Renewable Hydrogen to Vehicle (RH2V) – Operation Verification and Risk Mitigation Studies

Cooperative Research and Development Final Report

CRADA Number: CRD-15-00577

NREL Technical Contacts: Jennifer Kurtz, Andrew Kotz, and Jason Lustbader

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July 2025

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15013 Denver West Parkway
Golden, CO 80401
303-275-3000 • www.nrel.gov

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Cooperative Research and Development Final Report

Report Date: March 25, 2025

In accordance with requirements set forth in the terms of the CRADA agreement, this document is the CRADA final report, including a list of subject inventions, to be forwarded to the DOE Office of Scientific and Technical Information as part of the commitment to the public to demonstrate results of federally funded research.

Parties to the Agreement: Toyota Motor Sales, U.S.A., Inc.

CRADA Number: CRD-15-00577

CRADA Title: Renewable Hydrogen to Vehicle (RH2V) – Operation Verification and Risk Mitigation Studies: Original Agreement (Modification 0)

Modifications 1, 2, 3: Next Generation Hydrogen Station

Mod 4: Renewable Hydrogen to Vehicle Optimization

Mod 5: Renewable Hydrogen and Vehicle Fuel Cell Backup Power for Datacenters

Mod 6: FleetDNA Drive Cycle Evaluation to Inform Electrolyzer Hydrogen Station Requirements for Fuel Cell Trucks

Mods 7-8: -No-Cost Time Extension

Mod 9: Toyota Duty Cycle Analysis and Maintenance Study (Heavy Duty Commercial Vehicles)

Mods 10 – 11: -No-Cost Time Extension

Responsible Technical Contacts at NREL:

Mods 0-8: Jennifer Kurtz , jennifer.kurtz@nrel.gov (Lead)

Mods 9-11: Andrew Kotz, andrew.kotz@nrel.gov and Jason Lustbader jason.lustbader@nrel.gov (Co-Authors)

Name and Email Address of POC at Company:

Jaycie Chitwood | Jaycie.chitwood@toyota.com (Mod 1)

Jason Sekhon | Jason.Sekhon@toyota.com (Mod 2-8)

Luke Rippelmeyer | luke.rippelmeyer@toyota.com (Mods 9-11)

Sponsoring DOE Program Office(s): Office of Energy Efficiency and Renewable Energy (EERE), Hydrogen Fuel Cell Technologies Office

Joint Work Statement Funding Table showing DOE commitment:

No NREL Shared Resources

Estimated Costs	NREL Shared Resources a/k/a Government In-Kind
Original Agreement – Modification#11 (Years 1-7)	$0.00
TOTALS	$0.00

Acronyms:

BEV: Battery Electric Vehicle

CHAT: California Hydrogen Accounting tool

CHIT California Hydrogen Infrastructure tool

DriveCAT: Drive cycle analysis tool

FCEV: Fuel Cell Electric Vehicle

FleetDNA: Commercial Fleet Vehicle Operating Data

HyWAM: hydrogen wide area monitor

H2FIRST: Hydrogen Fueling Infrastructure Research and station Technology

MHDV: Medium or Heavy Duty Vehicles

PEM: Proton Exchange Membrane

PV: Photovoltaic

SERA: Scenario Evaluation, regionalization and analysis

Executive Summary of CRADA Work:

Original Agreement: Toyota has announced plans for commercial fuel cell vehicle deployment in 2015. To fully realize the benefits of fuel cell vehicles (zero emission with no performance loss in terms of vehicle range and capability), hydrogen produced efficiently from renewable sources is necessary. Most of the hydrogen fueling stations today utilize hydrogen reformed from natural gas (produced onsite or delivered). This enables more stations to be deployed cost-effectively within a network. Producing and using cost-effective renewable hydrogen in fuel cell vehicles will enable realization of the full potential. A viable option of green hydrogen that reliably delivers on the full suite of benefits for Toyota fuel cell vehicle drivers is needed.

NREL is in a unique position to analyze and optimize renewable hydrogen production scenarios using the Energy Systems Integration Facility (ESIF), a facility that is specifically designed to evaluate renewable energy integration technologies. As the U.S. Department of Energy's (DOE) primary national laboratory for renewable energy and energy efficiency research and development, NREL has extensive knowledge of photovoltaic systems as well as alternative renewable technologies for efficient and reliable production of green hydrogen.

Mods 1 - 3: Develop a vision of future hydrogen station design, allowing for different station types and market needs based on location. This project will continue to build on the future station design vision through focused research and development with key partners and hydrogen stakeholders to develop innovative sub-systems and components that enable advanced hydrogen station design. This project aims to develop a portfolio of station options, with research and development attention on cost reduction via the elimination of major capital equipment such as gas compressors, chillers, and gaseous storage, resulting in increased reliability and higher throughput. (In Mod 6, Task 3 is removed from Mod 2).

Mod 4: Evaluate the economic viability of a 3-in-1 station design by creating a model that integrates hydrogen fueling, battery electric vehicle charging, and solar generation. The analysis will include a conceptual design and size estimate of the sub-systems for light-duty fuel cell electric vehicles (FCEVs), light-duty battery electric vehicles (BEVs), and medium/heavy-duty FCEVs. The analysis will study the benefits and disadvantages for the integrated multi-fuel, multi-service stations. The work is considered an initial step for a potential flagship retail station based in a location in the Northwest.

