MC Formula Protocol for H35HF Fueling

Taichi Kuroki
Shaun Onorato
National Renewable Energy Laboratory
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Project Goal

- Develop a fully tested and validated H35 high-flow (H35HF) MC Formula fueling protocol for medium-duty (MD) and heavy-duty (HD) buses and trucks.

- The protocol development work is conducted in harmonization with SAE J2601/5, and the developed protocol will be reflected in SAE J2601/5 (there are no sufficient fueling data collected with the right hardware, so the protocol developed on the project will be reflected in a technical information report).

- NREL's hydrogen fueling model, H2FillS, will be upgraded for H35 MD and HD fueling and will be openly available to the public.

The fueling protocol enables other manufacturers and vehicle original equipment manufacturers (OEMs) to enter this space, which will accelerate the growth of the hydrogen market.

Overview

Timeline and Budget

- Project start date: 10/01/2021
- Project end date: 3/31/2024
- Total project budget: $699K
- DOE share: $545K
- Cost share: $154K
- DOE funds spent: $545K
- Cost share funds spent: $154K

(The funding from the industry partners will be used to perform fueling tests under a subcontract)

* As of 03/08/2024

Barriers

- There are no facilities equipped with the right H35HF hardware and a large onboard storage system to verify the protocol across the world.

Partners

- Taichi Kuroki (PI, NREL)
- Shaun Onorato (Co-PI, NREL)
- Frontier Energy Inc. (Industry lead)
  - ElDorado National
  - Gas Technology Institute
  - Luxfer Gas Cylinders
  - New Flyer of America
  - South Coast Air Quality Management District
  - Sunline
  - SoCalGas
  - Shell
  - FirstElement Fuel

Potential Impact

Currently, there is no existing H35HF fueling protocol across the world

- The developed protocol:
  - Is the first-of-its-kind H35HF fueling protocol.
  - Is developed by working closely with SAE J2601/5. The SAE J2601/1 light-duty fueling protocol has been used at commercial stations across the world, meaning the developed protocol is expected to be used broadly.
  - Provides guidelines to design H35HF stations and vehicles.
  - Enable other manufacturers and vehicle original equipment manufacturers (OEMs) to enter this space, which will accelerate the growth of the hydrogen market.

Approach – Project Level –

Year	Year 1												Year 2												Year 3								
Month	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9
Task 1																																	
Task 2																																	
Task 3																																	
Task 4																																	
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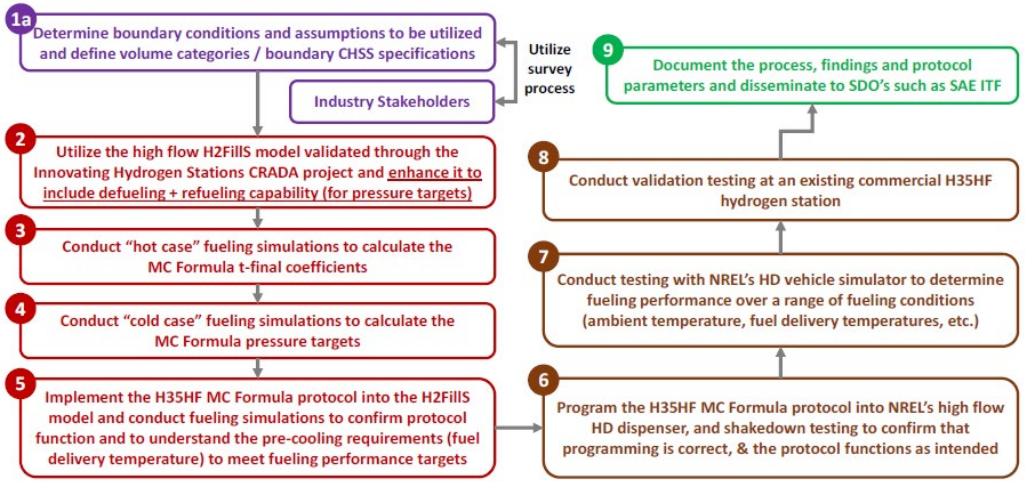
Task 8																																	
Task 9																																	

No-cost time extension is requested



The project can be broken up into four themes:

- Survey to determine H35HF fueling protocol boundary conditions.
- Modeling to help the protocol development
- Testing to verify the reliably of the protocol.
- Documentation to help SAE J2601/5 publish the protocol in their technical information report.

