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# Assessment of Heavy-Duty Fueling Methods and Components—Modeling and Analysis

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**Technical Report**
NREL/TP-5400-91062
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# List of Acronyms

| | |
|---|---|
| ATB | Annual Technology Baseline |
| CHSS | compressed hydrogen storage system |
| FASTSim | Future Automotive Systems Technology Simulator |
| FCEV | fuel cell electric vehicle |
| H2A | Hydrogen Analysis |
| H2FillS | Hydrogen Filling Simulation |
| HD | heavy duty |
| HDRSAM | Heavy-Duty Refueling Station Analysis Model |
| HDVS | Heavy-Duty Vehicle Simulator |
| HP | high pressure |
| HPC | high-performance computer |
| MCF-HF-G | MC Formula High-Flow General |
| MD | medium duty |
| NREL | National Renewable Energy Laboratory |
| P | pressure |
| PCV | pressure control valve |
| PRHYDE | PRotocol for heavy duty HYDrogEn refueling |
| SOC | state of charge |
| T | temperature |
| TEA | technoeconomic analysis |
| T3CO | Transportation Technology Total Cost of Ownership |
| TCO | total cost of ownership |
| VMT | vehicle miles traveled |

# Executive Summary

The goal of the Assessment of Heavy-Duty Fueling Methods and Components project was to comprehensively assess heavy-duty (HD) fuel cell electric vehicle fueling protocols and their effects on techno-economic assessments (TEA) and total cost of ownership (TCO). The project leveraged and built upon ongoing international HD fueling protocols and fueling component development activities to deliver component performance assessments, modeling tools and methods evaluations, TEA of industry-selected protocol structures, and experimental validations of the strategies at the station scale. The effects of the protocols on the fueling times, station costs, and TCO were explored. Fueling time, which was influenced by temperature and protocol selection, had a large impact on the station cost due to component sizing and satisfying hourly demand. As the fleet size increased, the station cost was shown to exponentially decrease by achieving economies of scale. Technology year and fuel economy were the largest contributors to the TCO; however, the choice of fueling protocol had a minor impact on the TCO.

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# 1 Introduction

Medium-duty (MD) and heavy-duty (HD) hydrogen fueling stations utilize fueling protocols to dispense hydrogen into fueling fuel cell electric vehicles' (FCEVs) onboard storage systems. These protocols prescribe the fueling characteristics based on the ambient temperatures, precooling temperatures, and quantity of gas to effectively fill the onboard hydrogen storage subject to flow rate, pressure, and temperature constraints. The implemented protocol influences fueling characteristics, station design, and, ultimately, the total cost of ownership (TCO) of FCEVs. Fast-flow fueling stations and protocols reduce the amount of time trucks spend refueling and allow higher station throughput in comparison to light-duty stations, but the performance increase results in higher equipment and infrastructure costs. For example, fast-flow stations might require upsized bulk hydrogen storage, larger hydrogen precooling systems (i.e. more power consumption), and other advanced infrastructure in comparison to traditional light-duty based stations. Overall, the market for HD FCEVs is relatively immature, so there is an opportunity to analyze the effects that different protocol structures—and the fueling methods within those structures—have on station and vehicle design and cost.

This project assessed the HD fueling protocols by developing and integrating a suite of tools to understand the effects that the protocol architectures, fueling methods, and associated boundary conditions have on the station design, the vehicle design, the associated costs, the functional safety requirements, and the holistic implications of these on the TCO for the HD high-flow fueling of MD/HD FCEVs with 70-MPa storage systems. Figure 1 shows the structure for combining the National Renewable Energy Laboratory's (NREL's) Hydrogen Filling Simulation (H2FillS™) software, Argonne National Laboratory's Heavy-Duty Refueling Station Analysis Model (HDRSAM), and NREL's Transportation Technology Total Cost of Ownership (T3CO) tool to determine the effect of fueling protocols on the TCO. H2FillS provides fueling tables to HDRSAM, which designs the station and calculates the levelized station cost. The levelized station cost is passed to T3CO to determine the TCO.

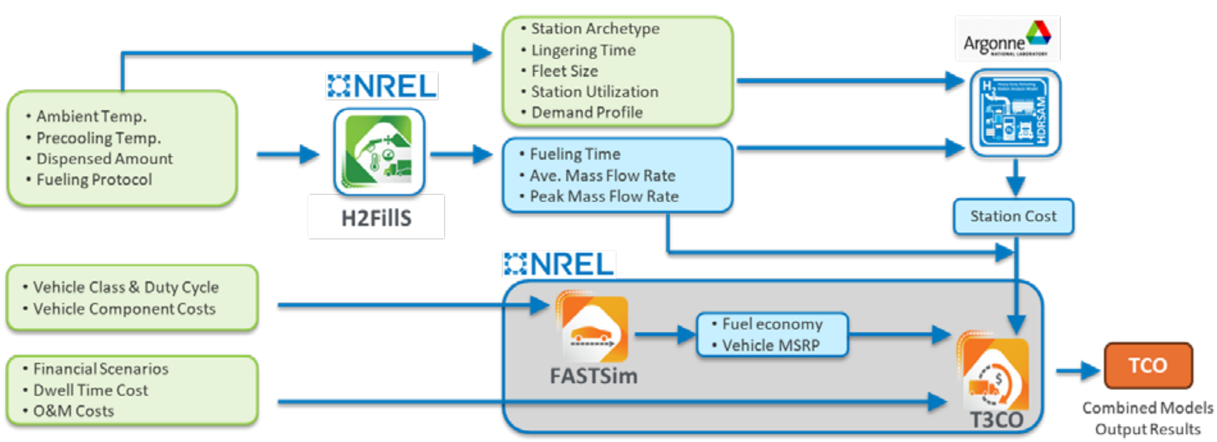


**Figure 1. Structure for combining the analysis models from NREL and Argonne National Laboratory**

*Illustration by Shaun Onorato, NREL*

## 1.1 Protocols

The SAE J2601/5 (SAE International 2024) and EU-PRHYDE (Hart et al. 2023) fueling protocol concepts for heavy-duty hydrogen fuel-cell electric vehicles are applied in this analysis. Both efforts target the development of fueling protocols for heavy-duty fuel cell electric vehicles.

The SAE J2601 protocol has been used since 2010 as the primary global standard for safely refueling light-duty and medium-duty hydrogen vehicles. It uses key assumptions about the vehicle tank system size, pressure, fuel delivery temperature, and ambient conditions to reference a lookup table approach (utilizing a fixed pressure ramp rate) or a formula-based approach (utilizing a dynamic pressure ramp rate continuously calculated throughout the fill). Both methods allow for fueling with communications or without communications from the vehicle to the station. In 2024, SAE released a Technical Information Report (TIR) which established fueling protocols for medium and heavy-duty vehicles with much higher flow rates under J2601/5 TIR. The revised protocol allows for much higher peak flow rates up to 300 g/s with expanded compressed hydrogen storage system volume capacities up to 7,500 L. The document was initially published as a TIR due to limited field testing of the fueling protocols and is expected to be later published as a completed standard.

The EU-PRHYDE project was funded by the European Union Fuel Cells and Hydrogen 2 Joint Undertaking to develop recommendations for heavy-duty hydrogen refueling protocols to support industry standardization efforts. The EU-PRHYDE fueling protocols are prescriptive protocols that build on the same general principles of SAE J2601 by determining a pressure ramp rate strategy based on ambient conditions, fuel delivery temperature, and tank volume, etc., but utilize a much more dynamic approach to optimize the fueling process by relying on information being transmitted continuously from the vehicle storage tanks to the station. There are four concepts included in the EU-PRHYDE fueling protocols including T-static, T-initial, T-initial+, and T-throttle. The T-static protocol uses static vehicle information including the compressed hydrogen storage system (CHSS) volume categories and thermophysical properties. The T-initial and T-initial+ protocols build upon the T-static protocol by using dynamic vehicle information such as the fueling history and CHSS initial temperature at hot soak, respectively. The T-throttle protocol includes the T-initial+ data and adds the station component thermophysical properties at worst case and soaked at ambient temperature. The protocol has not yet been published as a standard in 2025, as it requires field testing and further validation.

# 2 Thermodynamic Modeling of the Hydrogen Fueling Process

## 2.1 Overview of H2FillS

The Hydrogen Filling Simulation (H2FillS) software, developed by the Hydrogen Production Power and Storage group at NREL, is an advanced 1D thermodynamic hydrogen fueling model that simulates the real-world fueling process and interaction between station high-pressure storage system and a vehicle CHSS. The model tracks the transient changes in hydrogen temperature, pressure, and mass flow rate during the simulated filling process. This model not only fills knowledge gaps in the interaction between hydrogen stations and FCEVs but also provides substantial insights into the light-duty and HD fueling market. H2FillS supports the safe design and operation of station components and fosters the development of next-generation hydrogen stations to minimize the capital and operating expenses for hydrogen infrastructure.

With a user-friendly "drag-and-drop" graphical interface, H2FillS facilitates the simulation of station and vehicle systems with preset parameters for common hydrogen station components while also offering the flexibility for users to specify custom parameters for unique station or vehicle configurations. The model has two versions: (1) a full-station model that includes the transport of hydrogen from high-pressure bank storage through a dispenser to the vehicle tank and (2) a partial-station model that solely focuses on the dispenser components and the vehicle tank. In both versions, H2FillS capably generates fill performance data, capturing pressure, temperature, and mass flow rate dynamics throughout the fill event. Additionally, it permits users to input custom fill profiles, thereby enabling a diverse range of simulations tailored to specific needs or investigational purposes.

Figure 2 illustrates the fueling process for FCEVs in the real world and in H2FillS. Figure 2a shows a storage unit containing high-pressure buffer storage connected to a chiller system to precool the hydrogen to the desired preset temperature, e.g., −40°C, before dispensing. The dispenser includes a control panel, a breakaway mechanism, a hose, and a nozzle. Figure 2b depicts a schematic layout of a hydrogen station configuration designed in H2FillS. It details the systematic flow and control mechanisms for delivering gaseous hydrogen from the high-pressure storage tanks through various valves and controls to the vehicle tank.

a)

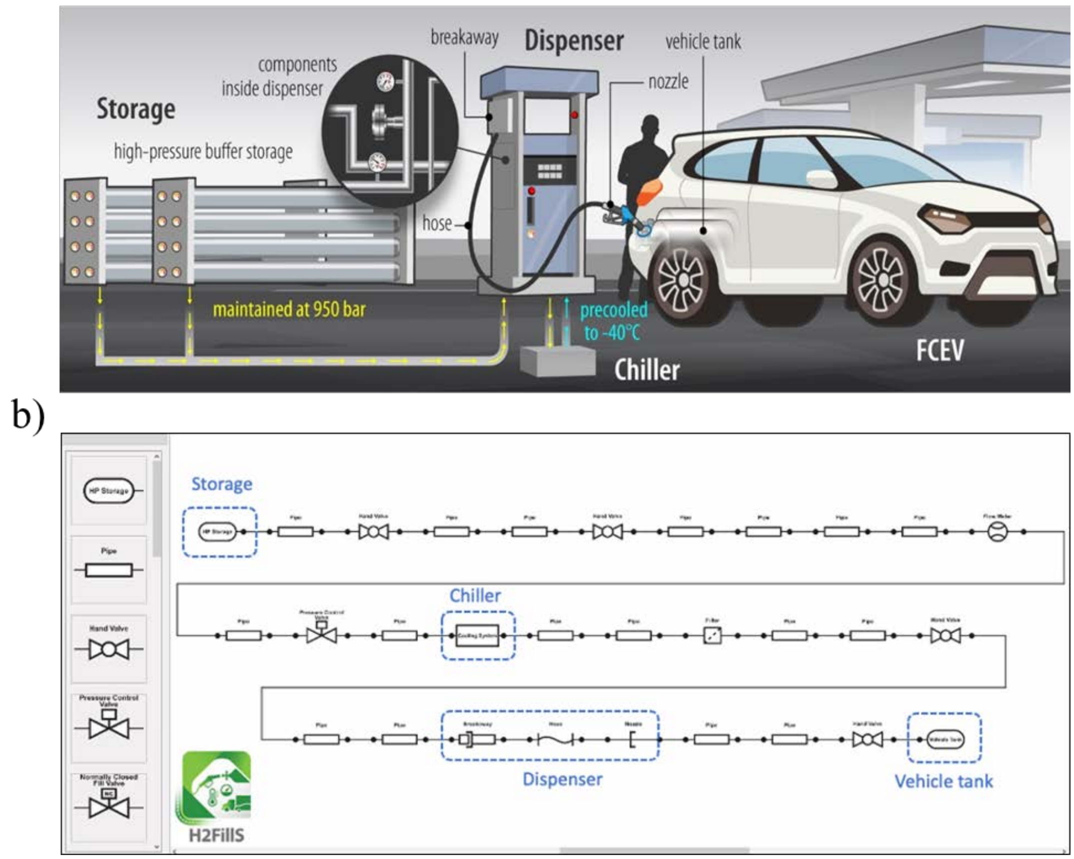


**Figure 2. Overview of gaseous hydrogen fueling: (a) real-world setup of a hydrogen fueling station for FCEVs featuring high-pressure buffer storage, a precooling chiller system, and a dispenser with an integrated control panel and safety; and (b) as modeled in H2FillS**

*Illustration by Alfred Hicks, NREL. Figure credit: NREL 2025*

## 2.2 Computational Workflow

H2FillS provides a comprehensive framework for users to design and simulate a hydrogen fueling system. Figure 3 illustrates the inputs and outputs of a hydrogen fueling simulation using H2FillS. The software enables the modeling of real-world fueling station specifications with components, such as high-pressure bank storage; pipe, hose, and nozzle; and vehicle tank parameters. Key metrics—such as the state of charge and the pressures and temperatures within various system points—are monitored to support the thorough analysis of the fueling process. Moreover, H2FillS provides an evolution of the fueling parameters (e.g., mass flow rate, pressure, and temperature of hydrogen at the nozzle), which are crucial for ensuring performance and safety in fueling operations.

