JULY 2024

Next Generation Fuel Cell Delivery Van Deployment

Final Report

Submitted by:
Center for Transportation and the Environment

A California Air Resources Board Zero- and
Near Zero-Emission Freight Facilities (ZANZEFF) Project

Acknowledgements

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cte

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PUTTING FUEL CELLS TO WORK

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Table of Contents

List of Tables

List of Figures

Acronyms and Abbreviations

ABS - Anti-locking Brake System
ACT - Advanced Clean Transportation
AFLEET - Alternative Fuel Life-Cycle Environmental and Economic Transportation
AHJ - Authorities Having Jurisdiction
ARFTVP - Alternative and Renewable Fuels and Vehicle Technology Program
AT&T - American Telephone and Telegraph
BDC - Bidirectional DC-DC converter
CA - California
CAN - Control Area Network
CARB - California Air Resources Board
CFR - Code of Federal Regulations
CNG - Compressed Natural Gas
CO - Carbon Monoxide
CO2 - Carbon Dioxide
CTE - Center for Transportation and the Environment
DAC - Disadvantaged Community
DC/DC - Direct Current to Direct Current
DIAD - Delivery Information Acquisition Device
DVIR - Driver Vehicle Inspection Report
ESS - Energy Storage System
EV - Electric Vehicle
FCDV - Fuel Cell Delivery Van
FHA - Functional Hazard Analysis
FMEA - Failure Modes and Effects Analysis
GAWR - Gross Axle Weight Rating
GFM - Ground Fault Monitor
GGRF - Greenhouse Gas Reduction Fund
GHG - Greenhouse Gas
GPS - Global Positioning System
GVW - Gross Vehicle Weight
GVWR - Gross Vehicle Weight Rating
HAZOP - Hazard and Operability Studies
HCM - Hydrogen Control Module
HSS - Hydrogen Storage System
HV - High Voltage
ID - Identification
IR - Infrared
IR TX - Infrared Transmitters
LCT - Low Carbon Transportation
LIC - Low Income Community
LIDAC - Low-Income and Disadvantaged Communities
LM - Liberty Mutual
LV - Low Voltage
MJ – Megajoule

MRI – Mitigation Risk Index
MSR - Data Logger Supplier
NEC - National Electrical Code
NFPA - National Fire Protection Association
NGFCDV - Next Generation Fuel Cell Delivery Van
NMHC - Non-Methane Hydrocarbons
OEM - Original Equipment Manufacturer
OMB – Company Name
OSHA - Occupational Safety and Health Administration
PEMS - Portable Emissions Measurement System
PM - Project Manager
PT - Pacific Time
SAE - Society of Automotive Engineers
SCM - Supervisory Control Module
SEVCON - Company Name
slpm - Standard Liters per Minute
SMR - Steam Methane Reformation
SOC - State of Charge
SOF - State of Fill
SOPO - Statement of Project Objectives
SSP - System Safety Plan
THC - Total Hydrocarbons
TRW - Thompson Ramo Wooldridge, Inc.
TXL - Thin-Wall Cross-Linked
UPS - United Parcel Service of America, Inc.
VOC - Volatile Organic Compounds
WPO - Wilkins Process Optimization
WTW - Well to Wheels
XALT - Company Name
ZANZEFF - Zero- and Near-Zero Emission Freight Facility project

Executive Summary

The Next Generation Delivery Van Project was a five-year project beginning in February 2019 and completing in May 2024. The Project Team, led by the Center for Transportation and the Environment, built and delivered four fuel cell hybrid-electric walk-in delivery vans featuring Linamar's Gen 2.0 eAxle design and Ballard's hydrogen mobile fuel cell technology. The Project's operating partner, United Parcel Service (UPS), deployed the vehicles from their Customer Center in West Sacramento, California. The purpose of this project was to accelerate the development and deployment of on-board fuel cell hybrid-powered Class 6 medium-duty delivery vans to substantially increase the zero-emission driving range, thereby reducing petroleum consumption and related emissions, and increasing the viability of these electric drive vehicles.

The Project Team's propulsion system and vehicle design criteria were industry and operator-focused, and based upon the needs of UPS. UPS's existing battery electric fleet vehicles meet approximately 70% of UPS route range requirements. When configured with the fuel cell hybrid electric propulsion system as a range extender, the vehicles meet approximately 95% of UPS service needs.

Despite cascading supply chain challenges from COVID-19 and barriers with public hydrogen fueling infrastructure, two vans were successfully demonstrated in package delivery service for a total of 113 hours and 555 miles, resulting in an average fuel economy of 16.4 miles per kilogram and a total estimated range of 246 miles.