As of March 8, no-cost time extension is requested to complete the protocol validation testing (Task 7).

*For **new projects**, this criterion counts for 20% of your score.

Approach – Boundary Conditions –

We will decide on optimal H35 high-flow fueling protocol structure

- Conduct surveys for H35 station operators and vehicle OEMs
- Integrate the survey results to define boundary conditions for H35 stations and vehicles. For example:
  - Pressure drops caused from components on both station and vehicle sides
  - Thermal masses for both station and vehicle sides
  - Range of allowable mass flow rate supplied from H35 dispenser
  - Upper limit hose pressure

Accomplishments –Define Boundary Conditions–

Determine boundary conditions for H35 high-flow fueling protocol (completed)

- NREL in consolation with SAE J2601/5 successfully collected necessary information to develop fueling protocol (generate fueling tables to regulate fueling speed).
- SAE J2601/5 also conducted surveys to accommodate more broad station providers and vehicle OEMs, and the results are integrated with the survey results conducted on the project.

Table 1 Survey results on station providers/manufacturers

Boundary conditions	Survey results
Desirable fueling time	Less than 15 min
Allowable mass flow rate	120 g/s (7.2 kg/min)
Range of ambient temp	-40 to 50°C
Range of pre-cooling temp	-40 to 20°C

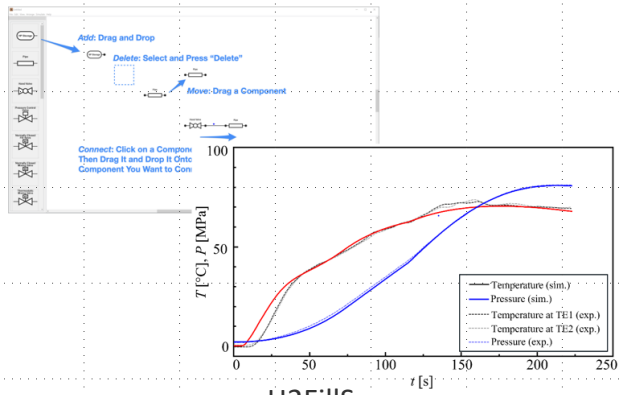
Table 2 Survey results on vehicle OEMs

Boundary conditions	Survey results
Desirable fueling time	Less than 15 min
Range of ambient temp	-40 to 50°C
Range of pre-cooling temp	-40 to 20°C
Lower limit of initial gas press	0.5 MPa
Range of onboard storage system size	20.0 to 70.0 kg
Tank type of onboard storage system	type III & IV

Approach – Modeling for Protocol Development –

We will upgrade H2FillS so that it can assist the protocol development.

- H2FillS's capabilities will be upgraded to accommodate fueling protocol development capabilities as below:
  - Defueling and subsequent fueling simulation capability for target pressure table generation.
  - Optimal pressure ramp rate search capability for fueling table generation.
  - Capability to automate target pressure and fueling table generation process on NREL's high-performance computing (HPC) system.
- Develop fueling protocol validation calculator for station providers to confirm the protocol implementation in their dispensers is sufficiently accurate.