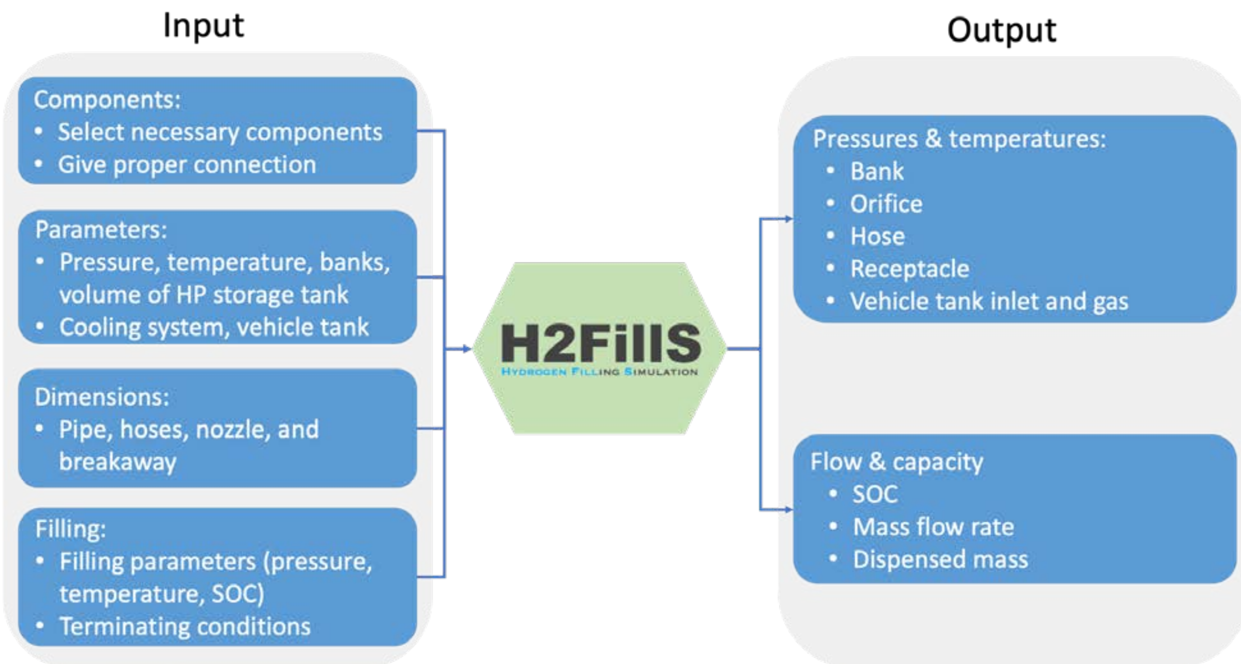


**Figure 3. Input and output of hydrogen filling station simulation using H2FillS**

HP: high pressure; SOC: state of charge

The computational flow diagram shown in Figure 4 describes the structured steps for simulating hydrogen fueling operations. The workflow initiates with the selection of the appropriate fueling modes and proceeds to establish the initial setup of the fueling station. Following this foundational setup, it advances to the calibration of parameters for both the high-pressure storage system and the vehicle's tank. Next, it considers the physical dimensions and the thermo-physical characteristics for the components involved, such as pipes, a nozzle, a hose, and a breakaway. Upon defining all the necessary parameters and physical dimensions, the workflow progresses to the configuration of the filling parameters. At this stage, the user has the option to specify the supply conditions (pressure and temperature) at the high-pressure bank storage for the full-station model and at the breakaway for the partial-station model. Prior to initiating the simulation, the workflow incorporates an error-checking option to ensure the integrity of the configuration. After checking for errors, H2FillS executes the simulation, thereby advancing the workflow toward the objective of simulating the comprehensive hydrogen fueling process.

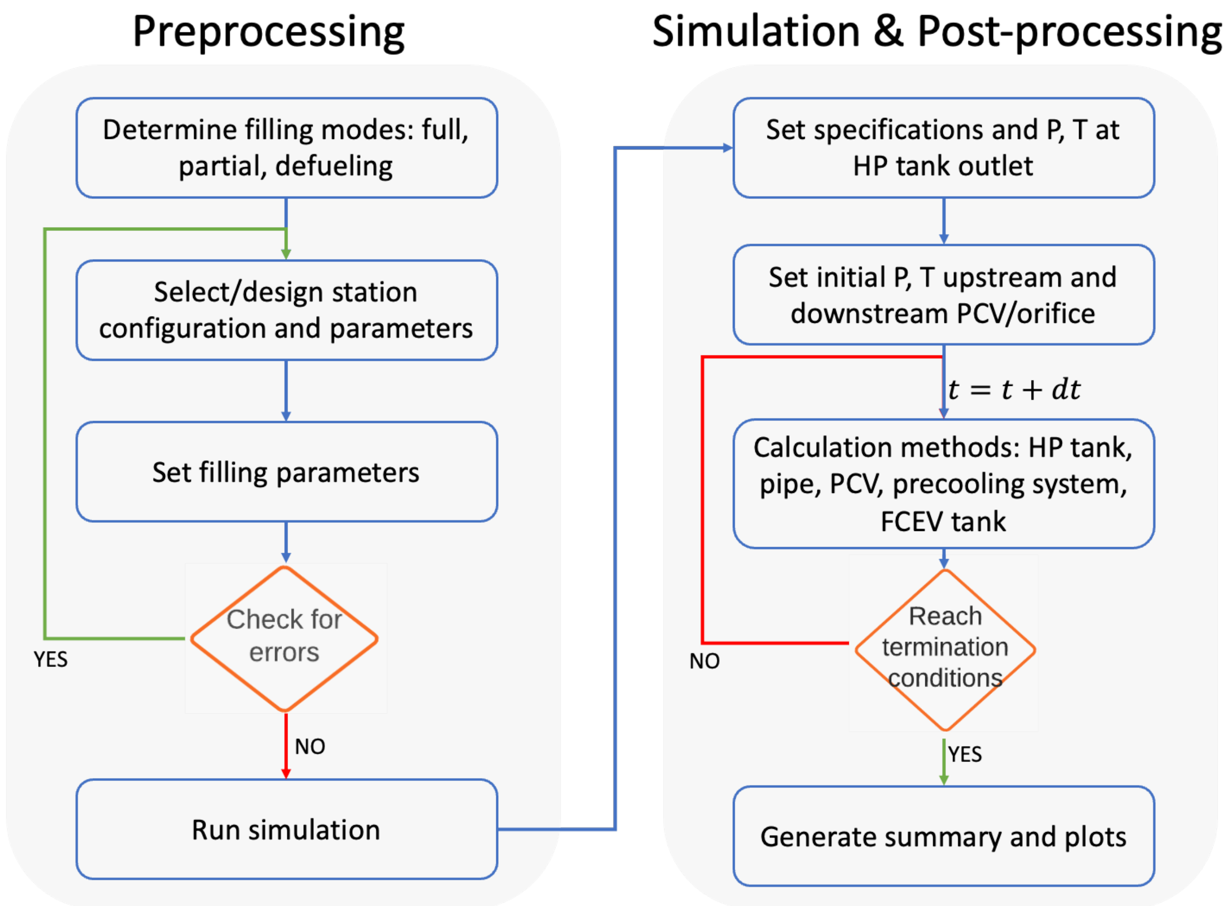


**Figure 4. H2FillS computation flow diagram of hydrogen fueling process from storage tank through vehicle tank. P and T stand for pressure and temperature, respectively.**

P: pressure; T: temperature; PCV: pressure control valve, HP: high pressure. *Source: Adapted from* (Kuroki et al. 2021)

The simulation and post-processing phases of the hydrogen fueling simulation involve setting the specifications for the high-pressure bank storage outlet conditions, initializing the pressure and temperature parameters upstream and downstream of the pressure control valve, and applying the calculation methods to different components of the system, such as the high-pressure bank storage outlet, pipes, and vehicle tank(s).

## 2.3 H2FillS Validation

### *2.3.1 Heavy-Duty Fueling Testing and Model Validation*

To validate the reliability of H2FillS, the model was compared against real world heavy-duty fueling data. Figure 5 shows NREL's Heavy-Duty Vehicle Simulator (HDVS), which is designed to replicate the fuel storage capabilities of a Class 8 semitruck. It consists of nine tanks total, with a maximum fill capacity of 86.8 kg. The configuration includes seven Type IV tanks, each with a fill capacity of 9.8 kg and a temperature rating of 85°C; as well as two Type III tanks, each with a fill capacity of 9.1 kg and a temperature rating of 125°C.

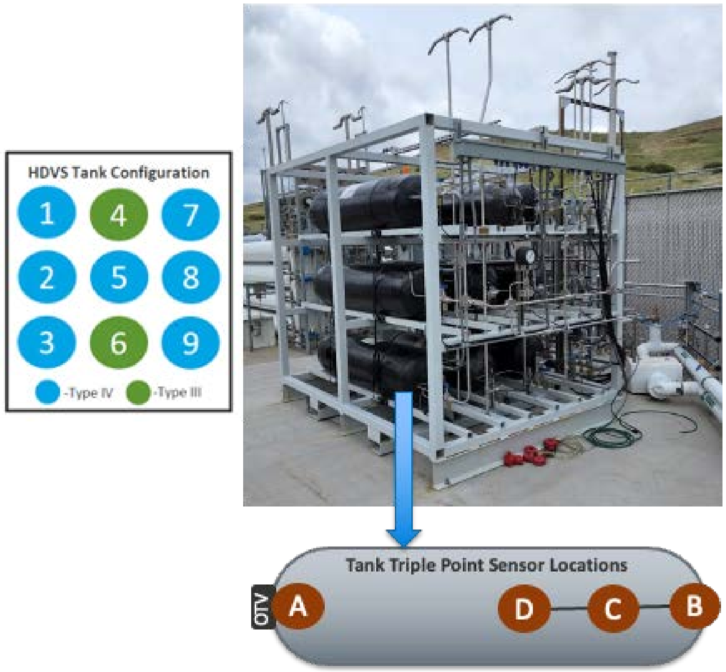


**Figure 5. Illustration of advanced Class 8 semitruck simulator with nine tanks (Type III and IV) and two integrated triple-point sensors installed in some of the tanks in the simulator.**

HDVS: Heavy-Duty Vehicle Simulator; OTV: on-tank valves. *Photo by Shaun Onorato, NREL*

The individual tanks in the HDVS are equipped with automotive on-tank valves that have integrated bulk gas temperature sensors and thermal pressure relief devices. There are also two triple-point sensors installed in some of the Type IV tanks and the Type III tanks. Additional pressure transducers are installed at the rear of the tanks. Moreover, the tank manifold is instrumented and built to ensure consistent inlet conditions. This setup allows for simulating the fueling process of a Class 8 semitruck under various conditions, allowing precise monitoring and analysis of the behavior of the HDVS.

Hydrogen was filled into the HDVS under the conditions presented in Table 1. The fueling process was conducted at an ambient temperature of 23°C. The HDVS has a capacity of 86.8 kg of hydrogen. The initial gas pressure in the HDVS was 1.7 MPa, and the gas pressure at the end of the fill was 76.2 MPa. The fill time for the process was 360 seconds. The dispenser pressure increased at a ramp rate of 12.4 MPa per minute. The time-averaged mass flow rate of hydrogen during the fill was 13.1 kg per minute, with a peak mass flow rate reaching 23.2 kg per minute.