Demonstrating the technology in West Sacramento, California supported CARB's focus on providing emission benefits to disadvantaged communities (DACs). West Sacramento suffers from high levels of diesel pollutants and traffic noise due to high freight traffic volumes in the area that disproportionately affect low-income communities. In comparison to a diesel UPS van, demonstrating these advanced technology vehicles saved 0.8 tons of greenhouse gas (GHG) emissions, from well to wheels (WTW), and saved 3.3 pounds of criteria pollutants that cause health problems such as asthma. The increased adoption of zero-emissions vehicles will improve public health in these DACs.

Although the range of this technology meets the needs of many UPS delivery routes, the reliability and high cost of hydrogen at public fueling stations present challenges for commercial fleet operators. At the completion of this demonstration, UPS elected to retire this fleet from their West Sacramento depot. However, the project provided several lessons for future demonstration success such as the need to plan for a resilient hydrogen fuel supply, the importance of working closely with operators and vehicle integrators, and extensive hydrogen safety planning and education tools to improve public perception of hydrogen safety and advance commercialization of the technology.

Introduction

Background

The California Air Resources Board is charged with protecting the public from the harmful effects of air pollution and developing programs and actions to fight climate change. From requirements for clean cars and fuels to adopting innovative solutions to reduce GHG emissions, California has pioneered a range of effective approaches that have set the standard for effective air and climate programs for the nation and the world.

Assembly Bill 118 (Nùñez, Chapter 750, Statutes of 2007), created the Alternative and Renewable Fuel and Vehicle Technology (ARFVT) Program. The statute authorizes CARB to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. On March 31, 2018, CARB issued a Zero- and Near Zero-Emission Freight Facilities (ZANZEFF) Project solicitation to provide funding for projects that leverage ARFTVP funds to bring federally cost-shared projects to California that provide GHG, criteria pollutant, and toxic air contaminant emission reduction benefits to disadvantaged communities.

In response to this solicitation, CTE partnered with Linamar Corporation, Ballard Power Systems, and UPS, collectively referred to as the "Project Team", to propose the Next Generation Fuel Cell Delivery Van Deployment project, which aimed to develop, validate, and deploy fuel cell hybrid electric walk-in delivery vans. Similar to pure electric drive systems, fuel cell hybrid electric drive systems can lead to substantial energy savings and reductions in imported petroleum and carbon emissions. The addition of fuel cell range extenders aids in eliminating the range limitations and charging times that pure battery electric vehicles face.

To realize these benefits and support their portfolio of fuel cell technologies and applications, CARB awarded CTE's Next Generation Fuel Cell Delivery Van Deployment project under this agreement on September 26, 2018. CTE executed the contract with CARB on February 7, 2019.

Partners and Roles

Project partners are roles are shown in Figure 1 and described below.

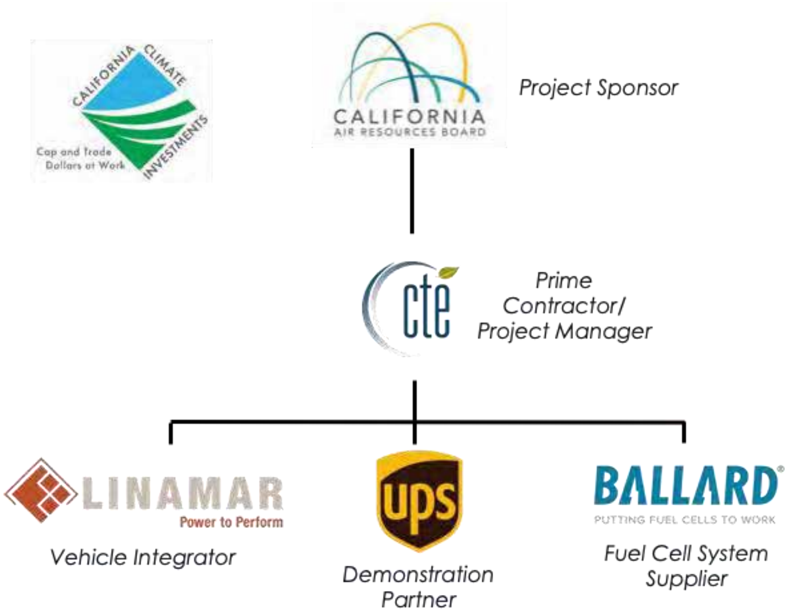

Figure 1: Project Organization Chart

California Air Resource Board (CARB) provided funding for the project through the Low Carbon Transportation Greenhouse Gas Reduction Fund (GGRF) Program to improve air quality, reduce petroleum consumption, and decrease GHGs. CARB provided oversight, project guidance on deliverables and overcoming barriers, and funds disbursement.

