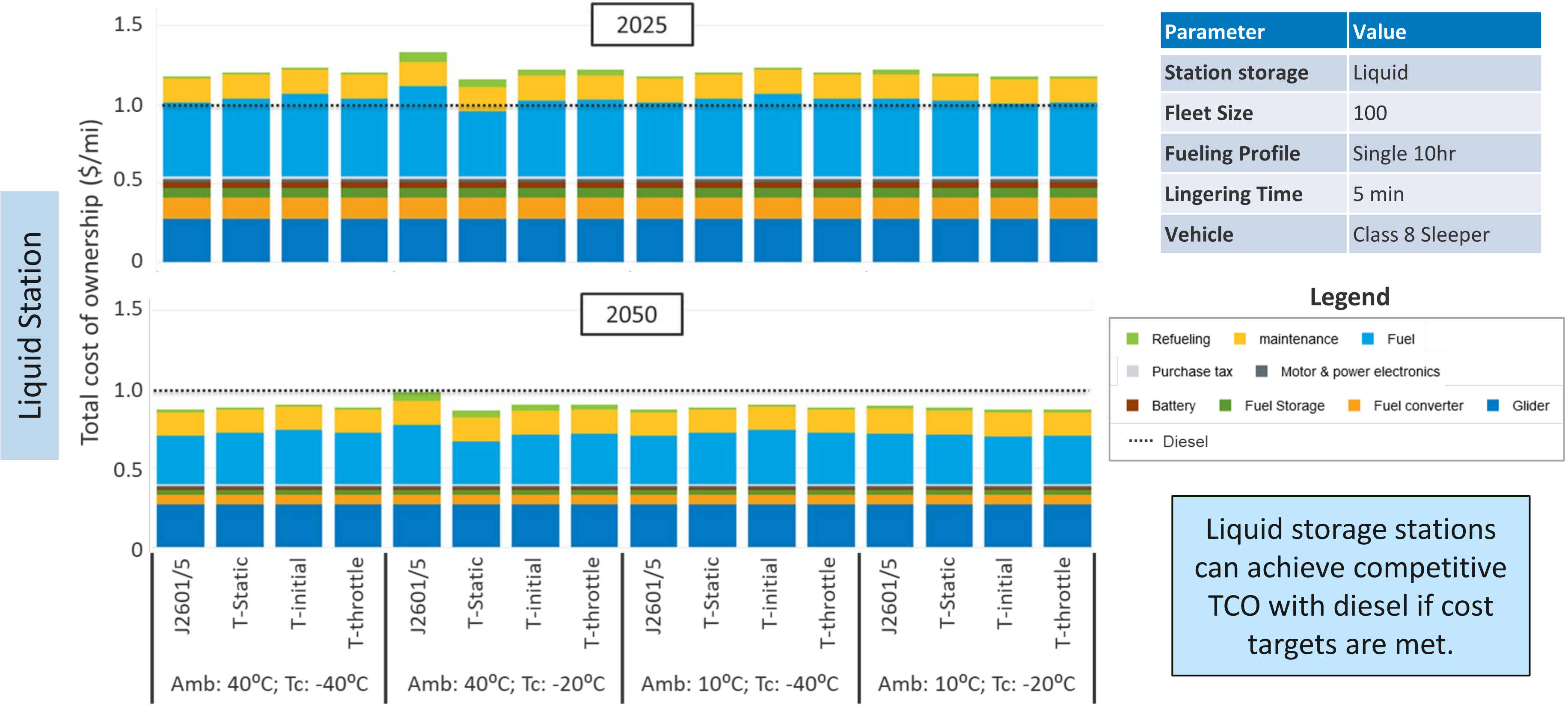


Parameter	Value
Station storage	Gaseous
Fleet Size	100
Fueling Profile	Single 10hr
Lingering Time	5 min
Vehicle	Class 8 Sleeper

Fuel price is the largest cost contributor in total cost of ownership.

Accomplishment: Analysis (TCO - NREL)

Total Cost of Ownership Results for Class 8 Trucks at Liquid Storage Fueling Stations (700 bar gaseous dispensed)



Parameter	Value
Station storage	Liquid
Fleet Size	100
Fueling Profile	Single 10hr
Lingering Time	5 min
Vehicle	Class 8 Sleeper

Liquid storage stations can achieve competitive TCO with diesel if cost targets are met.