**Table 1. HD Fueling Experimental Conditions**

| Name | Value |
|---|---|
| Ambient temperature | 23.0°C |
| HDVS capacity | 86.8 kg |
| HDVS initial gas pressure | 1.7 MPa |
| HDVS ending gas pressure | 76.2 MPa |
| Fill time | 360 s |
| Corresponding pressure ramp rate | 12.4 MPa/min |
| Time-averaged mass flow | 13.1 kg/min |

Figure 6 presents temperature data for the nine tanks during the filling experiment and the corresponding simulation over a time span of 360 seconds. The tanks are categorized by type, with Tank 4 and Tank 6 being Type III, and the others being Type IV. The tanks are color-coded to differentiate between Type III and Type IV tanks. The arrangement of the nine tanks is shown in a numerical diagram below the model.

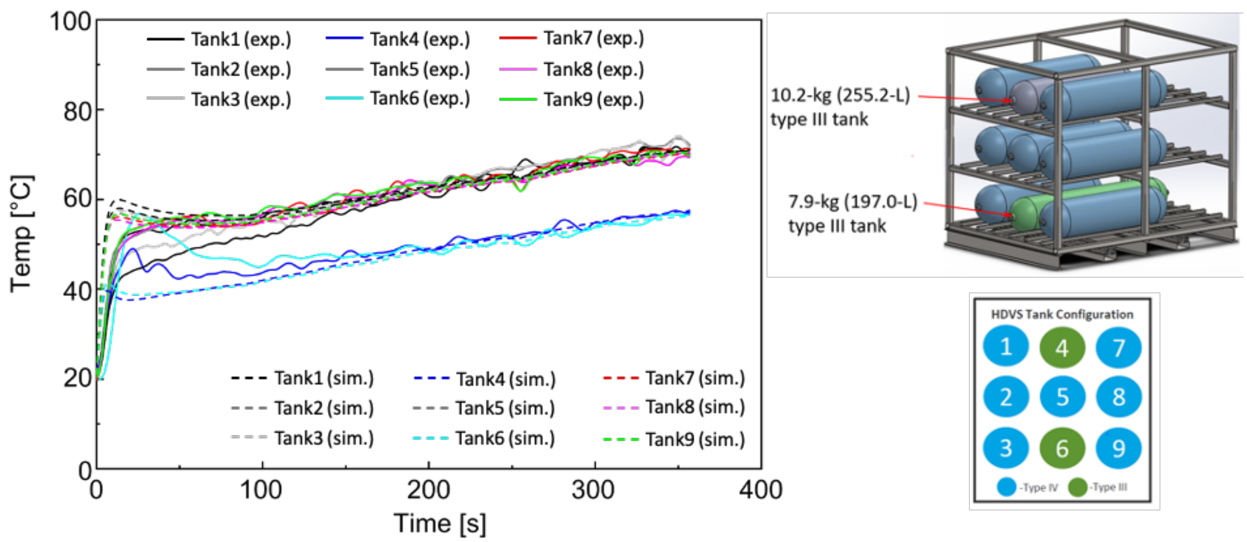


**Figure 6. Temperature dynamics during the filling experiment and the model validation along with the corresponding tank configuration**

At the start of the filling process, there was a sharp increase in temperature for all the tanks. After this initial spike, the temperature increase slowed and began to plateau toward the end of the filling period; however, the rate of the temperature rise and the subsequent stabilization pattern differs between tank types.

The Type III tanks (numbers 4 and 6 in Figure 6) showed a more gradual increase in temperature in the experimental data compared to the simulations. The model was unable to capture the rapid temperature rise at the early time steps. For the Type IV tanks, the experimental and simulation lines appeared to follow each other more closely, but with some initial overshoot in the simulations. This could mean that the simulation overestimated the rate of temperature rise in the early phase of filling for the Type IV tanks.

The two types of tanks exhibited different thermal behaviors during the filling process due to differences in thermal conductivity and heat capacity. Type III tanks have a metal liner with high thermal conductivity and heat capacity; on the other hand, Type IV tanks have a liner that is made of plastic whose thermal conductivity and heat capacity is relatively small. The higher thermal conductivity and heat capacity of Type III tank liner leads to a slower temperature rise of the hydrogen gas.

It is also possible that the initial conditions for the simulation did not perfectly match the experimental setup. For example, the model might not include the heat-exchange effects of the end boss area and onboard tank valve, which could lead to the observed discrepancies between the experimental and the simulated data.

Although there were mismatches between the simulation and the experimental results for all the tanks at the early time steps, H2FillS effectively modeled the thermal behavior of the hydrogen filling process. This level of detail is crucial for designing safe and efficient hydrogen filling protocols, especially considering the different tank types involved.

## 2.4 Assistance With Heavy-Duty Fueling Station- and Truck-Related Cost Analysis

### *2.4.1 Filling Data Table Creation*

The significant computational demands of creating fueling tables, which were essential to this project, required integrating H2FillS with NREL's high-performance computer (HPC) systems. Many fueling simulations were required to derive the total fueling times (t-final values) for wide ranges of ambient temperatures, precooling temperatures, and initial onboard storage system pressures. Figure 7 illustrates the coupling of H2FillS, the SAE J2601/5 fueling protocol (a high-flow prescriptive fueling protocol for HD gaseous fueling), and NREL's HPC systems to generate fueling tables. This capability was leveraged for the SAE J2601/5 MD/HD fueling protocol development, and all fueling tables generated on the HPC were reflected in the SAE J2601/5 Technical Information Report published in February 2024. The SAE J2601/5 fueling protocol used in this report is MC Formula High-Flow General (MCF-HF-G) for pressure class H70 and flow rate class FM300.

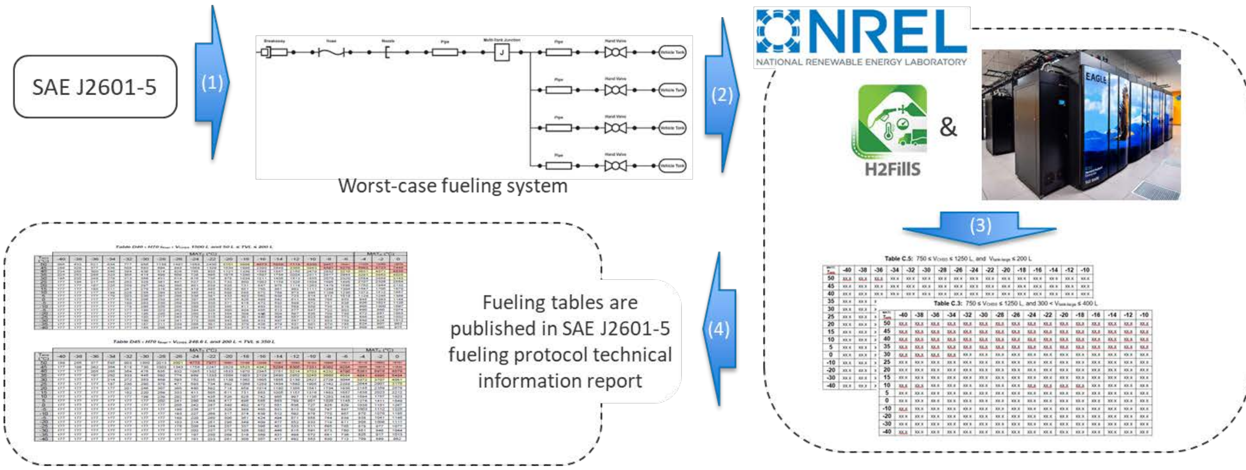


**Figure 7. Integration of HPC system and H2FillS to generate fueling tables for the SAE J2601/5 MD/HD fueling protocol**

*Illustration by Taichi Kuroki, NREL. Photo by Dennis Schroeder, NREL*

H2FillS was integrated with the SAE J2601/5 fueling protocol tables to enable SAE J2601/5 fueling simulations, as shown in Figure 8. Fueling simulations were then conducted using SAE J2601/5 with an 80-kg Class 8 semitruck onboard storage system and evaluated the peak flow rates, peak hydrogen temperature, and fueling times when the truck was filled based on the SAE J2601/5 fueling protocol under various conditions. In addition, the European Union's PRotocol for heavy duty HYDrogEn refueling (PRHYDE) was integrated into H2FillS to perform PRHYDE specific fueling simulations. The peak mass flow, hydrogen precooling temperature, and fueling time information for both SAE J2601/5 and PRHYDE were then fed into HDRSAM to evaluate the impact of SAE J2601/5 and PRHYDE on the station costs. Section 3 describes how the two fueling protocols influence the station costs.

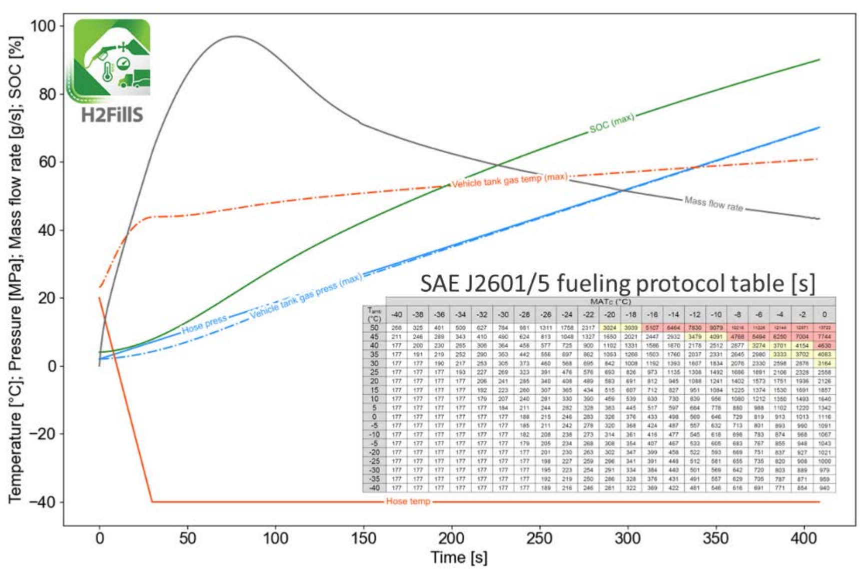


**Figure 8. Fueling process simulation using an SAE J2601/5 fueling protocol table**

# 3 Station Design and Cost

## 3.1 Fueling Cost Methodology

HDRSAM is an Excel-based techno-economic assessment model for fueling a fleet of HD FCEVs (Argonne National Laboratory 2017). The model evaluates the cost of hydrogen fueling for various fueling station configurations and demand profiles. In this project, H2FillS (Kuroki et al. 2021) was used to assess the hydrogen flow characteristics of a fueling event, including fueling time, mass flow rate, etc., for an HD FCEV's onboard hydrogen storage system following SAE J2601/5 (SAE International 2024) and PRHYDE (Hart et al. 2023). These flow characteristics were estimated for various combinations of boundary conditions, including the ambient temperature and precooling temperatures, following SAE J2601/5 (SAE International 2024) and PRHYDE. The fueling methods T-initial, T-static, and T-throttle are part of PRHYDE. The flow characteristics are later used to size the station and to estimate the levelized fueling cost using HDRSAM for each combination of the ambient and precooling temperatures. Then, the levelized cost of the station is later used to study the impact of the boundary conditions and the corresponding fueling protocol performance on the fueling cost.

The station configuration for this study is shown in Figure 9. Two gaseous dispensing fueling station scenarios were studied: (1) gaseous-storage stations and (2) liquid-storage stations. These station archetypes are representative of the current state of technology. Next generation technologies such as liquid dispensing were not considered in this analysis. In gaseous stations, gaseous hydrogen is either produced on-site or supplied from the central production plant via pipeline at 2 MPa. The supplied hydrogen is compressed to approximately 50 MPa from the supplied 2 MPa and stored in a mid-pressure buffer storage system. For the liquid station, the liquified hydrogen is transported from the liquefaction plant to the station via a liquid tanker trailer. The liquid hydrogen is transferred to an on-site cryogenic storage tank and used to supply hydrogen to the station. A cryogenic pump draws liquid hydrogen from the cryogenic storage tank, pressurizes it to 53 MPa, and stores it in the mid-pressure buffer storage after vaporizing it via an evaporator. The buffer storage system is maintained at 50 MPa and is used to supply hydrogen to a booster compressor to fuel a vehicle. When the dispenser is activated to fuel a vehicle, the hydrogen from the buffer storage system is pressurized to 90 MPa by a booster compressor and channeled to the vehicle tank and a precooling unit via an accumulator. The accumulator, a bank of small high-pressure tanks that are connected to the high-pressure hydrogen line connecting the dispenser and booster compressor outlet, dampens the pulsating effect of the booster compressor operation and safeguards sensitive hardware, such as the flow meter. The precooling unit cools the hydrogen to a required temperature, and the dispenser controls the fueling process following fueling protocols, such as SAE J2601/5 and PRHYDE. Finally, the compressed hydrogen is delivered to the hydrogen dispenser after it is precooled to a required temperature in a heat exchanger.