The Center for Transportation and the Environment (CTE) is an Atlanta-based 501(c)(3) nonprofit organization whose mission is to improve the health of our climate and communities by bringing people together to develop and commercialize clean, efficient, and sustainable transportation technologies. The CTE Team provided project management, engineering support, system integration support, operator and maintenance training, field deployment, and maintenance support. CTE served as the prime contractor to CARB and subcontracted with three organizations to provide the services necessary to carry out the development and deployment of the fuel cell delivery vans. These organizations include Linamar Corporation, Ballard Power Systems, and UPS.

Linamar Corporation has manufactured and supplied automotive markets for over 50 years, and the identification of market needs has driven continued hardware development and market study, with the primary goal to commercialize a product to meet the needs and wants of the customers. As part of this project, proven, off-the-shelf components were utilized to increase the technology readiness level of the vehicle, reduce project risk, and emerge the program with a commercial-ready product. Linamar served as the primary vehicle integrator, and in this capacity, Linamar’s roles and responsibilities included major component design and selection, vehicle integration, data collection, and development of a manufacturing plan as a commercial technology supplier.

Ballard Power Systems designs and manufactures market-leading clean energy proton exchange membrane fuel cell stacks and power modules as well as complete systems for both stationary and motive power applications. As the fuel cell engine and accessory system provider, Ballard provided the fuel cell engines, related accessories, and balance of plant; supported Linamar with integration of the fuel cell systems with the electric drivetrain; supported vehicle integration, commissioning, and testing; and provided after sales support for fuel cell technology.

UPS deployed and operated the vehicles out of its Customer Center located in West Sacramento, CA, which will support the state's focus on providing emission benefits to disadvantaged communities. The project team has strategically planned to deploy these vehicles at facilities near hydrogen stations with adequate fueling capacity and on routes that maximize the hours of service to and through these communities.

Roush Industries was a subcontractor to Linamar. Roush's responsibilities were to perform vehicle integration, build, test, and support, including major component design and selection.

Objectives

The goal of this project was to build a robust zero-emission, Class 6 fuel cell package delivery truck that effectively demonstrated reliable service on multiple service routes with differing duty cycles. The intent was to leverage the success of companies experienced at building fuel cell hybrid electric propulsion systems for medium- and heavy- duty truck OEMs. Working in partnership with Linamar, specifically their subsidiary McLaren Engineering, the Project Team engineered and built vehicles that were operated and evaluated over a three-month deployment on regularly scheduled routes servicing outlying communities in West Sacramento. Performance and operations data collected during the demonstration helped identify the pathways and barriers to commercialization.

Relevance and Outcomes

The project aimed to achieve the following outcomes for stakeholders:

- Deploy four zero-emission hydrogen fuel cell hybrid electric walk-in delivery vans
- Purchase larger quantities of advanced technology vehicle components and take advantage of supply chain benefits, such as economies-of-scale cost reductions
- Respond to the growing number of fleet operators who desire zero-emission electric-drive vehicles with greater range than the battery electric vehicles currently available
- Introduce a zero-emission alternative to traditional diesel powertrain repower or refurbishment

The project architecture for the FCDVs helps commercial operators implement zero-emission technology that meets the performance and operational needs of package delivery vehicles. The project also supports the goals of state regulatory bodies that seek to reduce or eliminate emissions from vehicles in West Sacramento.

Approach

The project approach section below discusses the methodology planned and implemented for the successful development and demonstration of the FCDVs. Four primary tasks were planned for the project as summarized below and depicted in the schedule shown in Figure 2.

Task 1 Project Administration: The CTE team would complete all administrative project requirements such as contracting, project kickoff and other meetings, project management plan, and reporting documents.

Task 2 Vehicle Design and Build: The Project Team would develop, manufacture, and validate four fuel cell assisted, electric drive delivery vans on time and at budgeted cost.

Task 3 Demonstration Readiness: The Project Team would complete all activities necessary for preparation for a safe and successful demonstration of the delivery vans. These activities included establishing hydrogen fueling through a local fueling station or private fueling partner, completing safety/operations manuals, and coordinating operator, fueling, and maintenance training.

Task 4 Vehicle Deployment: The Project Team planned to conduct a vehicle demonstration for a period of no less than twelve months for each vehicle which includes technical support as well as data collection as defined by the Project Sponsor.

There were deviations from the planned objectives, including in the schedule, budget, and demonstration duration and location, which are elaborated on in the *Results* sections of the report.