Mod 5: Leverage existing tools to create a regional analysis focused on the hydrogen supply options for fuel cells providing backup power to datacenters in the Northwest U.S. NREL will capture hydrogen demand from the datacenter by assuming a backup power need of 48 hours at a consistent power of 500 MW and 1 GW. The study of hydrogen storage will include high-level economics and technology readiness levels for gas, liquid, pipeline, and ammonia, as well as delivered or on-site production. The study will also consider options for replenishing the hydrogen storage after a backup power run.

Mod 6: Develop representative drive cycles for high-potential classes and vocations for a hydrogen powertrain. The driving information will provide data to inform requirements for electrolyzer production for hydrogen fueling stations supporting fuel cell trucks. (Removes Task 3 from Mod 2.)

Mods 7 and 8: No cost time extensions.

Mods 9, 10, 11: Toyota is developing fuel cell technology for medium- and heavy-duty vehicles (MHDVs) and has been working with NREL to develop vocationally representative duty cycles. To help disseminate and improve the results, NREL will append road grade to the identified cycles and publish duty cycle findings in a journal paper in addition to uploading these cycles to NREL's DriveCAT database. As a second separate task, NREL will acquire and analyze maintenance data that is representative of typical MHDVs in similar operations. These data and analyses will be used by Toyota internally and will not be published by NREL.

CRADA benefit to DOE, Participant, and U.S. Taxpayer:

- Assists the laboratory in achieving advances to hydrogen station infrastructure and next-generation concepts (Mods 0-5).
- Adds new capability to the laboratory's core competencies through detailed partnership discussions that inform the requirements for hydrogen stations based on FCEV demand and projections (Mods 1-5).
- Enhances the laboratory's core competencies and U.S. competitiveness by developing a unique understanding of hydrogen station requirements and the engineering of safely and quickly dispensing hydrogen (Mods 1-5).
- Assists the laboratory in achieving programmatic scope (Mods 6, 9-11).
- Enhances the laboratory's core competencies (Mods 6, 9-11).
- Uses the laboratory's core competencies, and/or (Mods 6, 9-11).
- Enhances U.S. competitiveness by utilizing DOE-developed intellectual property and/or capabilities (Mods 6, 9-11).

Summary of Research Results:

Modification 0, Original Agreement:

Description: Verify the efficiency, performance, and costs for the operation of a 22 to 55 kg/day electrolyzer powered by a mix of direct-connect solar and grid-simulated profiles over a typical year based on confidential grid profiles for Toyota facilities (e.g., Ontario, CA) to be supplied by Toyota. NREL will support this objective by utilizing its vast experience testing renewable hydrogen generation through its Wind-to-Hydrogen project. Building on the proof-of-concept experience for renewable hydrogen production, NREL is focusing on the generation system for the initial phase of this project. NREL will perform a simulation test that is specific to a Toyota facility. The test requires installation of hardware (e.g., electrolyzer and supporting infrastructure), annual solar irradiance data, photovoltaic system profile, and grid pricing for variable power electrolyzer operation and optimization specific to confidential grid profiles for that Toyota facility, which will be disclosed to NREL in accordance with the CRADA's terms.

Tasks 1 – 3: Electrolyzer Equipment Setup

The NREL research team utilized the 150 kW PEM electrolyzer stack for DC to DC PV power conversation to hydrogen generation. Materials developed include process and instrumentation diagrams, safety reviews, commissioning, and the test plan.

Tasks 4: Testing

The electrolyzer was operated per the test plan for the Toyota selected location.

Tasks 5 – 7: Economic Analysis, Decommissioning, and Reporting

Outputs of the work shared include system performance, efficiency on various solar and wind profiles based on the location of a Toyota facility. A final review of performance and economics was delivered to the Toyota team as a presentation. The output informed next steps and pushed forward our understanding of dynamic electrolyzer operations for renewable hydrogen generation and hydrogen stations capable of filling 15 cars/day reliably.

MODIFICATION 1:

Description: This project aims to develop a vision of future hydrogen station design, allowing for different station types and market needs based on location. This project will continue to build on the future station design vision through focused research and development with key partners and hydrogen stakeholders to develop innovative sub-systems and components that enable advanced hydrogen station design. This project aims to develop a portfolio of station options, with research and development attention on cost reduction via the elimination of major capital equipment such as gas compressors, chillers, and gaseous storage, resulting in increased reliability and higher throughput.

The project impact is a roadmap of feasible hydrogen station designs/technologies capable of meeting future market demands and matching with the pace of FCEV technology improvements.

Outputs

The future hydrogen station vision was summarized via a report and presentation. The vision report included assumptions, literature search results, station types, and station design concepts sections. The report provided a benefit of the hydrogen stakeholder community with the goal of raising awareness of the need for future station technology development, such as DOE's reference station designs and the development of a deployable device to characterize station capabilities.

What is the vision for future hydrogen station designs? There are many variations and possibilities for the future hydrogen station. We assume that the future hydrogen station design must be low-cost, reliable, and higher throughput than the current stations to meet consumer demand. We used peer-reviewed research to support assumptions on the market needs and locations (e.g., Scenario Evaluation, Regionalization, and Analysis (SERA) Public-Private Partnership - H2USA California Hydrogen Infrastructure tool (CHIT) - California Hydrogen Accounting tool (CHAT) - California Energy Commission (CEC) etc.) in the next five years, focusing first on California future scenarios. We also assume that there are going to be a variety of station types (i.e., one size will not fit all) and that different stakeholders have a variety of needs, so part of this task was analyzing those needs. The Kano customer satisfaction model [1] may be applied as a basis for technology performance with an impact on customer satisfaction.