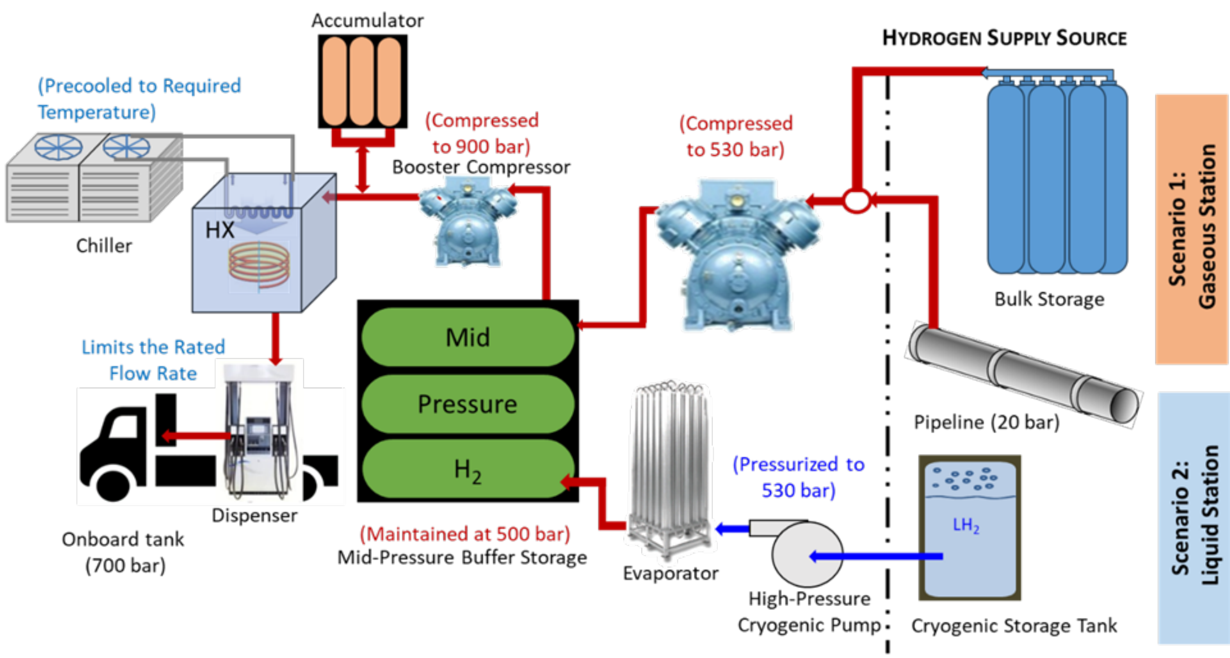


**Figure 9. The liquid and gaseous HDRSAM station configurations used for this project**

*Figure credit: Argonne National Laboratory 2017*

HDRSAM was used to size the gaseous hydrogen station for various boundary conditions, including ambient temperature, precooling temperature, fueling protocol, station size (also called the fleet size), hourly fueling demand, and lingering time (the time between the fills). The following assumptions are considered in HDRSAM to size and calculate the levelized fueling cost of hydrogen:

- A 1-year construction period is assumed.
- The dollar year for the cost estimates is 2019.
- The after-tax discount rate is 8.0%.
- A 15-year analysis period is assumed.
- A 10-year debt period with a 6.0% nominal debt interest rate is assumed.
- There is a maximum 100% annual utilization of the hydrogen station.
- There is a 2-MPa station supply pressure for the gaseous hydrogen station.
- The liquid truck net delivery amount to the liquid-storage hydrogen station is 3,800 kg.
- A low production volume representing current costs is assumed.
- The average mass flow rate (determines the fill duration) and the peak mass flow rate are obtained from the project partners (from H2FillS with new fueling protocols).
- The refrigeration unit of the station is sized for the specific maximum flow rate and fill duration for each combination of ambient temperature and precooling temperature.
- The uninstalled costs of major equipment (refrigeration, compressor, dispenser, electrical, cascade, etc.) are obtained from HDRSAM model data and original equipment manufacturer data.

## 3.2 Station and Fueling Simulation Parameters

Table 2 lists a brief overview of the station and fueling simulation parameters and the corresponding values that were used to size the station using HDRSAM and to estimate the cost of the gaseous and liquid fueling station analysis with different configurations and demand profiles. Gaseous and liquid hydrogen stations were sized for each combination of the values shown. The highlighted parameters are the base case parameters for the analysis presented in Section 3.3.

**Table 2. Brief Overview of Station and Fueling Simulation Parameters**

| Fill Amount | Fueling Pressure | Station Utilization | Fleet Size | Demand Profile | Fueling Protocols | Ambient Temperature | Precooling Temperature | Lingering Time | Station Type |
|---|---|---|---|---|---|---|---|---|---|
| 60 kg | 70 MPa | 100% | 20<br>40<br>100 | Single 10 hour<br>Double 5 hour | SAE J2601-5<br>PRHYDE (Methods)<br>T-static<br>T-initial<br>T-throttle | 40$^{O}$C<br>10$^{O}$C | -40$^{O}$C<br>-20$^{O}$C | 5 min<br>10 min | Gaseous<br>Liquid |

Two different demand profiles were used in this study: (1) single 10-hour and (2) double 5-hour, as shown in Table 2 and Figure 10. The single 10-hour fueling profile, shown in Figure 10a, fuels the whole fleet of vehicles within 10 hours; and the double 5-hour fueling profile, shown in Figure 10b, fuels the whole fleet in two 5-hour windows that are separated by 7 hours.

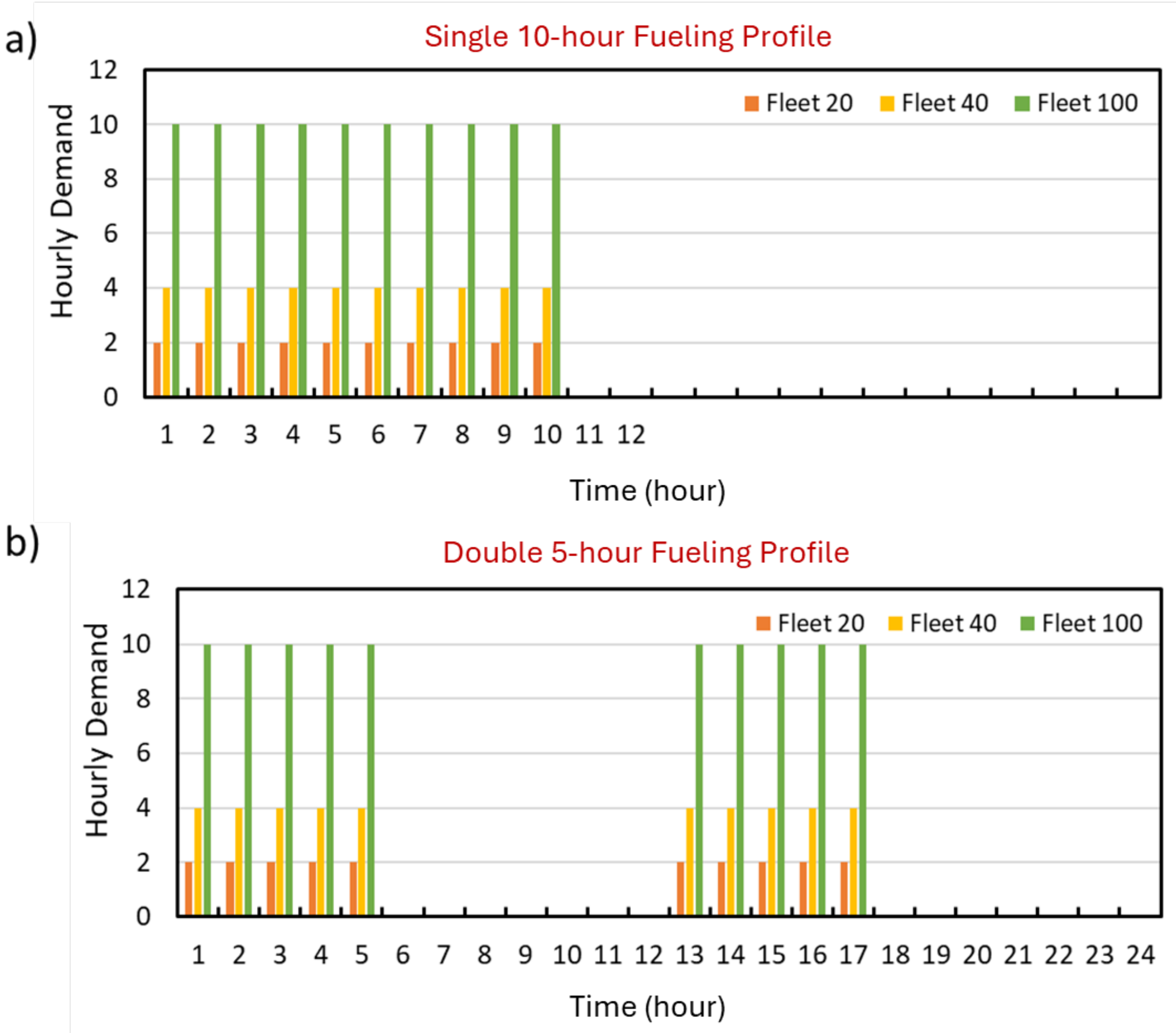


**Figure 10. Fueling profiles for different fleet sizes: (a) single 10-hour fueling and (b) double 5-hour fueling**

The average and peak mass flow rates obtained from H2FillS are shown in Table 3 for PRHYDE and SAE J2601/5 along with the corresponding boundary conditions, including the ambient and dispensing temperatures. The required number of hoses, as shown in Table 3, are calculated for each considered fleet size based on the hourly demand (from the fueling profile), fueling time, and lingering time.

**Table 3. Station and Fueling Parameters Used in the HDRSAM Simulations for Different Fueling Protocols With Different Lingering Times**

| Ambient Temp (°C) | Max Dispensing Temp (°C) | Fueling Protocol | Average Flow (kg/min) | Peak Flow (kg/min) | Fueling Time (min) | Lingering Time (min) | Hose Count 20 Fleet | Hose Count 40 Fleet | Hose Count 100 Fleet |
|---|---|---|---|---|---|---|---|---|---|
| 40 | –40 | SAE J2601/5 | 11.0 | 15.7 | 5.5 | 5.0 | 1 | 1 | 2 |
| | | | | | | 10.0 | 1 | 2 | 4 |
| | | PRHYDE- | 12.3 | 16.8 | 4.9 | 5.0 | 1 | 1 | 2 |

| Ambient Temp (°C) | Max Dispensing Temp (°C) | Fueling Protocol | Average Flow (kg/min) | Peak Flow (kg/min) | Fueling Time (min) | Lingering Time (min) | Hose Count 20 Fleet | Hose Count 40 Fleet | Hose Count 100 Fleet |
|---|---|---|---|---|---|---|---|---|---|
| | | T-static | | | | 10.0 | 1 | 1 | 3 |
| | | PRHYDE T-initial | 14.1 | 19.2 | 4.3 | 5.0 | 1 | 1 | 2 |
| | | | | | | 10.0 | 1 | 1 | 3 |
| | | PRHYDE-T-throttle | 12.2 | 15.9 | 5.0 | 5.0 | 1 | 1 | 2 |
| | | | | | | 10.0 | 1 | 1 | 3 |
| 40 | −20 | SAE J2601/5 | 2.3 | 3.2 | 26.1 | 5.0 | 2 | 4 | 10 |
| | | | | | | 10.0 | 2 | 4 | 10 |
| | | PRHYDE-T-static | 2.8 | 4.9 | 21.4 | 5.0 | 1 | 2 | 5 |
| | | | | | | 10.0 | 2 | 4 | 10 |
| | | PRHYDE T-initial | 3.53 | 6.0 | 17.2 | 5.0 | 1 | 2 | 5 |
| | | | | | | 10.0 | 1 | 2 | 5 |
| | | PRHYDE-T-throttle | 3.9 | 11.8 | 15.5 | 5.0 | 1 | 2 | 5 |
| | | | | | | 10.0 | 1 | 2 | 5 |
| 10 | −40 | SAE J2601/5 | 11.1 | 15.8 | 5.4 | 5.0 | 1 | 1 | 2 |
| | | | | | | 10.0 | 1 | 2 | 4 |
| | | PRHYDE-T-Static | 12.4 | 17.0 | 4.8 | 5.0 | 1 | 1 | 2 |
| | | | | | | 10.0 | 1 | 1 | 3 |
| | | PRHYDE-T-initial | 14.3 | 19.3 | 4.2 | 5.0 | 1 | 1 | 2 |
| | | | | | | 10.0 | 1 | 1 | 3 |
| | | PRHYDE-T-throttle | 12.4 | 17.0 | 4.8 | 5.0 | 1 | 1 | 2 |
| | | | | | | 10.0 | 1 | 1 | 3 |
| 10 | −20 | SAE J2601/5 | 5.3 | 7.9 | 11.3 | 5.0 | 1 | 2 | 4 |
| | | | | | | 10.0 | 1 | 2 | 5 |
| | | PRHYDE-T-static | 7.2 | 10.2 | 8.4 | 5.0 | 1 | 1 | 3 |
| | | | | | | 10.0 | 1 | 2 | 4 |
| | | PRHYDE-T-initial | 9.8 | 14.5 | 6.1 | 5.0 | 1 | 1 | 2 |
| | | | | | | 10.0 | 1 | 2 | 4 |
| | | PRHYDE-T-throttle | 10.6 | 16.2 | 5.7 | 5.0 | 1 | 1 | 2 |
| | | | | | | 10.0 | 1 | 2 | 4 |

## 3.3 Station Results

As previously mentioned, HDRSAM was used to estimate the hydrogen fueling cost for all the combinations of the parameters' values listed in Table 3. The fueling cost data were later used to study the effects of different fueling protocols, the cost contributions of different station components, the effects of fueling profile, and the effects of fleet sizes. In this report, SAE J2601/5 with a 40-fleet size, a single 10-hour fueling profile, and a 5-minute lingering time was considered as a base case scenario, as shown in Table 3 (the parameters are highlighted), based on feedback from CRADA partners.