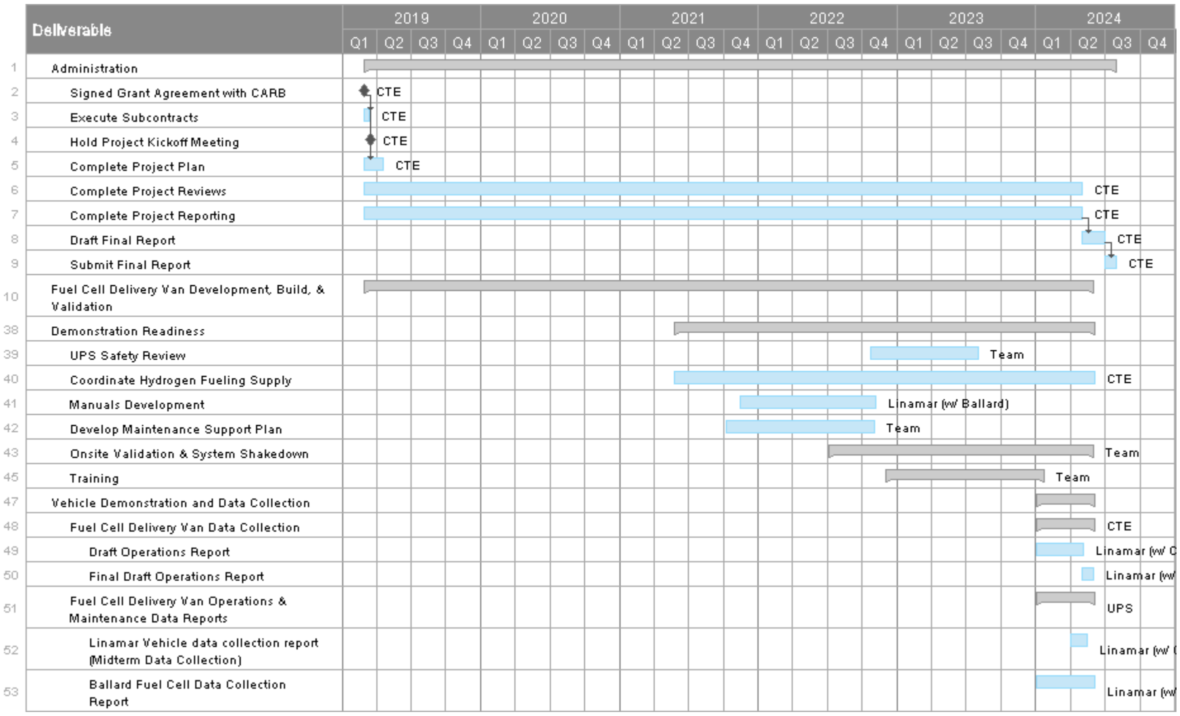

Figure 2: Project Schedule

The planned activities for each primary task is described in further detail below

Task 1 Project Management

As the prime recipient, CTE committed to provide project management and administration, including schedule and budget management, reporting to CARB, and project partner coordination. Schedules and budgets were reviewed and updated at regular team meetings throughout the project and reported to the sponsor. CTE established communication through weekly or biweekly team meetings and monthly sponsor reviews. Refer to the Project Management Plan (Appendix F) for detailed descriptions of schedule, budget, communication, and change management. The schedule is shown in Figure 2.

Risk Management

Certain risks were considered during the proposal and throughout the development of the budget. To manage these risks, the project team would identify, address, and discuss how to mitigate these risks through project team communication. The actual risks realized and managed are presented in the *Results* sections of the report.

Safety Management

The Project Team is committed to a safe and productive fuel cell delivery van demonstration project. To meet this goal, the Project Team performed a Project Safety Review and developed a System Safety Plan (SSP) during Task 2: Fuel Cell Delivery Van Development, Build, and Validation. The review identified and supplemented the individual equipment providers' safety plans, Failure Modes and Effects Analysis (FMEA), and Hazard and Operability studies (HAZOP). As such, the Project Team evaluated operation, maintenance, and fueling functions of the demonstration vehicles for proper safety features, procedures, and response plans. The review focused on the unique aspects of the vehicles that posed a safety risk, particularly high voltage and hydrogen systems. The hydrogen system safety review included reviewing the installation of hydrogen detection systems onboard the vehicle, ensuring the vehicle design included adequate ventilation and pressure relief devices, and guaranteeing that the mounting hardware for the hydrogen storage cylinders was properly designed. An FMEA was planned to determine the level of risk and mitigating strategies. A Functional Hazard Analysis (FHA) was planned with all demonstration stakeholders to formally identify and address any perceived risks. The FHA and SSP were reviewed prior to the start of Task 4: Vehicle Demonstration and Data Collection to ensure that risks were mitigated to an acceptable level.