This task built off the current station designs and capabilities, along with Hydrogen Fueling Infrastructure Research and Station Technology (H2FIRST) reference station designs [2] and be a high-level view of how future stations could and should evolve. This task covered expected requirements for cost, throughput, capacity, footprint, reliability, and type/location.

A station with over 600 kg of storage could dispense 300 – 400 kg of hydrogen (supporting approximately 90 FCEVs per day) with a delivery of an equal amount daily (Figure 1). This station dispensing capacity calculation can also be optimized based on a control strategy or new station configurations. One challenge with projected station capacity is it requires an estimate of station availability.

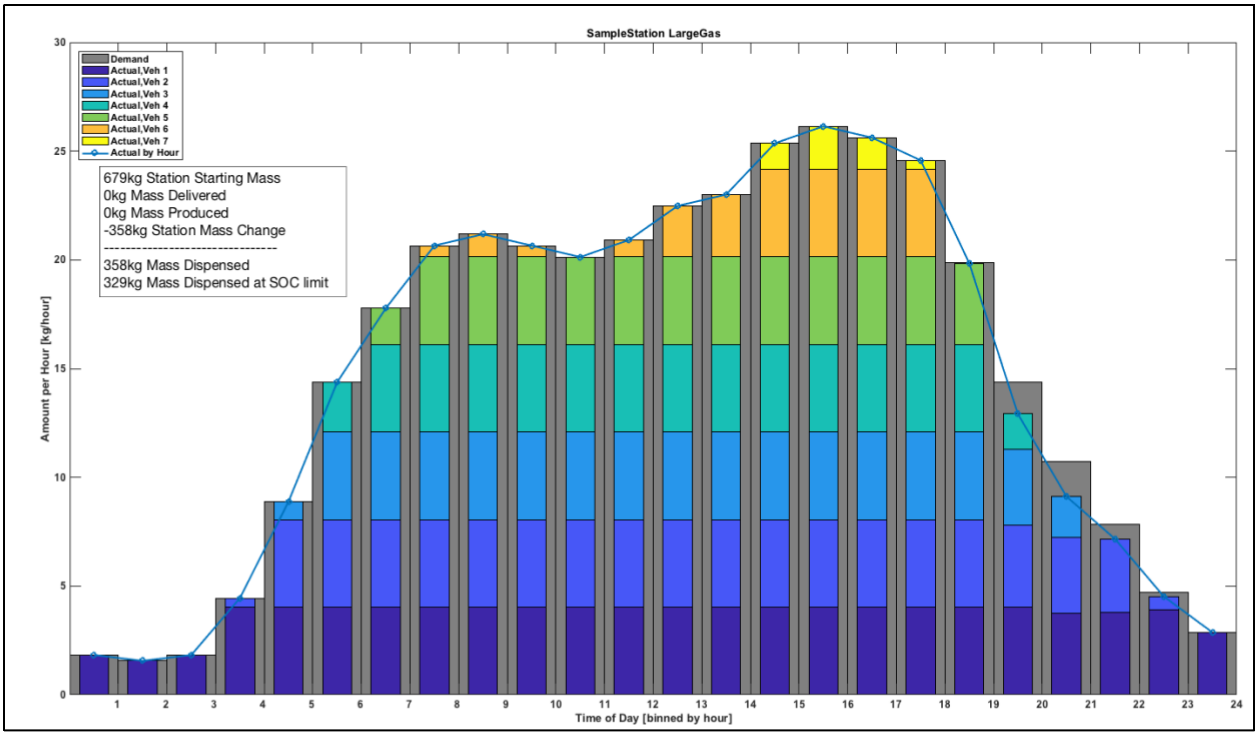

Figure 1. Sample delivered gas fueling capacity per CSA HGV 4.9 and a pre-defined fill profile

The future hydrogen station vision was summarized via a presentation to Toyota. Three scenarios were studied and included a high-throughput liquid station with integrated components, a hub and spoke with high-pressure pipeline delivery, and a renewable station. The vision presented solutions for price and availability challenges.

Recommendations	Options	
Eliminate or convert to lower-cost components without sacrificing reliability	Turboexpander for hydrogen cooling instead of chiller Share BOP for hub-and-spoke stations with high pressure pipeline Increase fueling temperature Integrated liquid cooling High capacity/pressure delivery (tube trailer and pipeline) Alternative storage (e.g., underground)	High throughput compression (recovery and direct fueling) Increase operating pressure ranges for compression High pressure evaporator Cryogenic liquid pump Simultaneous fueling (e.g., 4 positions) Identify and eliminate thermal/pressure losses Common manifolding
Decrease unscheduled maintenance costs without sacrificing capital cost	Active station health monitoring Prognostics for component remaining useful life Predictive fueling demand for maintenance scheduling and incentivized fueling Low temp, high pressure valves Station-to-X operation algorithms for supply, controllable load, and scheduled fueling Autonomous fueling	
Increase cost-effective, renewable hydrogen	Identify regional existing renewable energy for integration with electrolysis Network supply of the hydrogen to multiple stations PPAs and RECs	

The turboexpander idea turned into a separate partnership activity with Toyota and DOE. Another idea for integrating fast charge and hydrogen stations was also picked up for a future activity.

Modification 2:

Note: Task 3 of Mod 2 was later removed in Mod 6. This task and associated funding are now covered under CRD-18-00773.

Description: Expand the future hydrogen station design to understand the impact of ammonia and the latest on station reliability and safety sensors.