### 3.3.1 Effects of Fueling Protocols

Two fueling protocols, SAE J2601/5 and PRHYDE, including the fueling methods T-static, T-initial, and T-throttle, were studied. As shown in Table 3, the maximum and average flow rates depend on the fueling protocol for the same boundary conditions as the precooling temperature, the ambient temperature, and the tank size, etc. The average flow rate determines the sizing of the compressor and storage combination. A lower average flow rate would require a smaller size and thus a lower capital cost for the compressor and storage combination. And because the compressor and storage together typically account for more than 85% of the station cost, a lower capital cost for the compressor and storage combination would mean a lower fueling cost. This is true as long as the lower average flow rate would not require additional hoses to fill the fleet following the hourly demand profiles considered. Because the considered station configuration includes a dedicated booster compressor and a heat exchanger for each dispenser, additional dispensers would mean additional booster compressors and heat exchangers, which would increase the station capital cost and thus the fueling cost. Figure 11 shows the levelized hydrogen fueling cost of different fueling protocols for the gaseous and liquid fueling stations with the 40-fleet size, a single 10-hour fueling hourly demand profile, and a 5-minute lingering time. As shown in Table 3, SAE J2601 has a lower flow rate for all the considered combinations of the ambient and precooling temperatures. For a warmer dispensing temperature of −20°C, though the average flow rate for SAE J2601/5 is low compared to the PRHYDE fueling methods, it requires a greater number of hoses to fill the fleet following the hourly demand profiles considered, as shown in Table 3. SAE J2601/5 is the cheaper option for cooler, −40°C precooling, whereas the T-static fueling method of PRHYDE is the cheapest option for warmer, −20°C precooling.

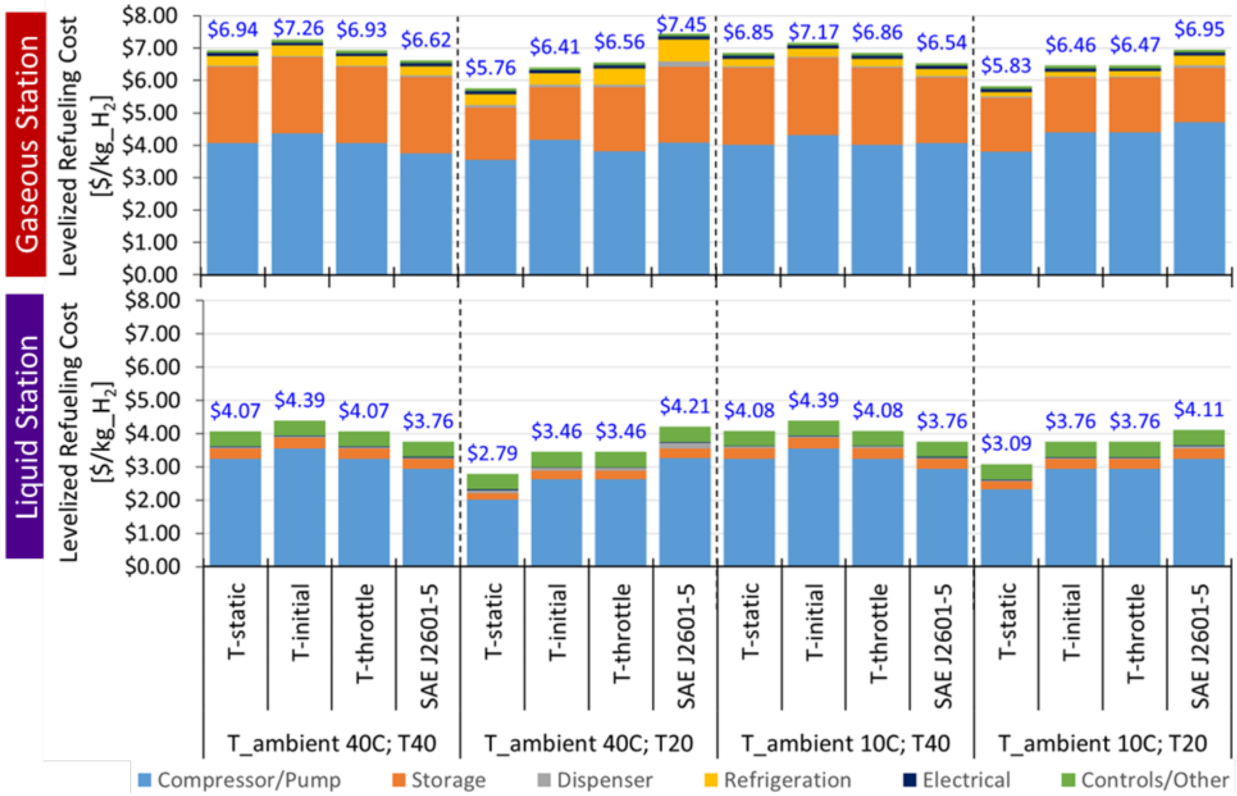


**Figure 11. Effects of different fueling protocols for gaseous and liquid fueling stations: 40-fleet size, single 10-hour fueling profile, and 5-minute lingering time. Costs do not include the cost of hydrogen production and delivery to fueling station.**

### 3.3.2 Cost Contributions of Different Station Components

The cost contributions of different station components for different ambient and dispensing temperatures are shown in Figure 12 for the base case of SAE J2601/5 with a 40-fleet size, a 10-hour single fueling profile, and a 5-minute lingering time. The cost contributions of the individual fueling components (such as the compressor, storage, dispenser, and refrigeration units) for gaseous and liquid fueling stations are plotted. The figure also shows the capital, energy/fuel, and other operations and maintenance costs for each component. For both gaseous and liquid fueling stations, the compressor and pump are the major cost drivers and compose a significant portion of the fueling cost. The compressor/pump together with storage accounts for approximately 90% of the fueling cost.

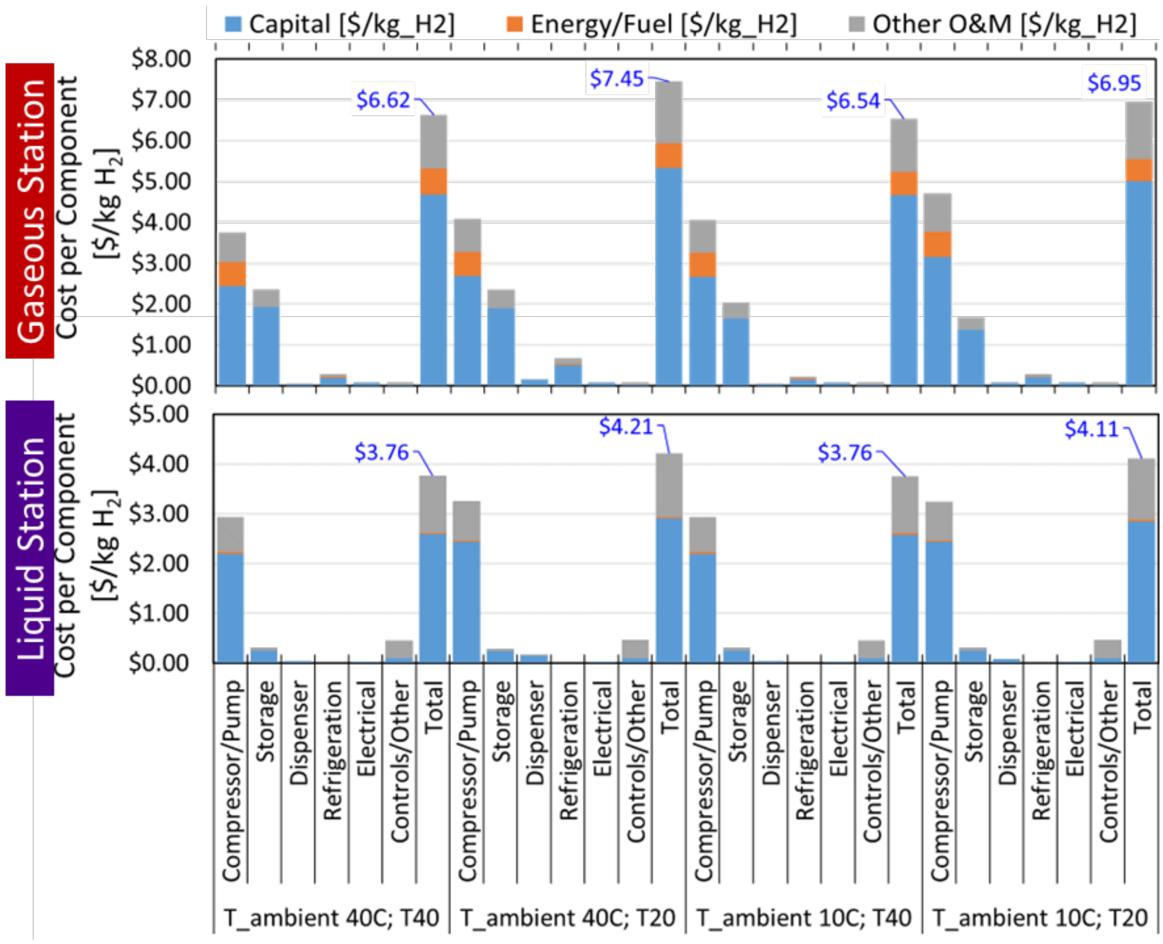


**Figure 12. Cost contributions of different station components for gaseous and liquid fueling stations: SAE J2601/5, 40-fleet size, single 10-hour fueling protocol, and 5-minute lingering time**

### 3.3.3 Effects of Fueling Demand Profile

As stated earlier, two fueling profiles (shown in Figure 10) were considered in this study. Figure 13 shows the effect of the fueling demand profiles on gaseous and liquid fueling stations. For gaseous fueling stations, the fueling cost of the distributed or double 5-hour fueling profile is lower than that of the single 10-hour fueling profile. For the distributed or double 5-hour fueling profile, the idle time between the 5-hour fueling windows allows replenishment of the storage system, thus requiring smaller compressor and storage capacities, as shown in Figure 13. Smaller compressors and storage capacities reduce the capital cost of the station, thus reducing the levelized cost of hydrogen. The liquid station does not demonstrate any difference in the levelized fueling cost between the two considered hourly demand profiles primarily due to a lack of real-world market data regarding cryopumps of varying sizes. HDRSAM currently only has market data for cryopumps at one size and corresponding capital cost.