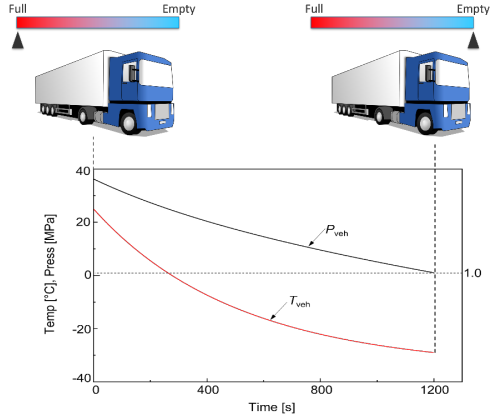


H2FillS

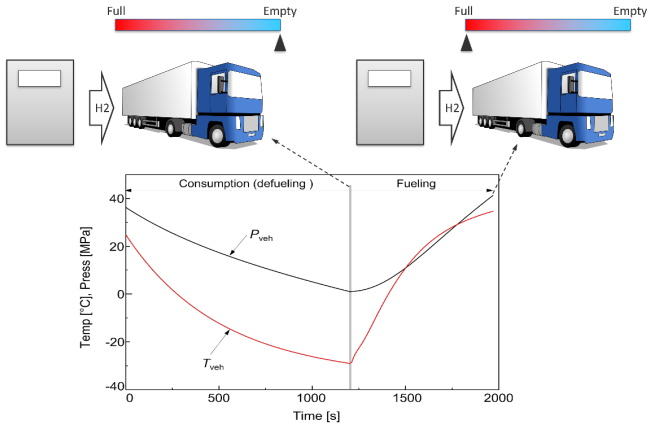
NREL's HPC

Accomplishments –Modeling(1)–

(a) Defueling simulation



(b) Subsequent fueling simulation



(c) Target pressure table generation on HPC

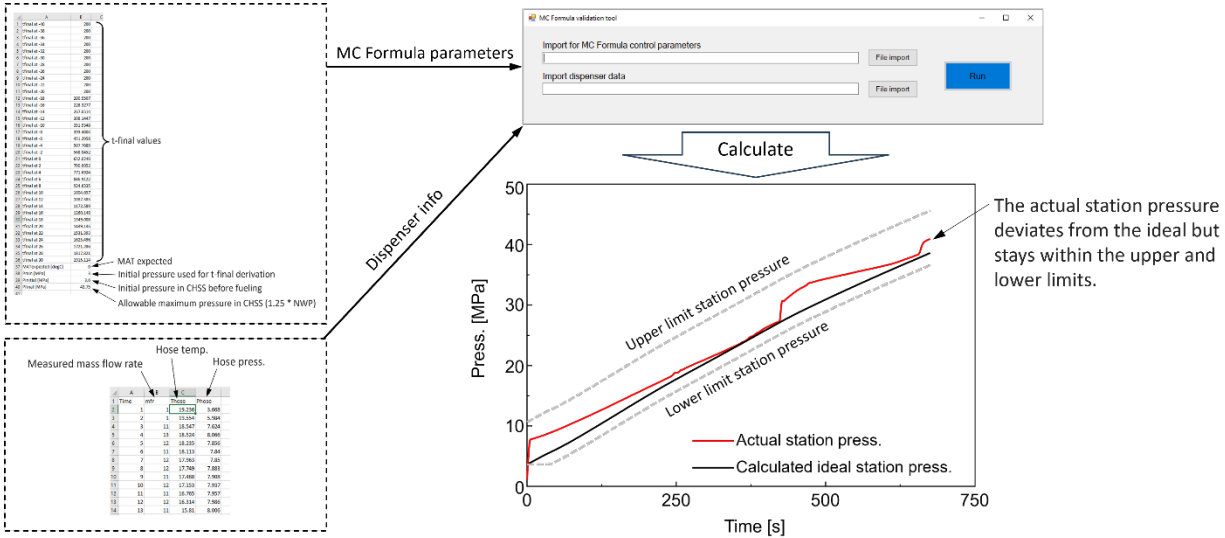
Modeling work – Target pressure/fueling table generation –(completed)

- Developed a defueling algorithm (a).
- Combined the defueling algorithm with H2FillS's fueling algorithm to perform subsequent fueling simulations (b).
- Integrated the defueling & fueling algorithms with the HPC system to generate target pressure table generation (c).
- Developed the automation process of the fueling table generation.

All generated fueling tables have been reflected in the SAE J2601/5 MD/HD fueling protocol document.

H35HF		Target Fueling Pressure, P_{target} [MPa]							
		Initial Tank Pressure, $P_{initial}$ [MPa]							
		≤ 3	5	10	15	20	30	35	> 35
Ambient Temperature, T_{amb} [°C]	> 50	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling
	50	43.75							no fueling
	45	43.75							no fueling
	40	43.75							no fueling
	35	43.75							no fueling
	30	43.75							no fueling
	25	43.75						no fueling	no fueling
	20	43.75	42					no fueling	no fueling
	10	43.75						no fueling	no fueling
	0	43.75						no fueling	no fueling
	-10	43.75						no fueling	no fueling
	-20	43.75					no fueling	no fueling	no fueling
	-30	43.75					no fueling	no fueling	no fueling
	-40	43.75					no fueling	no fueling	no fueling
	< -40	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling	no fueling

Accomplishments –Modeling(2)–



Modeling work – Protocol validation calculator development–(completed)

- Developed an HD fueling protocol validation calculator.
  - This calculator helps MD/HD fueling station providers to ensure that the implementation of the protocol in their dispenser is sufficiently accurate.