Task 2 Vehicle Design and Build

The purpose of this task was to successfully develop, manufacture, and validate a fuel cell delivery van with a next generation *eAxle*. Linamar would build upon its existing hybrid electric design by modifying the drive system to include a Ballard fuel cell and a hydrogen storage system (HSS) in place of the internal combustion engine and fuel tank. The energy storage system (ESS) and supervisory control system would be reconfigured and optimized to meet the operational requirements of the fuel cell hybrid configuration. The Ballard fuel cell would be based on an existing product. Base vehicle and long lead components would be ordered as they were confirmed by the design and/or subsystem testing. All associated electrical and mechanical integration work was planned to be accomplished during the course of the design and manufacturing phases of this project.

Requirements Definition

Linamar with support from Ballard, CTE, and UPS planned to complete a final requirements definition and document the vehicle specification along with the fuel cell system requirements as prepared by Ballard. This activity would include modeling and simulation analysis of collected operator duty cycle data and establishment of operational requirements.

Vehicle System Design

Linamar with support from Ballard aimed to then perform the design integration necessary to incorporate the fuel cell and hydrogen storage system and optimize the electric drivetrain to meet the requirements previously established. As part of this task, Linamar would complete the electrical and mechanical design of the *eAxle* (including traction motor, motor drive and gearbox), ESS, fuel cell integration, power electronics, HSS, thermal management, and supervisory controls.

Procure Long Lead Components

Linamar planned to place orders for and receive the major, long-lead components of the fuel cell hybrid delivery van to ensure timely arrival as the delivery van was built out. Components included:

- Hydrogen Storage System Components (including tanks) or Complete System
- Fuel cell DC/DC Converter
- Traction Battery Modules
- eAxle Components including Traction Motor, Motor Inverter, Gearbox, Cradle
- Vehicle Controller Unit

CTE was to procure the base Delivery Van chassis.

Fuel Cell System Build and Delivery

Ballard would procure hardware, build the four fuel cell systems, complete factory acceptance testing, and ship the four systems for integration into the fuel cell delivery vans.

Full Powertrain Build and Test

Linamar planned to complete all mechanical and electrical integration of the initial vehicle powertrain. Low voltage and high voltage systems would be commissioned on the vehicle. Linamar with support from Ballard would integrate the fuel cell and DC/DC converter into the vehicle and perform coordinated checkout of the integrated system. Linamar would complete full powertrain bench testing and tuning. Any resulting design and controls modifications would be made.

Vehicle Build and Assembly

Linamar aimed to complete the full vehicle build for all four vehicles including complete mechanical integration of all components, mounts, brackets, plumbing, and low voltage and high voltage wiring harnesses in the trucks. Linamar would complete all electric integration including termination of components and completion of high voltage and low voltage checkouts. Linamar with support from Ballard planned to integrate the fuel cell and DC/DC converter into the vehicles and perform coordinated checkout of the integrated system.

Vehicle Test and Validation

A fully executable validation plan was to be developed by Linamar at the outset of this task to accurately track and manage testing. Linamar with support from Ballard would complete functional testing and tuning of the fully integrated vehicle.

Vehicle Shipping and Acceptance

Linamar planned to prepare, ship, and deliver the four vehicles. Receipt of delivery and completion of acceptance procedures were to be confirmed by UPS.

Production Plan Development

Linamar planned to update its Production Plan based on lessons learned from the build and test of the four vehicles.

Task 3 Demonstration Readiness

The purpose of this task was to complete all the supporting activities necessary to prepare for the safe and successful demonstration of the fuel cell delivery trucks. The activities included establishing the hydrogen fueling plan, completing manuals development, preparing for and coordinating training, vehicle shipping, preparing for maintenance support, and onsite vehicle and fueling plan validation and shakedown.

Coordinate Hydrogen Fuel Supply and Demonstration Location

The project expected to utilize an existing public station to provide the necessary hydrogen fueling upon deployment of the vehicles. The originally selected station was owned and operated by StratosFuel at 1850 Holt Boulevard, Ontario, CA. The station produced hydrogen on-site via electrolysis and was projected to have 100% renewable production by 2019. Throughout 2019, CTE continued to monitor the reliability of the StratosFuel station and the progress of a nearby Shell hydrogen fueling station. However, given the multiple vehicle deployments taking place at a single UPS center, CTE began exploring potential backup demonstration locations as a risk mitigation measure due to potential overutilization of the Shell station in Ontario CTE. UPS had identified several options for the backup demonstration location including West Sacramento based on fuel availability, fuel proximity to operations, local staff hydrogen familiarity, and operator enthusiasm. The demonstration location and hydrogen fuel supplier were changed due to several factors discussed in *Results, Coordinating Hydrogen Fuel Supply and Demonstration Location.*

Manuals Development

Linamar, with the support of CTE and Ballard, planned to develop and deliver maintenance and operation manuals for the fuel cell delivery vans. UPS would review the draft manuals and provide feedback for incorporation by Linamar. Linamar would then deliver the final manuals to UPS.