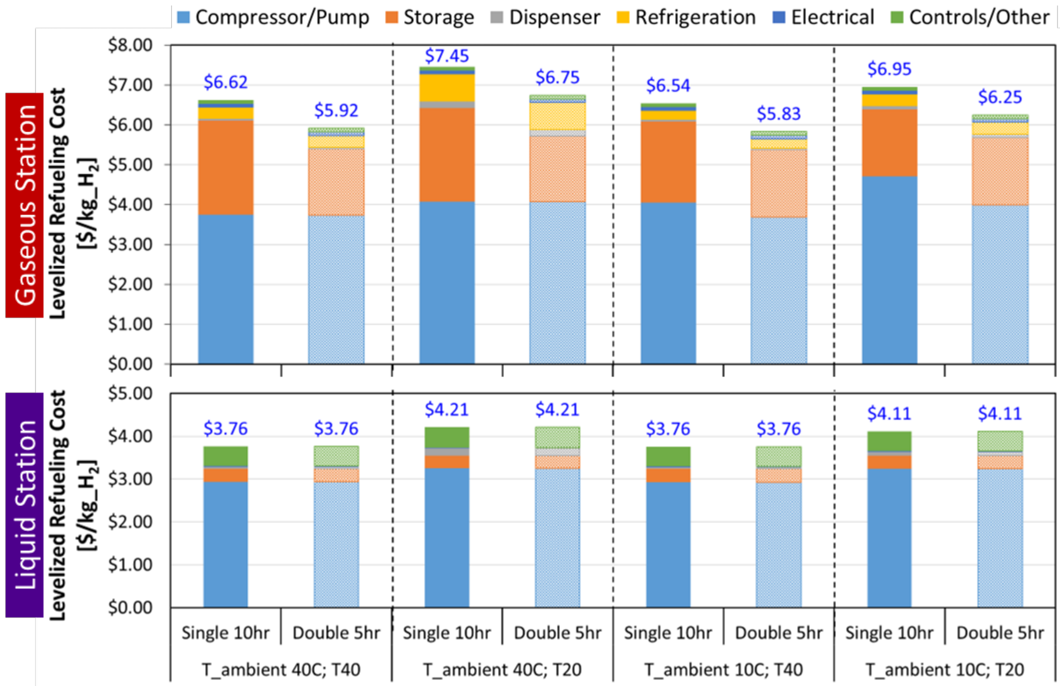


**Figure 13. Effects of fueling profile for gaseous and liquid fueling stations: SAE J2601/5, 40-fleet size and 5-minute lingering time**

### 3.3.4 Effects of Lingering Time

Figure 14 shows the effects of lingering time on the levelized fueling cost of gaseous and liquid hydrogen fueling stations with 40-fleet sizes. The secondary vertical axis in Figure 14 shows the total flow rate across all dispensers for different combinations of ambient and precooling temperatures. The levelized cost understandably follows the same trend as the total flow rate, which influences the sizing of the compressor and storage and is determined by the number of dispensers. When the lingering time did not impact the number of dispensers required to fill the fleet within the 10-hour fueling window (i.e., the rounded-up integer number of dispensers can achieve the same maximum hourly demand for both lingering time options), there is no significant change in the station configuration, so there is no difference in the levelized cost; however, when the longer lingering time would necessitate an additional dispenser to fill the fleet within the 10-hour fueling window, the total flow across the dispensers would increase, thus requiring a larger compressor and storage, leading to an increase in the levelized fueling cost of hydrogen. For example, the levelized fueling costs remain the same for the 5-minute and 10-minute lingering time cases, with a 40°C ambient temperature and a −20°C maximum dispensing temperature for the 40-fleet size. In this case, the required maximum fueling rate of the station (hose number x average fueling rate) is the same; however, for a 40°C ambient temperature and a −40°C maximum dispensing temperature, when the lingering time is 10 minutes, a larger number of hoses is required (as shown in Table 3) to address the fueling demand profile. So, the required maximum instantaneous station flow rate significantly increases, increasing the compressor size and the fueling costs.

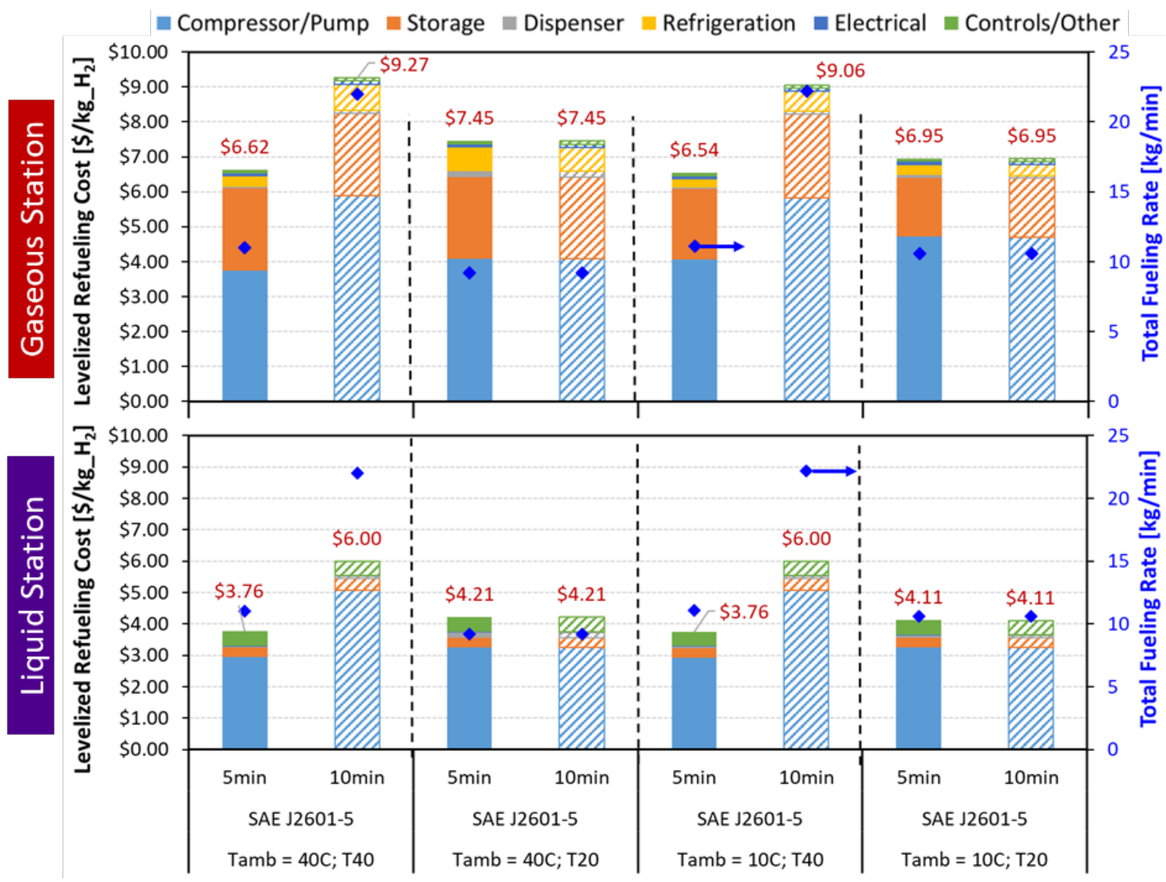


**Figure 14. Effects of lingering time for gaseous and liquid fueling stations: SAE J2601/5, 40-fleet size, and single 10-hour fueling profile**

### *3.3.5 Effects of Fleet Size*

Figure 15 shows the effects of different fleet sizes on the fueling costs of gaseous and liquid stations for SAE J2601/5. Generally, the fueling costs exponentially decrease with the increase in fleet size due to economies of scale; however, the trend of levelized fueling cost slightly changes for the 40°C ambient temperature and the T20 dispenser primarily because of the disproportionate increase in the dispensers with an increase in fleet size and the associated costs of the dedicated booster compressors and heat exchangers for each dispenser. The cost reduction from the economies of scale from the compressor, pump, and refrigeration decreases, distorting the trend.

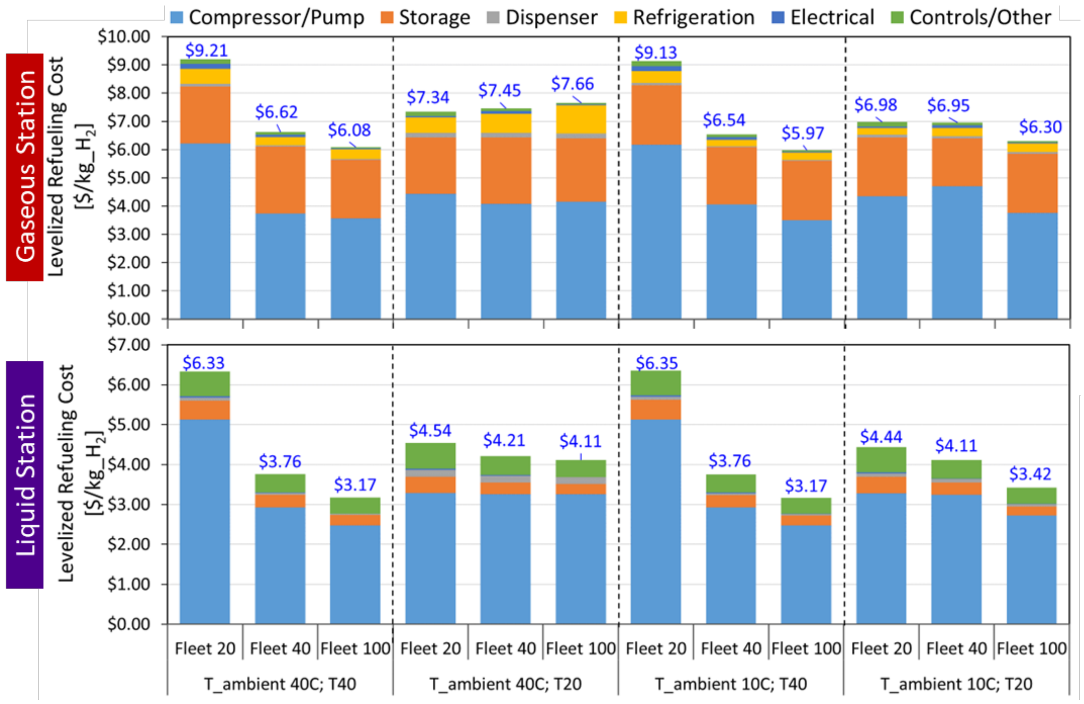


**Figure 15. Effects of fleet size for gaseous and liquid fueling stations: SAE J2601/5, single 10-hour fueling profile, and 5-minute lingering time**

# 4 Total Cost of Ownership

The TCO was calculated using NREL's T3CO tool. T3CO is a Python-based tool that enables levelized assessments of the full life cycle costs of advanced technology commercial vehicles (Lustbader et al. 2024). The T3CO tool incorporates NREL's Future Automotive Systems Technology Simulator (FASTSim™) (Brooker et al. 2015) to understand vehicle performance. FASTSim provides a simple way to compare powertrains and to estimate the impact of technology improvements on light-duty, MD, and HD vehicle efficiency, performance, cost, and battery life (Lustbader et al. 2024). T3CO accounts for the diverse vocations with various performance and economic requirements as well as technology considerations associated with decarbonization. The primary result of the T3CO assessments is the TCO expressed in $/mile.

In this study, T3CO was used to calculate the TCO based on sensitivity to fueling protocols, station designs, and vehicle scenarios. H2FillS (Kuroki et al. 2021) was used to calculate the critical hydrogen fueling characteristics of each protocol and the temperature conditions, such as fueling time, average fueling rate, and peak flow rate for an HD FCEV onboard hydrogen storage. The results of H2FillS are passed to HDRSAM (Argonne National Laboratory 2017), where the station size and the levelized fueling cost are estimated for each fueling protocol, ambient temperature, and precooling temperature condition. HDRSAM considers sensitivity to the station design parameters, including the fleet size and lingering time. The levelized fueling cost informs the T3CO model as a component of the fuel price, shown in Figure 16. T3CO incorporates the sensitivities in both H2FillS and HDRSAM to calculate the TCO and ultimately understand the effects that fueling protocols have on the TCO.

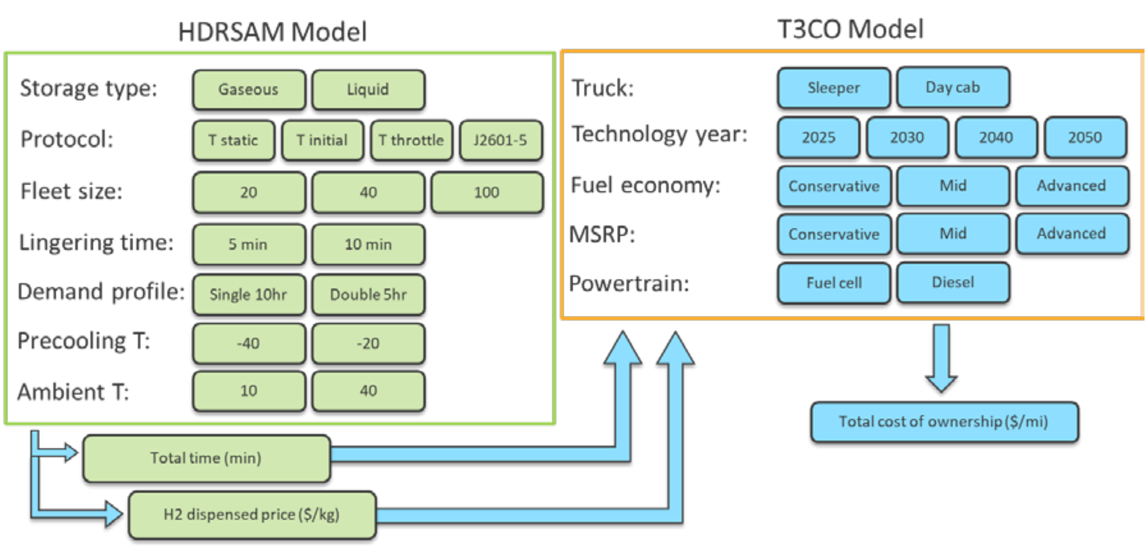


**Figure 16. Model flow between HDRSAM and T3CO**

The TCO modeling data flow in T3CO is summarized in Figure 17. TCO analysis requires several input parameters about the vehicle design, operating conditions, cost metrics, and financial structure. First, T3CO requires information about the vehicle, including the weight and size of individual components, the fuel converter efficiency, and the allowable quantity of onboard fuel. The mass of individual components for each vehicle included the glider, fuel converter, fuel storage, motor and power electronics, auxiliary battery, transmission, and cargo.