Approach: Safety Planning and Culture

- Safety culture has been integrated into this project by conducting a thorough process hazard analysis (PHA) for the design and operation of the H35HF fueling protocol validation testing at the NREL HD station.

Approach – Testing for Protocol Verification –

The H35HF fueling protocol is validated at NREL and ZBT (German H2 testing facility).

Validation at NREL's HD station

- Advantage:
  - There is an available large onboard storage system mimicking a bus that can store about 50 kg of hydrogen at 35 MPa.
  - Hydrogen can be sourced at a high-flow rate >= 120 g/s
- Disadvantage:
  - The fueling hardware consists of H70HF and does not represent an H35HF commercial fueling station.

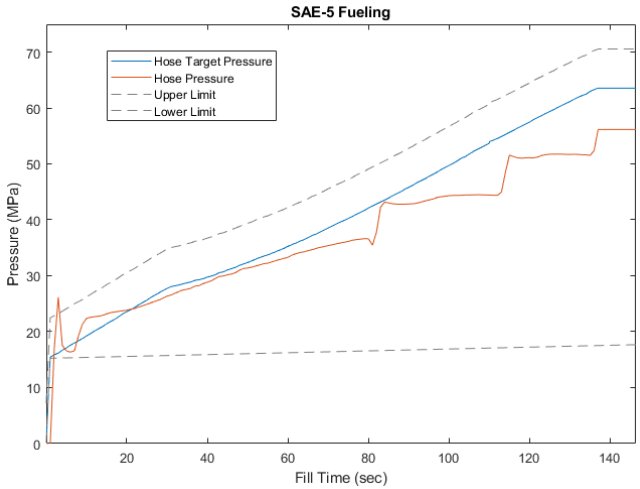
NREL HD station

Validation at ZBT

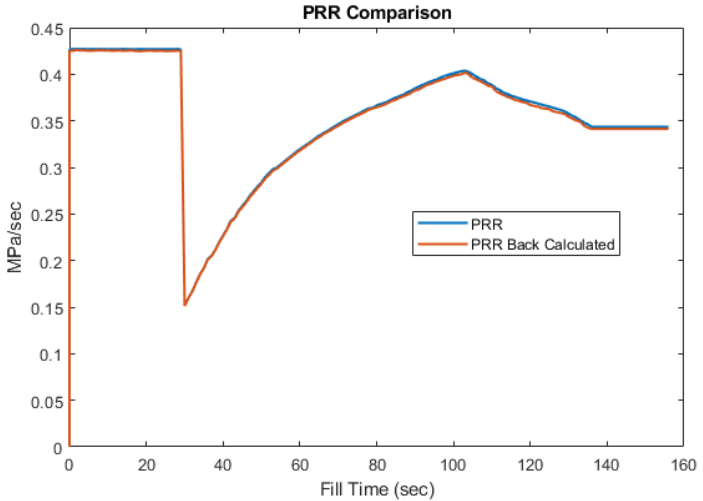
- Advantage:
  - ZBT's fueling system is designed for H35HF fueling.
  - Hydrogen can be sourced at a flow rate up to 120 g/s
- Disadvantage:
  - ZBT cannot perform H35HF fueling with a large onboard storage system consisting of multiple tanks.

ZBT H35HF station (https://lbst.de/wp-content/uploads/2022/09/4_PRHYDE_Final_Workshop_22-09-2022_WP5_Test_Campaign.pdf)

Accomplishments –Testing at NREL–



Target and actual dispenser pressure profiles



Evaluation of accuracy of protocol implementation

H35HF protocol validation process

- Implement the H35HF protocol in NREL's HD dispenser (completed).
- Confirm the dispenser sources hydrogen based on the protocol's fueling control logic (completed).
- Perform H35HF protocol fueling and confirm the vehicle tank temperature and pressure stay within the safety boundary conditions set by the protocol (incomplete).