Maintenance Support Plan

Linamar, Ballard, and UPS, with the support of CTE, planned to develop a comprehensive maintenance support plan for the duration of the project to ensure maximum system uptime and performance. The support plan would establish roles, communications, and expectations for fuel cell delivery vans.

Onsite Validation and System Shakedown

CTE planned to provide overall coordination with all project members to conduct on-route validation and system shakedown for the vehicle. This would include multiple days of monitored test service and fueling to ensure any issues were discovered and addressed prior to going into regular service. This would also ensure the vehicle was received in the same condition that it was in when it left the integration facility. Any issues identified in the system shakedown would be addressed and any additional vehicle tuning would be made.

Training

CTE, Linamar, Ballard, and UPS planned to develop and execute a training plan for the fuel cell delivery vans. This would cover both operations and maintenance for the aspects that were unique to the fuel cell electric version of the fuel cell delivery vans. Each training module would include appropriate safety components for handling hydrogen and high-voltage equipment. Linamar would provide fuel cell delivery van maintenance training. CTE, with the help of Linamar, would coordinate and execute a training plan for first responders. The training sessions would be efficiently provided at the UPS facility.

Task 4 Vehicle Deployment

The purpose of this task was to demonstrate and support the four FCDVs in parcel delivery operations and associated fueling, including:

1. Van Operations and Support
2. Data Collection

Fuel Cell Delivery Van Operations and Support

The demonstration of the four FCDVs was proposed for 12 months in Ontario, CA. UPS would be the sole entity that would operate the vehicles. The vehicles would be deployed and operated in typical parcel delivery applications, and UPS would operate the four vehicles out of its Customer Center located at 3480 E. Jurupa Street in Ontario, CA. UPS would utilize its standard package distribution facilities and normal procedures when operating the trucks. The vehicles would benefit from being in a fleet environment where the end-user, UPS, had dedicated operations, maintenance, and fueling staff in one facility.

Project stakeholders anticipated potentially rotating the vehicles to one or more locations to account for changes in hydrogen demand at the public stations as fuel cell vehicles and stations emerge, to maximize utilization at certain stations, or simply to evaluate the effects of different duty cycles on the delivery vans. CTE would work with UPS to develop a deployment plan that would fully enable the movement of vehicles from one distribution site to another if for any reason the identified station was unable to provide fuel. As described in the *Results, Coordinating Hydrogen Fuel Supply and Demonstration Location* section of this report, the demonstration location was changed to West Sacramento.

At the time of project planning, the Ontario facility was located on the border of two census tracts. One tract had a CalEnviroScreen 3.0 Percentile score of 75-80%, and the second tract had a CalEnviroScreen 3.0 [1] Percentile score of 95-100%. The location was thus considered to be in a DAC which would benefit from zero-emissions, quiet operation of the vans in the community. The new demonstration location in West Sacramento is also defined as a DAC.

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[1] At the time of project planning, CalEnviroScreen3.0 was the latest version. It has since been updated to 4.0.

During the operations period, the project team would provide technical support to address any issues the vehicles may encounter. The team would focus on maintaining optimal reliability, efficiency, and performance.

Establish and Execute Data Collection

There are four main sources of data that were planned for the data collection effort:

- Linamar operational data
- Linamar and UPS maintenance, service, and safety data
- Fueling and Operational Infrastructure Data
- Miscellaneous one-time inputs provided by the various project partners

Linamar planned to install data logging devices to collect data from the trucks' CAN bus system and record quantitative operational data such as distance traveled, speed, energy usage, state of fill (SOF), and error codes at a maximum frequency of 1 Hz. Once a month (at a minimum), this data would be uploaded from each vehicle in service, consolidated into daily logs, and uploaded to Dropbox to allow CTE to process and integrate the data into the online dashboard that would be shared with the project team.

Linamar planned to be responsible for tracking quarterly data related to vehicle maintenance, reliability, and safety.

CTE planned to work with UPS to gather cost and major specifications related to UPS's facility modifications for hydrogen safety. While a fuel provider was not officially contracted through the project, the team planned to work with the hydrogen station operator to gather data on refueling rates. Other refueling data would be reported via UPS fuel purchase history such as total quantity and price.