Output:

With respect to the impact of ammonia on hydrogen stations: The tasks are designed to answer questions like 1) Where are U.S.-located ammonia pipelines? 2) What are ammonia distribution (pipeline and truck) costs? 3) What are ammonia to hydrogen conversion costs? First, the team collected ammonia pipeline and production maps. Second, the team found cost estimates for pipeline, trucking, and conversion options. These maps and cost estimates were summarized via presentation to Toyota. The current U.S. ammonia pipeline and production capacity and transportation costs with a comparison to different transportation methods were included in the presentation.

With respect to hydrogen station component reliability: To support the growth in hydrogen infrastructure, new manufacturers are entering the market, supplying new technologies and solving infrastructure problems. Success in the market for new manufacturers is dependent on their technologies meeting the rigorous safety standards and performance specifications for hydrogen infrastructure. However, the infrastructure required to research infrastructure problems and evaluate technologies can be prohibitively expensive, increasing the risk to companies as they enter the market. One possible solution to managing company risk is to leverage third-party expertise and capabilities, collaboratively addressing critical problems that inhibit the growth of the industry. The third-party entity must provide a platform for exploring innovative solutions and validation of technology, generate publicly available operational, maintenance, and safety data, and act as an incubator for promising new technologies. This proposal provides a framework for building upon existing expertise to create a collaborative hydrogen infrastructure center and incubator at NREL's Hydrogen Infrastructure Testing and Research Facility (HITRF) in Golden, CO.

NREL leveraged their expertise in Hardware-in-the-Loop (HIL) testing to evaluate components under a range of conditions and demand profiles. HIL testing provides validation data for model development, allowing researchers to combine model components and extrapolate to the large throughput hydrogen station scenarios needed to support widespread deployment of light-, medium-, and heavy-duty fuel cell electric vehicles while minimizing cost.

Currently, retail hydrogen stations require too much maintenance (see Figure 2) for both scheduled and unscheduled events that result in large operating costs. Through December 2016, the maintenance cost for stations submitting data to NFCTEC [3] was very high, at approximately \$21/kg hydrogen dispensed. A maintenance cost much higher than a target sale price of \$4/gge [4] is not sustainable for station operation.

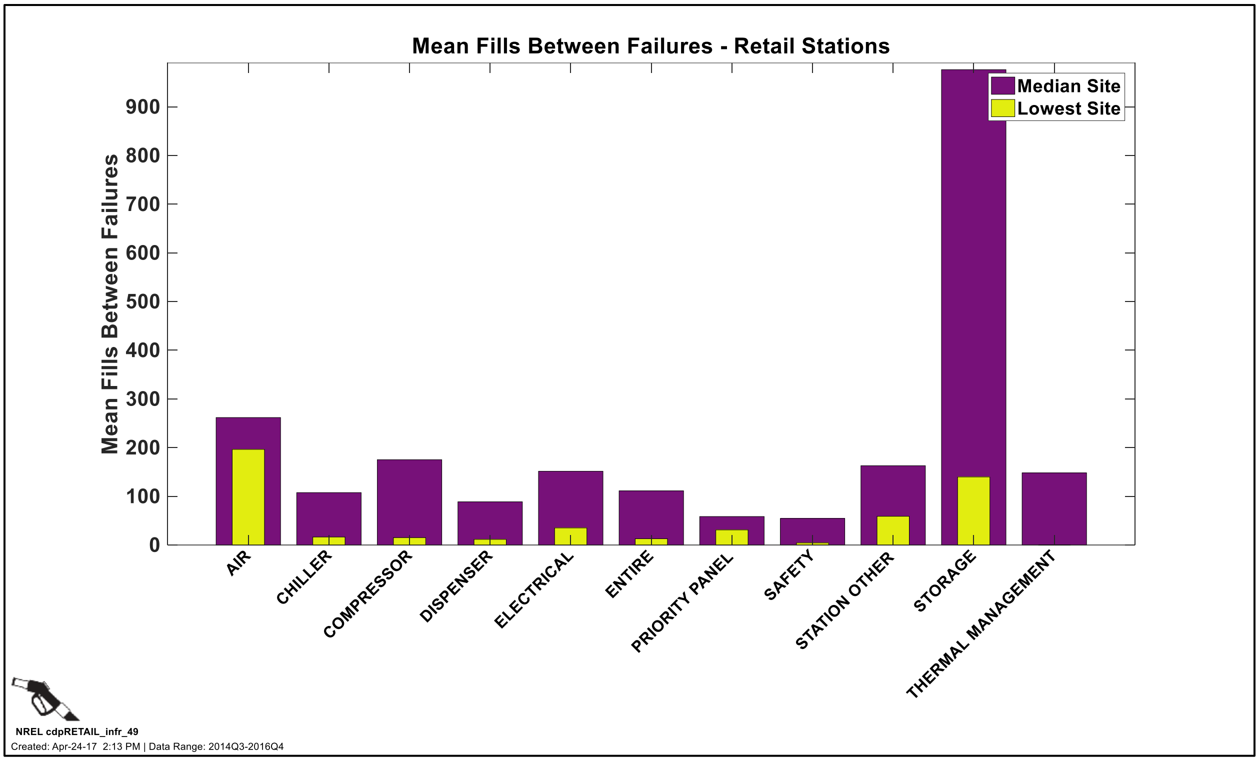

Figure 2. Mean fills between failures by category (CDP-INFR-49)

We hypothesize that the station operation and maintence (O&M) costs can decrease with the use of 1) preventative maintenance informed by both best practices and current station health estimates, 2) preventative maintenance scheduled to minimize impact on hydrogen sale revenues, and 3) predictive fueling demand that enables controlled operation for additional revenue options like grid services.