* As of 03/08/2024

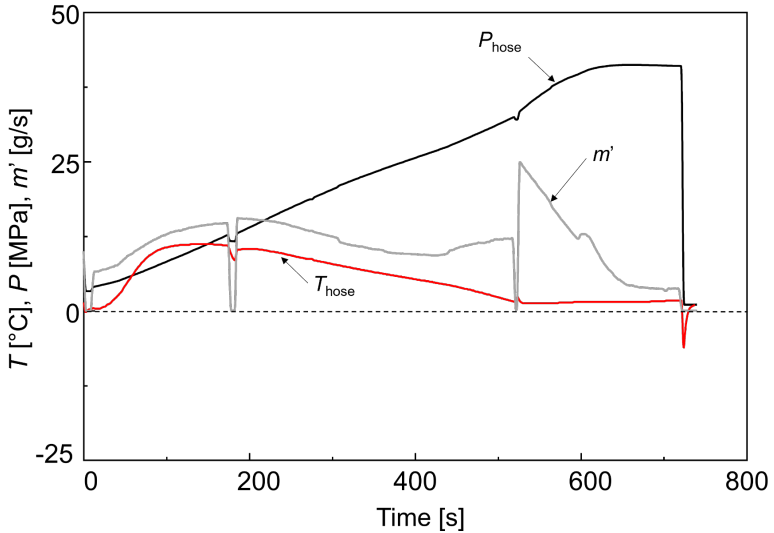
Accomplishments –Testing at ZBT (1)–

	Test conditions			
Test ID	**Tank type**	**Precooling temp. [°C]**	**Initial press. [MPa]**	**Fueling table**
1	IV (244-L)	-16	3	Hot case
2	IV (244-L)	0	3	Hot case
3	IV (244-L)	Ambient temp.	3	Hot case
4	IV (244-L)	-16	1	Hot case
5	IV (244-L)	0	1	Hot case
6	IV (244-L)	Ambient temp.	1	Hot case
7	III (322-L)	Ambient temp.	1	Hot case
8	III (322-L)	-20	1	Cold case
9	IV (350-L)	-16	3	Hot case
10	IV (350-L)	0	3	Hot case
11	IV (350-L)	Ambient temp.	3	Hot case

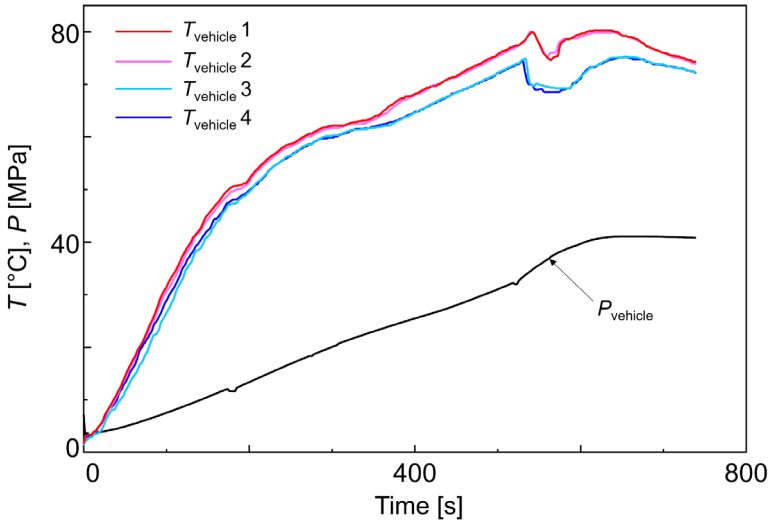
- A total of 11 tests were completed with each of 244-L type IV, 350-L type IV, and 322-L type III tanks.
- Part of the testing was conducted under ambient temperature fueling conditions because the protocol enables ambient temperature fueling when the temperature is equal to or below 20°C.
- All the data will be published as the final report or another publication.

* As of 03/08/2024

Accomplishments –Testing at ZBT (2)–



Supply conditions from H35HF dispenser



Vehicle tank temperature and pressure

H35HF protocol validation at ZBT (completed)

- Succeeded in the implementation of the H35HF protocol in ZBT's H35HF dispenser.
- Confirmed the vehicle tank temperature and pressure stayed withing the safety boundary conditions even under the ambient temperature fueling conditions.

* As of 03/08/2024

Accomplishments and Progress (1):
Response to Previous Year Reviewers' Comments

Q. The project is proceeding on its stated pathway and making progress. However, there was no mention of how the barrier to controlling the dispenser flow/pressure will be resolved, especially since it is listed as not being capable with existing hardware.

Ans. The testing at ZBT (German company) shows that the dispenser pressure is precisely controlled based on the protocol. On the other hand, the NREL dispenser pressure is not smoothly ramped up with sufficient control accuracy; however, the NREL team confirmed that the dispenser pressure profile is still within the protocol's upper and lower limit corridors.

Q. The project clearly delineates its excellent progress toward objectives, categorized by themes. However, some incomplete items in "Theme 3: Validation testing" lack expected timeline dates.