Accomplishment: Analysis Summary

Technoeconomic Assessment (TEA) Summary of Results:

- Refueling cost depends on the individual contributions of different station components.
- Station cost difference varies between fueling protocols with the precooling and ambient temperature.
- Levelized refueling cost is ~$2.0-3.8/kg cheaper for liquid hydrogen stations vs. gaseous stations.
- Fueling profiles have a moderate effect (~$0.70/kg) on gaseous stations: constant 10-hr fueling demand is more expensive vs. two separated 5-hr peaks.
  - Liquid station results show no influence due to current data available in the model → liquid pump is oversized for current station usage.
- Levelized cost decreases exponentially as fleet size increases.

Total Cost of Ownership (TCO) Summary of Results:

- Total cost of ownership (TCO) depends on the station cost and the performance of the vehicle.
- Fuel price is the largest contributor to the TCO.
- TCO decreases if FCEV technology achieves proposed targets.
  - Approx. 0.4 $/mile decrease.
- Analysis shows scenarios with long fueling times incur larger fueling cost, but the overall affect on the TCO is minor at < 0.1 $/mi for most scenarios.
  - SAE J2601/5 TCO has a small cost variation compared to PRHYDE, specifically for higher ambient temperature and warmer precooling conditions (40^{o}C ambient, -20^{o}C precooling).

Accomplishments and Progress: Response to Previous Year Reviewers' Comments

Comment 1: The project should consider sharing HD component performance requirements with ISO/TC 197 (beyond WGs 24 and 5) to facilitate development of these requirements. Comment 2: The project should expand collaborations with industry partners and codes and standards bodies to meet objectives.

Responses: NREL, NextEnergy, and industry group partners are active members of the ISO TC/197, with multiple industry group members participating in expert or leadership roles. NREL participates on the SAE Task Force for J2601/5 and was a key contributor to fueling table generation.

- Test data will be shared with ISO working groups 5, 22, and 24 as well as new working groups under 19885-2 and 19885-3.
- The project expanded to include two additional component suppliers and is performing specific testing to accelerate efforts under ISO/TC 197 working groups 5 and 22 (connection devices and hoses).

Comment 3: The project has a great number of partners. NextEnergy is an industry/partner group on its own. It is unclear in the slides how well this group is coordinated and tied into this effort.

Response: The Industry Group participates in weekly internal meetings to manage internal coordination of partners with NextEnergy and monthly CRADA calls with NREL. Active industry members contribute to project scope, specifically Shell HyConnect and SAE/ISO working groups.

Comment 4: Attention is needed to all the details provided by the modeling effort (e.g., the comment about jet impingement). This is easily dealt with simply by coding up the tank material and monitoring the temperature, pressure, and space–time history of the entire system. That will be very instructive.

Response: The CFD modeling work provides the peak hydrogen temperature in any location within the vehicle tank model, which allows us to confirm that the hydrogen temperature always stays below the 85°C upper limit even if the injector jet impinges and stagnates on the tank material.

Comment 5: A recommendation is to code up the tank material, along with the gas phase, and calculate the temperature, pressure, and space–time history throughout the filling process. That will prove to be very interesting. Having a complete validated computational package in the United States will be very valuable.

Response: NREL confirmed the temperature deviation between the hydrogen and liner material under fast- and slow-fill conditions because the CFD modeling works enables us to monitor the hydrogen and tank material temperatures. The liner temperature was confirmed colder than gas by at least 10 Kelvin.

Comment 6: Liquid hydrogen onboard solutions are ideal for semi-truck applications. A liquid hydrogen fueling protocol and the associated hardware will be a barrier for the industry. Addition of this scope is recommended to support adoption of fuel cell electric semi-trucks.

Response: The project scope did not include liquid hydrogen fueling and NREL does not currently have liquid hydrogen fueling test capabilities.