Additional parameters, such as frontal area and rolling resistance, were used as inputs to FASTSim to model the vehicle fuel economy. Cost data are also supplied to T3CO for each component to determine a total vehicle purchase price. The purchase price or cost correlations are included for the glider, fuel converter, fuel storage, auxiliary battery, and motor and power electronics. Last, financial structure information, such as tax rates and discount rates, are added to calculate the TCO.

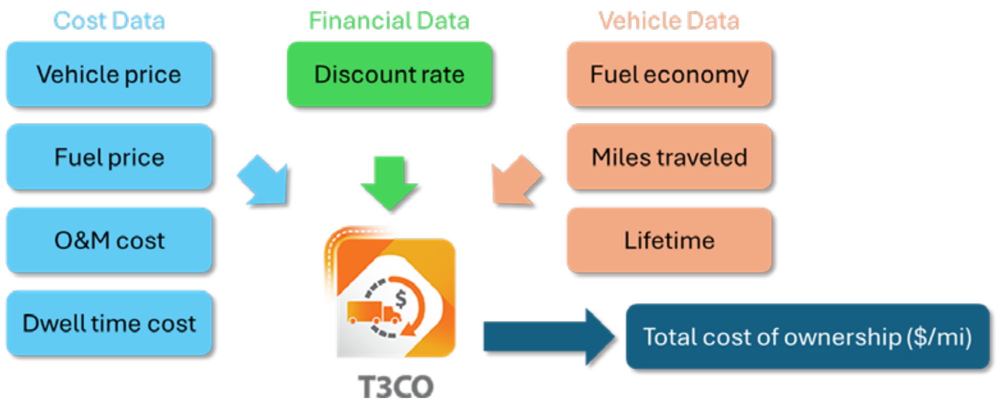


**Figure 17. T3CO data flow and model inputs**

The TCO financial analysis follows a discounted cash flow analysis methodology. The discounted cash flow analysis incorporates a discount rate to discount future cash flows to calculate the present value of the vehicle. In the TCO analysis, this manifests as a dollar amount, which is normalized by the vehicle miles traveled (VMT), such that TCO is expressed in units of $/mi. The cash flows considered in this analysis are categorized into glider, fuel converter, fuel storage, auxiliary battery, motor and power electronics, purchase tax, fuel, maintenance, and fueling dwell time. The glider describes the capital expenditure associated with purchasing the tractor but trimmed to not include the engine, storage, auxiliary battery, or motor and power electronics.

TCO analysis requires many assumptions about the vehicle and operation scenario that can influence the TCO. In this analysis, the vehicles are assumed to operate for 4 years before a major overhaul is required, which aligns with the adoption model payback requirements (Booker et al. 2021). Additionally, this analysis assumes a discount rate of 7% (Ledna et al. 2024). The VMT for each individual year is defined as an input to the analysis. The VMT varies for each vehicle and is explained in later sections. The various components of the TCO were individually computed using a discount rate of 7% and then summed to provide the TCO of the vehicle.

## 4.1 Vehicle and Scenario Parameters

T3CO incorporates inputs that are categorized under either vehicle or scenario. The vehicle inputs describe the physical parameters of the vehicle, which can range from the mass of various components on the vehicle to the frontal area and drag coefficient of the vehicle. These input parameters are incorporated into T3CO in the form of a FASTSim input file to describe the vehicle. The scenario input parameters describe the situation in which to model a vehicle, such as the cost of the various components of the vehicle, the tax rate to consider, and the discount rate to consider. The combination of the vehicle and scenario inputs provides the basis to determine the TCO.

The HD transportation sector can include many types of vehicles. The present analysis focuses on Class 8 vehicles, specifically long-haul sleeper semitrucks. Class 8 tractors were chosen because they represent nearly 70% of total MD and HD fuel consumption (U.S. Census Bureau 2004; R.L. Polk and Co. 2013; Hunter et al. 2021). These vehicles are also anticipated to be the majority of vehicles at HD fueling stations (Gilleon et al. 2022).

Each vehicle type is assumed to drive a specified number of miles each year, referred to as VMT. The VMT is specified for the two vehicle types considered: sleepers and day cabs. The vehicle is modeled for a 4-year lifetime, and the VMT changes each year. The VMT are shown in Table 4 from (Booker et al. 2021; U.S. Census Bureau 2004).

**Table 4. VMT for Class 8 Vehicles Assumed in the TCO Analysis Over the 4-Year Lifetime**

| | VMT (mi) | | | |
|---|---|---|---|---|
| Year | 1 | 2 | 3 | 4 |
| Sleeper | 108,010 | 117,983 | 114,998 | 104,732 |
| Day cab | 74,563 | 73,479 | 71,710 | 68,573 |

The TCO analysis includes sensitivity to improvements in technology. Fuel cells and onboard hydrogen storage are expected to improve in both performance and cost through research, development, and deployment. Technology years are incorporated into the TCO analysis to reflect expected or targeted improvements in technology that could be reflected in cost and/or performance metrics. The key assumptions that are incorporated into the TCO for fuel cells include fuel cell power, fuel cell cost, and fuel storage cost. Assumptions of fuel cell power and peak efficiency were based on targets previously published in the U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Hydrogen and Fuel Cell Technologies Office Multi-Year Program Plan (Department of Energy 2024; Marcinkoski 2019). Targets were used directly where available, and values for intermediate years are based on the High case in Islam et al (Islam et al. 2023). Table 5 shows the trajectories used for fuel cell power and peak efficiency for the technology years 2025, 2030, 2040, and 2050. These assumptions were combined with assumptions of component cost, based on the NREL Transportation Annual Technology Baseline (ATB) (National Renewable Energy 2024), as described below.

**Table 5. Fuel Cell Assumptions and Targets**

| | | **Technology Year** | | | |
|---|---|---|---|---|---|
| | **Vehicle** | **2025** | **2030** | **2040** | **2050** |
| Fuel cell specific power (kW/kg) | Sleeper | 0.7 | 0.8 | 0.9 | 1.0 |
| | Day cab | 0.7 | 0.8 | 0.9 | 1.0 |
| Peak efficiency (%) | Sleeper | 64 | 68 | 70 | 72 |

| | | Technology Year | | | |
|---|---|---|---|---|---|
| | Day cab | 64 | 68 | 70 | 72 |

The fuel cell cost is similarly expected to improve in future technology years. This analysis uses NREL's 2024 ATB to guide the cost trajectories (National Renewable Energy Laboratory 2024; Islam et al. 2023). The ATB provides trajectories for the fuel cell costs of HD vehicles, and costs of other components (e.g. vehicle chassis, electronics, auxiliary battery) are based on Islam et al. (Islam et al. 2023). The ATB defines the advanced trajectory as: "technology advances occur with breakthroughs, increased public and private R&D investment, and other market conditions that lead to significantly improved cost and performance levels, but the technologies do not necessarily reach their full technical potential" (National Renewable Energy Laboratory 2024). In the mid-trajectory technology, "cost and performance improve at moderate levels, with continued industry growth and R&D investment (both public and private). Vehicles include moderate technological advancements (in between the currently manufactured technology and the Advanced trajectory) to achieve higher performance, lower costs, or both, and attaining this level of cost improvement is assumed to be moderately uncertain" (National Renewable Energy Laboratory 2024). Last, in the ATB conservative trajectory, "technology cost and performance improve from base year levels at rates based on the *Annual Energy Outlook*" (National Renewable Energy Laboratory 2024). Table 6 shows the conservative, mid, and advanced trajectories for the fuel cell cost and the onboard storage[1]. In this analysis, sleeper long-haul vehicles are expected to carry 80 kg of hydrogen, and regional day cabs are expected to carry 60 kg.

**Table 6. ATB Trajectories for Fuel Cell and Hydrogen Fuel Storage Costs**

| | | Technology Year | | | |
|---|---|---|---|---|---|
| | **Trajectory** | **2025** | **2030** | **2040** | **2050** |
| Fuel cell cost (2022$/kW) | Conservative | 236 | 188 | 155 | 137 |
| | Mid | 236 | 121 | 90 | 81 |
| | Advanced | 231 | 82 | 66 | 56 |
| Fuel storage cost (2022$/$kg_{H2}$) | Conservative | 795 | 770 | 665 | 608 |
| | Mid | 747 | 448 | 360 | 340 |
| | Advanced | 700 | 389 | 340 | 320 |

The fuel efficiency is not a direct input into the model but instead a calculated output; however, to match trajectories specified by NREL's 2024 Transportation ATB, the model iterates on drive performance to achieve a specified fuel economy. The weight trajectories for each Class 8 vehicle by technology year and drivetrain were based on (Islam et al. 2023; Hunter et al. 2021).

[1] Onboard fuel storage costs shown are not expressly depicted on the ATB but are endogenously incorporated in vehicle price. The 2025 technology year values align with (Simmons et al. 2025) after accounting for production volume.

The cargo weight is held constant across all technology years, and it is the same across day cab and sleeper vehicles. In addition, the conventional diesel and FCEVs carry the same cargo weight to maintain a fair comparison. Table 7 shows the fuel efficiencies used in this analysis, which considers the conservative, mid, and advanced ATB trajectories.

**Table 7. Fuel Economy Trajectories From NREL ATB for Sleepers and Day Cabs**

| | | | Technology Year | | | |
|---|---|---|---|---|---|---|
| | | Trajectory | 2025 | 2030 | 2040 | 2050 |
| Fuel efficiency (mi/gde) | Sleeper | Conservative | 8.0 | 8.0 | 8.0 | 8.0 |
| | | Mid | 9.1 | 10.2 | 12.0 | 13.3 |
| | | Advanced | 9.6 | 13.2 | 15.8 | 17.6 |
| | Day cab | Conservative | 7.7 | 7.7 | 7.7 | 7.7 |
| | | Mid | 8.8 | 9.9 | 11.7 | 13.0 |
| | | Advanced | 9.4 | 12.9 | 15.3 | 17.0 |

The TCO analysis incorporates the manufacturer's suggested retail price, illustrated in Figure 18, into the model categorized by components. The components included are glider, fuel converter, fuel storage, auxiliary battery, motor and power electronics, and purchase tax. The glider is not expected to decrease in cost in future technology years, but the fuel converter, fuel storage, auxiliary battery, motor and power electronics are expected to see improvements in performance and decreases in cost. The diesel truck (black line) is shown for comparison between the two drivetrains.

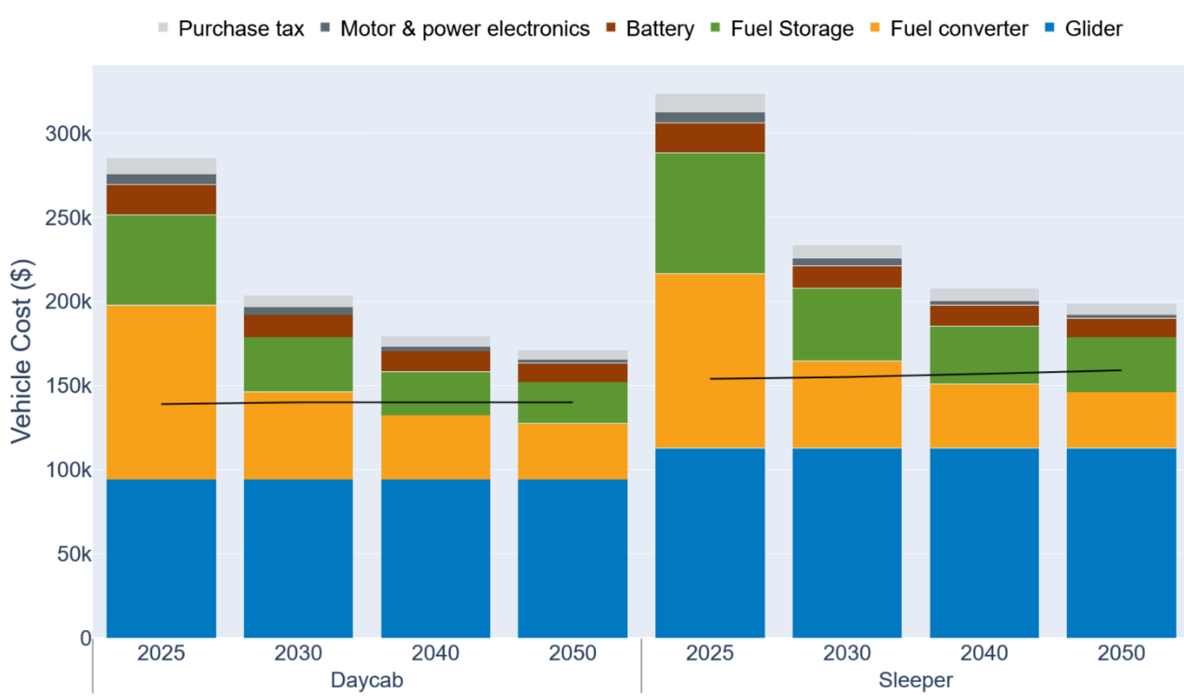


**Figure 18. Estimates of vehicle cost for fuel cell trucks, assuming costs in ATB mid trajectory**

## 4.2 Fueling Protocols and Dwell Time

The present analysis investigates the effects of fueling protocol on the TCO. The fueling protocols included are SAE J2601/5 (SAE International 2024) and the PRHYDE protocols of T-static, T-initial, and T-throttle (Hart et al. 2023). The protocols primarily affect the station design by influencing fueling time. The fueling time dictates the sizing of the equipment to handle the prescribed demand profile. In this analysis, the variation in protocol is modeled to affect the TCO only through its impact on dispensed cost and through its impact on the amount of time that the truck is idling, as demonstrated in Figure 16 and explained below.