Metrics such as vehicle miles in and out of DACs would be post-processed based on partner data inputs. Any changes in planned service routes would be documented to ensure accurate reporting.

CTE planned to be responsible for aggregating all data inputs from partners, processing the raw data, performing calculations, and integrating the data into the online dashboard. CTE also planned to conduct surveys to gather operator feedback on the vehicles.

Results

Task 1 Project Management

The objective of this task was to accomplish all routine and non-routine activities for managing the project defined under the CARB solicitation. Project Management included execution of subcontracts with members of the Project Team, administration of a kickoff meeting, administration of critical project review meetings, completion and submission of monthly and quarterly status reporting including the Final Report, identifying and obtaining required permits, and identifying and obtaining matching funds when necessary. This task also included the development of the Project Management Plan (Appendix F), the development of the System Safety Plan, and the submission of project sponsor status reporting (monthly and quarterly reports).

CTE managed risks associated with the project and worked with CARB to manage changes to the project schedule and budget. CTE worked with project partners to ensure the completion of expected deliverables and project milestones. This independent ability enabled the successful completion of major milestones and provided CARB, as well as the industry, with essential lessons learned for this technology commercialization.

Over the course of the project, there were three amendments to the original Grant Agreement with CARB. There was no change in the total budget, however funds were shifted between tasks.

Initial Grant Agreement

- Executed February 7, 2019
- Project end date planned for March 31, 2021

Amendment 1 (executed April 7, 2021):

- Extended project end date to November 15, 2022
- Extended Task 2 end dates starting with vehicle build due to delays from the COVID-19 pandemic and unexpected vehicle build challenges (see *Vehicle Design and Build* for details) The new final date for vehicle acceptance was May 17, 2021

Amendment 2 (executed November 15, 2022)

- Extended project end date to February 28, 2024
- Extended Task 2 end dates starting with vehicle validation testing. The new final date for vehicle acceptance was November 2022.
- The vehicle acceptance milestone was split into separate milestones per van

Amendment 3 (executed February 20, 2024)

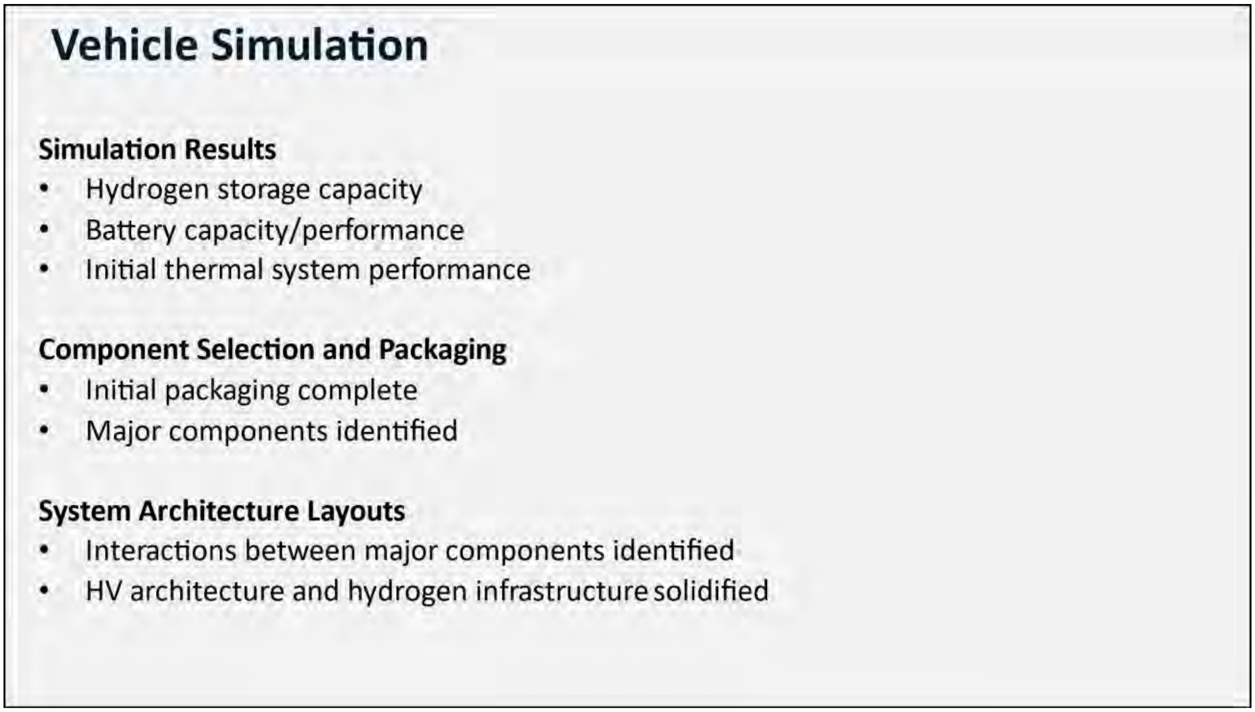
- Extended end date to August 31, 2024
- Extended Task 2 end dates starting with vehicle test and validation due to the UPS safety review. The new final date for vehicle acceptance was December 31, 2023.
- Added Task 3.5.1 Additional Training due to UPS request following delay in deployment since initial training (see *Demonstration Readiness* for details). Funds were shifted from Task 4.1 Operations Report and Task 4.2 Data Collection to support the new task.