This alternative fueling concept project will provide proof of concept test data on a turboexpander designed to replace the Joule-Thomson valve currently used for control of SAE J2601 pressure ramp rates. The advantage of using an expander is that it will extract energy from the flow, providing a significant temperature drop at a near isentropic expansion. The expander would minimize the need for a chiller and heat exchanger (see Figure 3). The following are project objectives: 1) System Analysis: Complete system thermodynamic sizing and performance analysis. System analysis optimized expander operation over transient flow conditions. System controls were used to achieve the needed dispensed gas temperature. 2) Design/Build/Validate: Fabricate prototype hydrogen expander hardware capable of conducting proof of concept testing. 3) Reporting: Work was summarized in a final report. This work informed the development of an alternative fueling concept for dispensing stations. Reporting includes recommendations for a final design that will meet system needs for 70 MPa hydrogen dispensing. This relates to a 50% cost share from the H2@Scale DOE project [5].

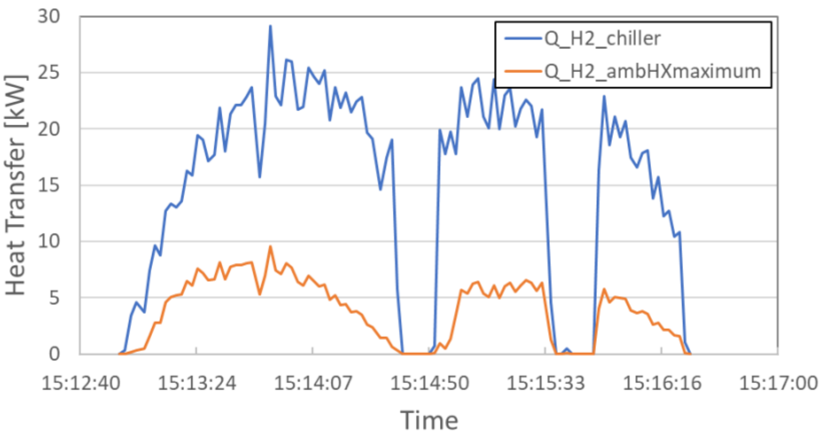

Figure 4. A low-cost hydrogen-to-air heat exchanger upstream of the chiller could reduce capacity and capital cost

With respect to hydrogen station safety sensors: NREL has developed a prototype hydrogen detection system capable of continuous distributed monitoring of hydrogen releases. This system can form the basis of a *hydrogen wide area monitor* (HyWAM). It was field demonstrated at an LH2 facility but is also amenable for GH2 operations. HyWAM is a means to improve facility safety at medium- to large-scale H2 operations as envisioned by H2@Scale. However, an economical, automated, and easily implemented HyWAM does not exist in the market. HyWAM refers to the temporal and 3-dimensional spatial quantitative characterization of hydrogen releases, which can be either intentional or unintentional. Currently, many potential sites for hydrogen fueling stations employing bulk hydrogen storage cannot meet the required storage setback distances. The availability of an intelligent HyWAM to quickly characterize H2 leaks (see Figure 5) not only improves facility safety but can also be used to alleviate restrictive facility design requirements (e.g., national fire protection association (NFPA) 2 setback distances). The NFPA 2 requirements are particularly problematic for LH2 storage. However, NFPA allows for code variances where the applicant can demonstrate an equal or greater level of safety than that set by the prescriptive code requirements. One option for achieving this safety equivalency for liquid storage systems is using a HyWAM that would sense hydrogen at likely system leak points and quickly shut down the system at this incipient leak stage. The task includes an update for sensor selection and integration. Hydrogen releases were profiled by hydrogen sensors and other gas sensors. Facility characterization to include physical sensors (T, RH) and environmental sensors (wind speed and direction). Ultimately, when coupled together, the various sensors allow for the identification of a leak location.

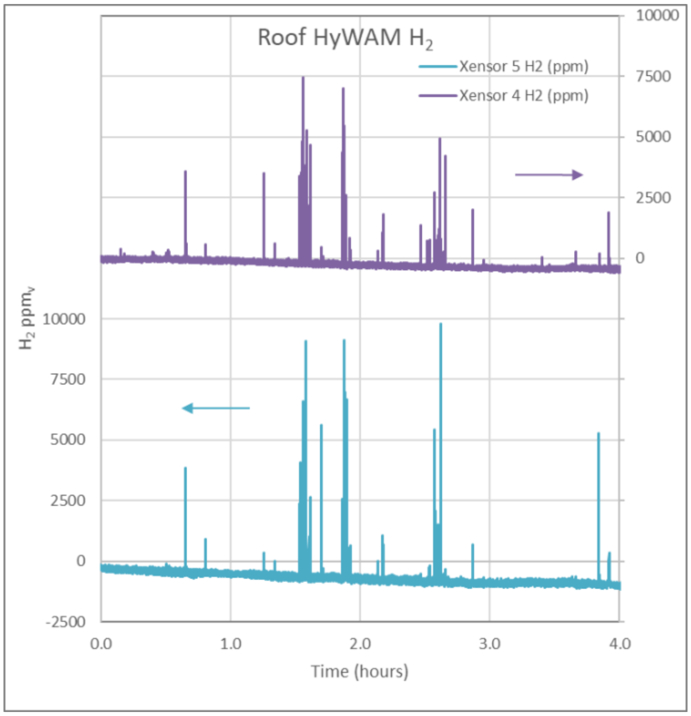

Figure 5. HyWAM hydrogen detection at HITRF

MODIFICATION 3:

Adds funds to complete the work under the existing scope. No changes to the scope of work.