For each combination of protocol, precooling temperature, and ambient temperature, the fueling rate and time are calculated in H2FillS (Kuroki et al. 2021). The total time at the dispenser is the sum of the fueling time and the lingering time. The calculated total time is imported into the T3CO to determine the dwell time cost accrual. Under certain temperatures and protocols, the fueling time for an HD FCEV might be relatively longer than a conventional diesel fill. In this analysis, dwell time refers to the on-duty time that the vehicle and driver are not in transit moving the products, and it includes the time loading and unloading equipment, as well as the time spent fueling (Hunter et al. 2021; Federal Motor Carrier Safety Administration 2015). Slow-fueling protocols increase forced downtime, which consumes hours of service (Hunter et al. 2021).

In this analysis, if a hydrogen fill surpasses 5 minutes (the assumed diesel fill time), then a dwell time cost is incurred. This analysis also assumes that vehicles are fueling enroute and not at a depot. A dwell time rate is taken at 75 $/h (Hunter et al. 2021; Ledna et al. 2024) for the sum of all time exceeding the 5 minute cutoff; therefore, a 6-minute duration fill would incur a 1-minute dwell time charge, but a 4-minute fill would not incur any dwell time cost. The number of fill-ups per year is determined by dividing the VMT by the mileage efficiency and the tank size:

$$C_{dwell} = \frac{VMT\ [mi/yr]}{Mileage\ efficiency\ [mi/kg_{H2}]} \times \frac{Dwell\ time\ [h]}{Fuel\ tank\ size\ [kg_{H2}]} \times Dwell\ rate\ [\$/h]$$

## 4.3 Fuel Price

The vehicles in the TCO analysis are assumed to purchase a full tank's worth of hydrogen at the station, and it is purchased at a consistent fuel price over the vehicle's lifetime. The fuel price is the sum of the levelized station cost and the price of the hydrogen delivered to the station. The levelized station cost is calculated in HDRSAM for each protocol, ambient temperature, precooling temperature, fleet size, lingering time, and demand profile. Sensitivity analysis in Section 4.4 varies the price of hydrogen delivered to the station based on different assumptions of the type and cost of hydrogen production.

The ranges for cost of hydrogen delivered to the station consider hydrogen production costs of $1.5–$5/kg[2] and an assumed cost of hydrogen liquefaction, terminal operations, and delivery of $3.9/kg (Bracci et al. 2024). The resulting cost of hydrogen delivered to the station is $5.4–

[2]This range of production costs is intended to reflect the price of natural gas reforming ($1-$2/kg) and the price of electrolysis (~$5-$7/kg) (Bracci et al. 2024; Hubert et al. 2024)

$8.9/kg. The production method, delivery pathway, storage option, deployment scale, and location can all significantly influence the price; therefore, this analysis abstracts the hydrogen delivery price to the station with three static values to focus the analysis on the effects of the protocols. The levelized station cost calculated in HDRSAM for the full sensitivity range of parameters is $2.7–$12.2/kg. Combining the cost of hydrogen production, delivery to the station, and the levelized station cost, the fuel prices considered are $8.1–$21.1/kg.

## 4.4 Total Cost of Ownership Sensitivity Analysis

### 4.4.1 Sensitivity Parameters

Tornado plots were prepared to compare the TCO sensitivity to key parameters in the techno-economic analysis. The tornado plots start at a base case scenario under the following parameters: Class 8 sleeper, hydrogen delivered to the station at $7.15/kg (midpoint of the cost range of hydrogen delivered to the station), technology year 2030, fleet size of 40, a mid-trajectory manufacturer's suggested retail price, the single 10-hour demand profile, a 5-minute lingering time, the mid-trajectory for fuel economy, an ambient temperature of 10°C, and precooling temperature of −20°C. The base case scenario is depicted in the tornado charts as the vertical dotted line at the given TCO units in $/mi. The blue bars represent an increase in TCO for the change in parameter denoted by the label on the left. The changed parameter is color-coded so that the updated value corresponds with the bar chart value. When there is no sensitivity or only two parameter choices, the value will not be plotted.

Four tornado charts were created to distinguish between gaseous and liquid storage at the station, and between SAE J2601/5 and the PRHYDE T-throttle protocol. Figure 19 shows the sensitivity analysis for a gaseous storage-designed station on a Class 8 sleeper long-haul truck. The PRHYDE T-throttle and SAE J2601/5 protocols are both shown as subplots (a) and (b), respectively. For the base case scenario, the PRHYDE T-throttle protocol has an average flow rate of 13 kg/min, leading to a fueling time of 6 minutes for 80-kg dispensed, whereas J2601/5 requires 5 minutes under these conditions. The highest sensitivity for both protocols was the technology year and fuel economy, followed by the delivered price of hydrogen. The delivered price gets added to the station cost to calculate the fuel price. For long-haul vehicles that travel more than 100,000 miles per year, many fueling events are required and can play a significant role in the TCO. Future years are expected to reduce the TCO based on reductions in the purchase cost of multiple components and the fuel economy. Reducing the fleet size from 40 to 20 only affected the relatively slower T-throttle protocol. In this analysis, the ambient and precooling temperatures affected the station design as well as the dwell time costs. The temperature had a minor effect on the TCO (less than $0.1/mi). The TCO was similar in magnitude between the two protocols, indicating that the protocol selection did not have a significant effect on the TCO.

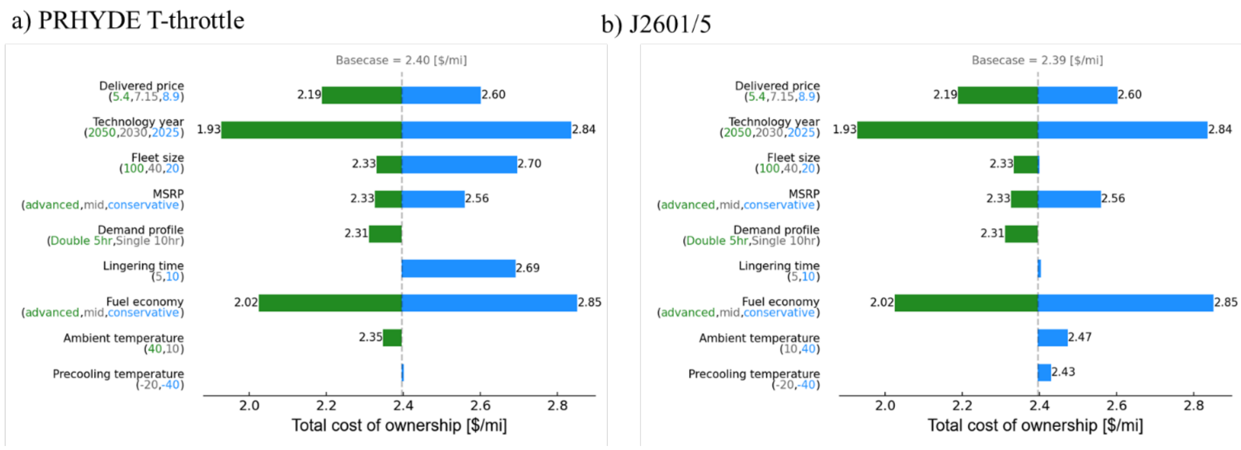


**Figure 19. TCO sensitivity analysis for gaseous storage stations and sleeper long-haul trucks**

Figure 20 shows the sensitivity analyses on the TCO of sleeper long-haul trucks for liquid storage stations. Similar to gaseous storage stations, the TCO was the most sensitive to the technology year and the fuel economy, which can affect the TCO by approximately $0.6–$0.8/mi. The TCO was also sensitive to the delivered price (approximately $0.4/mi). The liquid storage station had no sensitivity to the demand profile, which is due to the ability to satisfy demand without recharging time for the station, whereas the gaseous storage station benefits from a break in the demand profile. The liquid storage station case confirmed the observation from the gaseous storage station that the protocol choice did not have a significant effect on the TCO relative to other parameters in the sensitivity analysis.

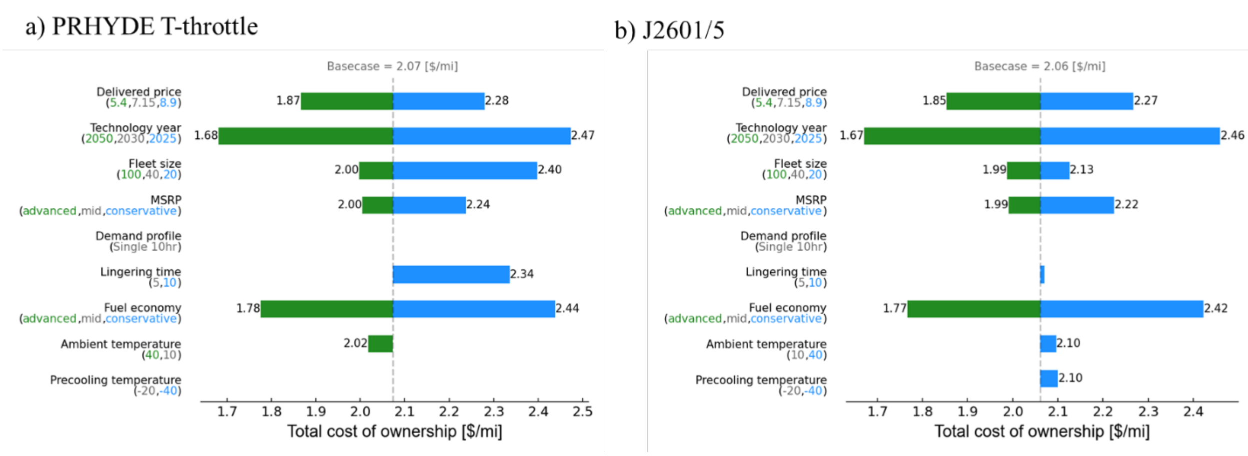


**Figure 20. TCO sensitivity analysis for liquid storage stations and sleeper long-haul trucks**

# 5 Conclusions

HD FCEV fueling protocols were incorporated into the H2FillS-HDRSAM-T3CO model framework to analyze the effects of fueling protocols on fueling time, station cost, and the TCO. The HDRSAM analysis showed that the compressor for gas-supplied stations and the pump for liquid-supplied stations contributed the largest portion to the station cost. The effect of protocols on the station cost was noticeable at high ambient and precooling temperatures, which necessitated the need for additional hoses, booster compressors, and chillers. In general, protocol performance parameters that reduce fueling rates and therefore necessitate additional dispensers are expected to result in relatively more expensive stations. The demand profile showed a negligible effect on the liquid station but up to $1/kg higher levelized station cost for a single 10-hour demand profile compared to the double 5-hour demand profile in the gaseous-storage station. This is mainly because the liquid station is oversized due to a lack of real-world market data regarding cryopumps, which remains a topic for future work. The station cost also showed sensitivity to lingering time, in which increasing the lingering time from 5 to 10 minutes could increase the station cost by up to $3/kg due to the increase in the required number of hoses and the associated capital cost increase. The TCO analysis showed that the delivered price could influence the TCO by approximately $0.4/mi. The cost of vehicle technologies (e.g., fuel cell, storage) also had a large effect on the TCO. Cost reductions, such as those achievable by research, development, and economies of scale might reduce the TCO by approximately $0.8–$0.9/mi. Finally, improving the fuel economy from the conservative trajectory to the advanced trajectory might reduce the TCO by approximately $0.6–$0.8/mi. The protocol selection, however, had a smaller effect on the TCO, at less than $0.1/mi in many scenarios. The filling process, station design, and vehicle characteristics all play an important role in choosing effective protocols for fueling HD FCEVs and will guide future fueling protocol development. It is also important to note that the cost analysis in this report does not necessarily reflect the likely market price for hydrogen fuel, which is affected by other forces, such as supply chain constraints, inflation, and mark-up. Real-world prices for hydrogen fuel at bus stations in recent years have ranged from ~$8-$9/kg (Post and Collins 2023), whereas prices at light-duty stations have ranged from $15-$30/kg (S&P Global 2025).

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