Collaboration and Coordination

- **Industry:** NextEnergy, Chevron, & Argonne National Lab
  - Weekly hardware/modeling meetings
  - Monthly progress updates
  - Provide feedback on technical approach
  - Annual on-site visits to NREL and partner facilities
- **International:** EU and Japan
  - **EU Protocol for Heavy-Duty Hydrogen Refuelling Project**- NREL admitted as a technical expert
  - **ISO TC/197 Working Groups 5, 22, and 24** – NREL/NextEnergy admitted as a technical experts
  - **SAE J2601/5 Task Force -** NREL admitted as a technical expert and key contributor
  - **NEDO/JARI** - Coordination on CFD work
  - **Kyushu University** - Continued collaboration on H2FillS
- **Component Suppliers:** Tatsuno, Parker, WEH, and Staubli
- **DOE HFTO Workshops, meetings, and webinars (H2IQ):** Presentations and contributions as requested
- **Release of public modeling tools from National Labs:** H2-FillS, HDRSAM, and H2FAST

Remaining Challenges and Barriers

Challenge/Barrier	Solution
Delayed installation and commissioning of industry supplied fueling hardware could result from supply chain constraints (of peripheral components) or unexpected component failures.	The project team has worked to place orders for long lead time components and spare parts in-advance of test schedules. Two sets of each industry component were provided to mitigate the risk of failure and delays.
Potential for current flow control technology to not meet performance requirements demanded by new fueling protocol concepts.	This issue remains and industry wide technology gap. NREL is working with valve manufacturers to provide more dynamic and robust solutions for HD fueling applications. Evaluations of new valve designs is currently being investigated (Parker & Fujikin).
Lack of accurate cost data to provide as inputs to the TEA and TCO models for heavy-duty hydrogen station components that currently do not exist or are under development.	The analysis team is working closely with industry partners to obtain updated cost data for modeling efforts, as available. The team is leveraging DOE MYRD&D plans and cost data from parallel DOE projects and efforts (Strategic Analysis, ANL, etc.).
Public release schedule delays for full TEA/TCO model structure due to individual development schedules of models (maintained under their own unique projects/programs).	The analysis team created a public facing website to display the results of the TEA/TCO analysis (pending release). The results are displayed in a configurable way so that partners can interact with the data without having to run the individual models.

Proposed Future Work

Hardware:

- Evaluate additional advanced HD fueling protocols with industry supplied HD fueling components under the developed hardware test plan.
- Perform fast flow tests with commercial ready HD dispenser systems (Bennett Pump Co. or others).
- Inform codes and standards working groups, industry partners, and DOE on performance data and technology gaps to facilitate/expedite fueling protocol and component standardization.

Modeling:

- Validate HD-H2FillS against new HD fueling data and integrate liquid hydrogen station storage capabilities for release to the public.
- Conduct CFD analysis on industry supplied fueling components to assess pressure drop and heat transfer characteristics to inform fueling protocol and codes and standards development.
- Provide feedback to SAE (or other fueling protocols) regarding suggested modifications to the protocols or fueling tables.

Analysis:

- Perform iterations of techno-economic assessments (TEA) and total cost of ownership (TCO) based on industry selected inputs and factors. Specifically, integrate NREL's Scenario Evaluation and Regionalization Analysis (SERA) tool to the overall model structure.
- Release a combined model structure for public use when all modeling tools are ready for deployment.

Note: Any proposed future work is subject to change based on funding levels.

Summary

Hardware:

- Implemented station hardware improvements, controls, and conducted safety analysis to install industry supplied fueling components for testing.
- Evaluated refueling hardware with new HD fast flow fueling protocols and advanced communications concepts to assess performance, reliability, usability, and characterizations data.
- Identified key technology gaps that must be addressed for commercial deployment of HD fueling infrastructure.
- Informed codes and standards organizations on project progress (i.e., SAE J2601/5, FCH-JU PRHYDE, ISO TC 197 Working Groups 5, 22, and 24). Negotiated new project scope to test fueling hardware for ISO working groups to accelerate decision making processes.

Modeling:

- Modified H2FillS for heavy-duty applications, fueling protocols, and verified model accuracy with fast flow fueling data.
    - Modifications included fueling protocol implementation and fueling table derivation.
- Performed numerous CFD simulation runs on hydrogen tanks that informed research and fueling protocol decisions.

Analysis:

- Utilized the combined model structure to perform TEA and TCO on industry identified metrics and scenarios.
- Performed sensitivity analysis on two HD fast flow fueling protocols (SAE J2601/5 and PRHYDE) to investigate the affects on station design, station cost, and vehicle cost.
- Established a baseline strategy for displaying the model results on a public website and planned release to partners.

Thank You

www.nrel.gov

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