MODIFICATION 4:

Description: Evaluate the capability, sub-system sizes, and economic viability of a 3-in-1 station concept with hydrogen, BEV charging, and solar generation, highlighting the benefits and disadvantages of the system in a published report.

3-in-1 Concept Development:

The NREL team evaluated the economic viability of a 3-in-1 station design by creating a model that integrates hydrogen fueling, battery electric vehicle charging, and solar generation. The analysis included a conceptual design and size estimate of the sub-systems for light-duty FCEVs, light-duty BEVs, and medium/heavy-duty FCEVs. The analysis studied the benefits and disadvantages for the integrated multi-fuel, multi-service stations. The work is considered an initial step for a potential flagship retail station based in a location in the Northwest. Figure 6 illustrates all the subsystems in the 3-in-1 concept.

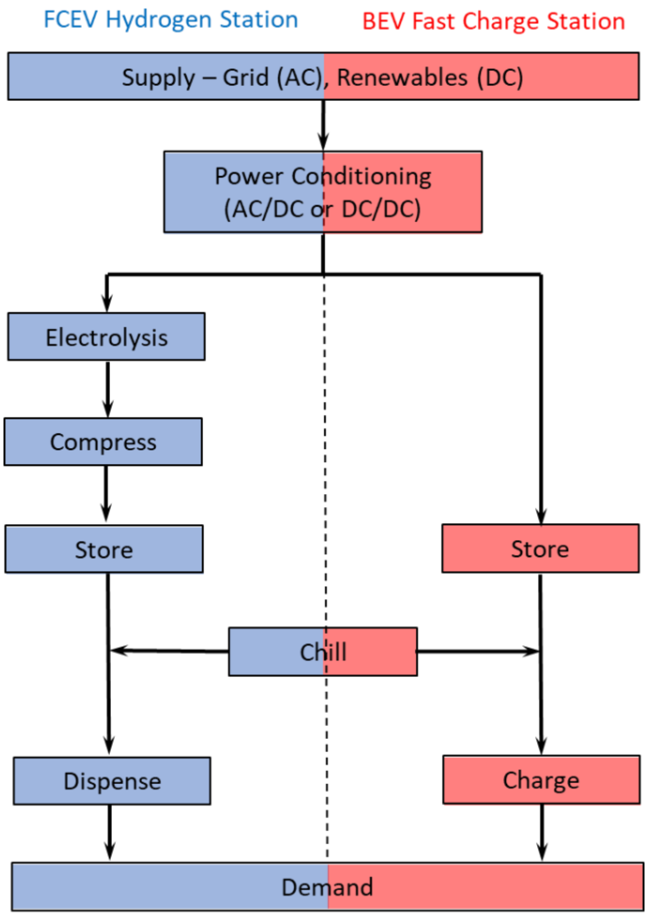

Figure 6. Simple hydrogen and DC fast charge infrastructure

The output of this task was a conceptual station design, size, capability, and operation strategy. The sub-system sizing allows for different priority scenarios, such as the primary factor establishing size being the typical Electrify America charging station size or a specific hydrogen vehicle demand or energy storage for grid management. The research team includes NREL researchers with expertise in each key system area and leverages existing work completed by UC Davis [6].

MODIFICATION 5:

Description: Analyze the supply and demand logistics for a hydrogen fuel cell datacenter in the Northwest U.S. with renewable generation and a vehicle fuel cell system distributed inside the datacenter.

Task 1 – Northwest Datacenter Analysis:

In this task NREL leveraged existing tools to create a regional analysis focused on the hydrogen supply options for fuel cells providing backup power to datacenters in the Northwest United States. NREL captured hydrogen demand from the datacenter by assuming a backup power need of 48 hours at consistent power of 500 MWs and 1 GW.

The study of hydrogen storage included high level economics and technology readiness levels for gas, liquid, pipeline, and ammonia, as well as delivered or on-site production. The study also considered options to replenishing the hydrogen storage after a backup power run. This analysis leveraged previous work as presented at the 2017 Fuel Cell Seminar [7].

NREL ran an initial analysis of this datacenter concept utilizing vehicle fuel cell powerplants for stationary backup power with recommended storage technologies and provide slides to Toyota for distribution at upcoming meetings or conferences. Collecting and implementing feedback from the initial analysis allowed the NREL team to iterate on the analysis assumptions and framework, resulting in a presentation to Toyota for their own distribution.

MODIFICATION 6:

Note: Task 3 of Mod 2 was removed in Mod 6. This task and associated funding are now covered under CRD-18-00773.

Description**:** Developed representative drive cycles for high-potential classes and vocations for a hydrogen powertrain. The driving information provides data to understand the alternative powertrain design and requirements for electrolyzer production for hydrogen fueling stations supporting fuel cell trucks.

Task 1: Provide Initial Vocational Assessment on FleetDNA Drive Cycles

NREL's Fleet DNA was used for five heavy-duty vocations (drayage, long haul, regional haul, local delivery, and transit bus); see Figure 7 for the data preprocessing flow chart. The daily metrics of vehicle speed, distance, time, and speed and torque distributions were used for daily trip analysis for power profiles. The five heavy-duty vocations were selected based on collaboration with Toyota to determine the priority for the detailed analyses.