Ans. At the previous year's AMR, the NREL team could not estimate the schedule for the validation testing due to the international subcontracting process; however, the team managed to place the subcontract with ZBT and complete the validation testing. The NREL team expects to complete the testing at NREL by the time this year's AMR will be held.

Q. Themes 1 and 2 are complete, although it would be preferable if more information could be provided regarding the results of the Theme 1 surveys. It is unclear why this information was not shared in the presentation. More results should be presented, rather than indicting tasks are complete.

Ans. The survey results are included in Slide 7 in this presentation.

Q. Themes 1 and 2 are complete, although it would be preferable if more information could be provided regarding the results of the Theme 1 surveys. It is unclear why this information was not shared in the presentation. More results should be presented, rather than indicting tasks are complete.

Ans. It took longer than expected for the subcontract to be signed, and therefore, the team could not make progress as expected; however, the team managed to have the subcontracting and collect the protocol validation data.

Accomplishments and Progress (2): Response to Previous Year Reviewers' Comments

Q. It is not clear whether the stated SAE J2601-2 standard is the intended target, as it is understood that this effort would be incorporated into SAE J2601-5.

Ans. The outcome of this project would be reflected in an SAE J2601/2 protocol document due to the original intention of SAE J2601/2 members. However, J2601/2 decided to include an H35HF fueling protocol in a J2601/5 document along with an H70HF fueling protocol, so the NREL team started working closely with the SAE J2601/5. For this reason, the previous presentation contained two words J2601/2 and J2601/5, which confused reviewers.

Q. The future work mentions adoption within SAE J2601-2 but does not describe how that will be done or whether the project team has developed consensus within that team that this work will be adopted. The partners are primarily related to bus fueling, so the protocol might not gain broad support unless a plan is in place. In addition, limited testing at one site might be insufficient to lock into a standard. Additional testing might be needed first.

Ans. The NREL team worked closely with SAE J2601/5 and attended the SAE J2601/5 meetings so that the direction of the project aligned with the SAE J2601/5's protocol development. The NREL team mainly helped SAE J2601/5 by leveraging the modeling and performing the protocol validation testing.

Q. A barrier is listed that existing hardware might not be sufficient to meet the developed H35HF MC protocol. If so, then it is premature to advance that in SAE J2601 unless that issue is resolved first.

Ans. As described in the project goal slide (Slide 2), there are no sufficient fueling data collected with the right hardware. The protocol being developed on the project aims for a technical information report published by SAE J2601/5 and not for a standard.

Accomplishments and Progress (3): Response to Previous Year Reviewers' Comments

Q. The project should proceed and continue with its planned future work.

Ans. MD/HD fueling testing is required for the project, and the testing involves high-flow fueling that current commercial fueling stations are not capable of. Due to this new technology, the project has not been moving forward as planned.

Collaboration and Coordination

Administrative Role:

- Frontier Energy

Industry Partners:

- ElDorado National
- Gas Technology Institute
- Luxfer Gas Cylinders
- New Flyer of America
- Shell
- South Coast Air Quality Management District
- Sunline
- SoCalGas
- Trillium

<u>Other collaborations</u>

- SAE J2601/5
- NDEO & Kyushu University: Continued H2FillS development

Remaining Challenges and Barriers

Completion of fueling protocol validating testing at NREL HD station

Expected challenges/barriers:

- NREL's HD station capabilities are shared with other projects, so there is a possibility of timeline overlaps between projects that could result in a delay.
- The flow control valve does not actuate as quickly as to control the dispenser pressure based on the protocol, so the fueling data generated on this task may be different than expected.

Proposed Future Work

Future work for rest of FY24

- Complete the protocol validation testing at the NREL HD station.
- Write up the final project report and publish data.

Note that any proposed future work is subject to change based on funding levels.

Summary

- This project is developing a fully tested and validated H35 high-flow MC Formula fueling protocol for MD and HD buses and trucks by working closely with SAE J2601/5.
- The work complected on the project was reflected in an SAE J2601/5 technical information report (the report will be revised and then published as a standard once sufficient MD/HD fueling data come out).
- The protocol boundary condition setting, modeling work, and part of the protocol validation testing were completed; however, the protocol validation testing at the NREL HD station (Task 7) has not been completed. The team and the project partners have been making progress to complete the final task and then successfully conclude the project.