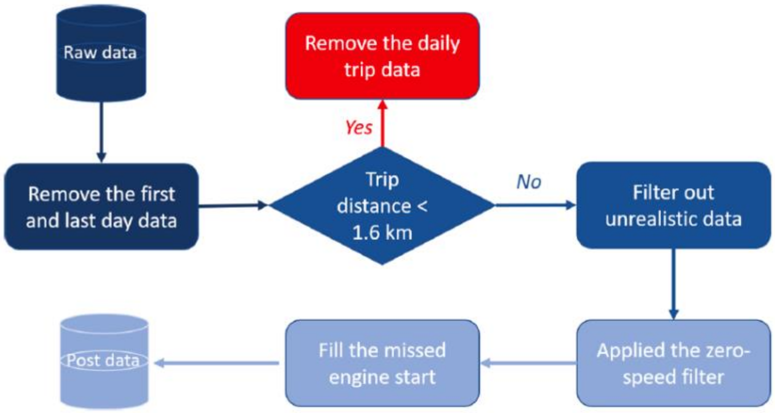

Figure 7. Data preprocessing flow chart

Task 2: Detailed Vocational Assessment and Representative Drive Cycles

With the five heavy-duty vehicle vocations selected in task 1 and with representative route data (Figure 8) and the following drive cycle categories were used to develop the representative duty cycles. The five driving cycle types included:

1. Daily trip with max energy consumption – informs the energy storage requirement.
2. Daily trip with maximal power-weighted work – informs the high-power requirement.
3. Daily trip with maximal time duration at high speed (over 88 km/h or 55 mph) – _informs high speed operation, which produces the most aerodynamical drag force.
4. Daily trip with minimal fuel economy – informs the low efficiency operation of diesel engine and indicates the opportunities for alternative powertrain system.
5. Daily trip that is most representative – informs the typical energy use for the vocation.

Figure 8. U.S. roadways showing freight volume (red) and Fleet DNA data coverage (green) and different vehicle vocation images

To provide an example of the representative duty cycle data for the local delivery vehicle vocation can be seen in (Figure 9 and Figure 10).

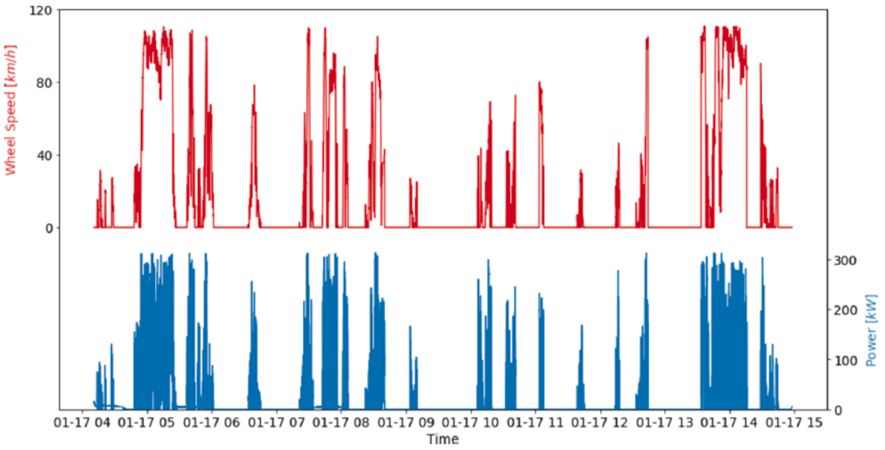

Figure 9. Local delivery daily trip with the most representativeness

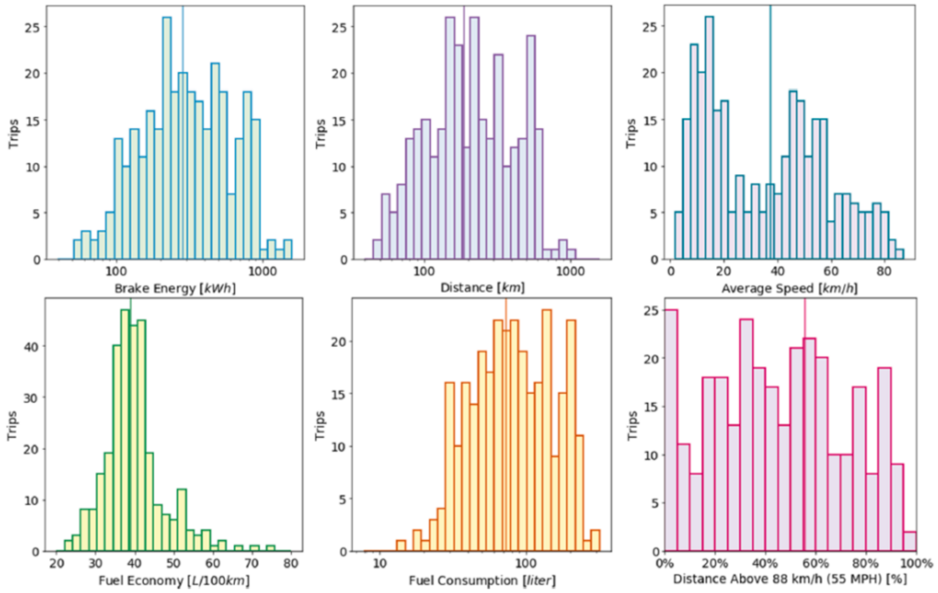

Figure 10. Additional metric distributions for local delivery (vertical lines are the most representativeness trip)

The representative duty cycles included traditional data like speed and acceleration, as well as engine power and fuel consumption. Each vocation has distinct driving behavior/metrics that affect fuel economy and powertrain and infrastructure requirements.

Task 3: Documentation and Publication

The results of this study were published in a peer-reviewed journal in 2021, in Elsevier's Transportation Research Part D [8].

MODIFICATIONS 7 AND 8: NO COST TIME EXTENSION (NO SCOPE/TASKS)

MODIFICATIONS 9-11:

Task 1: Duty Cycle Analysis and Medium- and Heavy-Duty Vehicle Maintenance Cost Study

Description: Toyota is developing fuel cell technology for medium- and heavy-duty vehicles (MHDVs) and has been working with NREL to develop vocationally representative duty cycles. To help disseminate and improve the results, Toyota has asked NREL to append road grade to the identified cycles and publish the findings in a journal paper in addition to uploading these cycles to NREL's DriveCAT database. In addition, Toyota needs maintenance data that is representative of typical MHDVs in similar operations. These data and analysis will be used to model total cost of ownership and develop technical targets.

Work Completed: Using internally developed tools, NREL appended grade to developed duty cycles identified under a previous contract. These cycles are sampled at a 1Hz frequency, and the grade was appended at the same frequency. Outputs of this work include CSV files containing identified duty cycles along with road grade at a 1Hz frequency as well as the following metrics:

- Time (in seconds)
- Speed
- Road Grade
- Engine On-off
- Engine Speed
- Engine Torque
- Engine Power

Disseminating research findings was a key objective of this work. NREL finalized and submitted the journal article corresponding to the drive cycle development to the high- impact journal of Transportation Research Part D: Transport and Environment. This process will involve review by NREL's communications team and revisions based on reviewer comments. Once the publication was finalized, NREL linked to this journal on their website and posted the developed and grade appended cycles on NREL's DriveCAT website [9].

Next, NREL explored the maintenance costs of various advanced technology powertrains, including compressed natural gas (CNG), hydrogen fuel cells, and battery electric, compared to the diesel baseline. NREL has a history of evaluating MHDVs that include maintenance analysis of transit buses and trucks. NREL worked with internal team members to locate existing data sets representative of the vocation of interest. Specifically, the data included the following information:

- Vehicle specifications
- Description of duty-cycle
- Detailed maintenance work orders:
    - Date
    - Unique vehicle identifier
    - Odometer reading
    - Work order number
    - Type of maintenance (scheduled, unscheduled)
    - Description of problem
- Description of repair
- Labor hours per repair type
- Individual parts replaced
- Cost for each part
- Fluid additions and cost per unit (DEF, oil, coolant)

After gathering the data, NREL used existing programs and processes to analyze the data and characterize cost per mile by vehicle system. High level systems include the following categories:

- Propulsion-related systems—Repairs for exhaust, fuel, engine, electric motors, fuel cell modules, battery modules, propulsion control, non-lighting electrical (charging, cranking, and ignition), air intake, cooling, hydraulics, and transmission
- Cab, body, and accessories—Includes body, glass, and paint repairs; cab and sheet metal repairs on seats and doors; and accessory repairs such as hub odometers and radios
- Preventive Maintenance Inspections (PMI))—Labor for preventive maintenance
- Brakes
- Frame, steering, and suspension
- Heating, ventilation, and air conditioning (HVAC)
- Lighting
- Axles, wheels, and drive shaft
- Air system, general
- Tires

Outputs of this work included a presentation to Toyota summarizing the analysis and outlining the overall cost per mile, cost per mile by system, expected cost trend over time, and differences in maintenance between baseline diesel/CNG and fuel cell electric vehicle (FCEV). Results from this data set indicate that there is large month-to-month and bus-to-bus variability in monthly maintenance costs for all propulsion types. This is especially true for the fuel cell buses. The fuel cell buses also display a higher initial maintenance cost, which declined sharply in the first year of operation, suggesting a higher learning curve for maintenance staff and/or initial challenges with the new technology. For all bus types, the cumulative maintenance cost per mile increases steadily over time as the buses age. The aggregated totals from this data set showed very little difference in cumulative maintenance cost per mile between each propulsion type, averaging between $0.40 per mi and $0.46 per mile (Figure 11). These results are influenced by the maintenance practices at each agency and the specific make/model/year of the vehicles included in the evaluations.

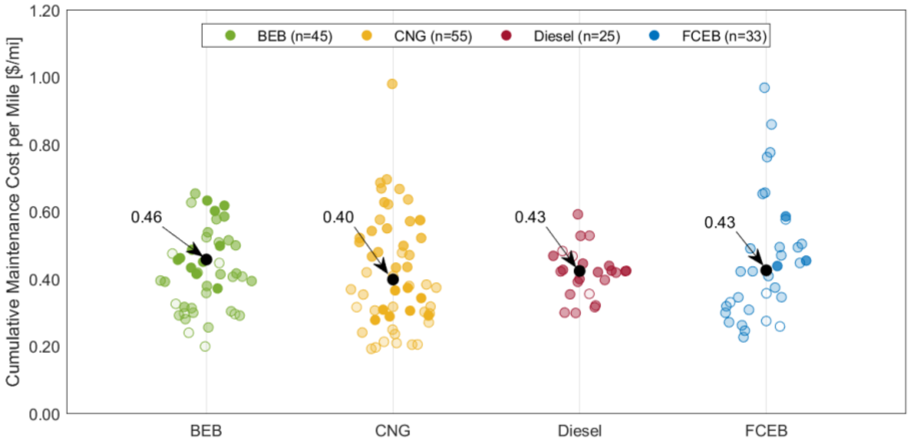

Figure 11. Transit bus cumulative maintenance cost per mile by fuel type

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Subject Inventions Listing:

None.

ROI #:

None.