- Changed the location of demonstration from Ontario to West Sacramento, CA and the hydrogen supplier from Shell to Iwatani (see *Demonstration Readiness* for details)
- Reduced the demonstration period to three months

Task 2 Vehicle Design and Build

Requirements Definition and Vehicle System Design

Linamar entered into a subcontracted collaboration with Roush Industries for vehicle design and build. Linamar and Roush reviewed UPS route data for simulating and sizing the vehicle fuel cell hydrogen storage and high-voltage battery requirements (Figure 3). These requirements were subsequently modeled using Roush's existing in-house software. The Simulation Results are summarized in Figure 4 - Figure 8**.** Linamar and Roush created a Preliminary Design based on the Simulation Results and subsequently presented this information in a Preliminary Design Review (PDR).



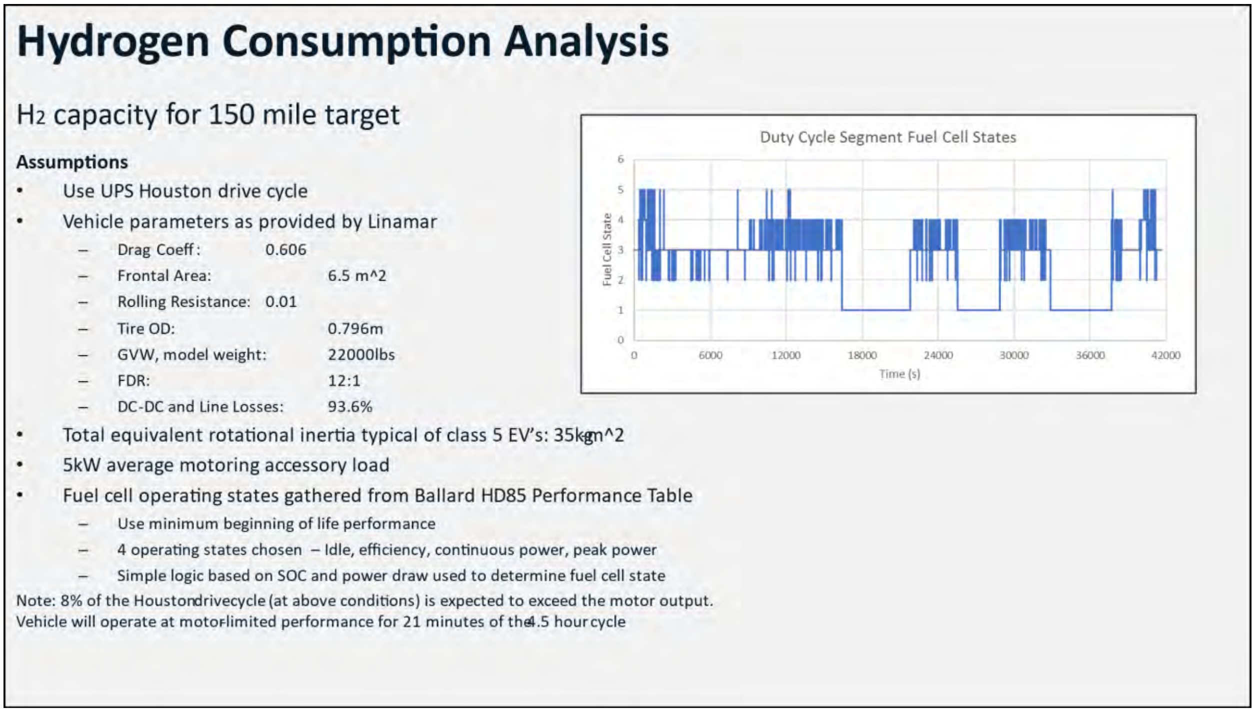
Vehicle Simulation

Simulation Results
- Hydrogen storage capacity
- Battery capacity/performance
- Initial thermal system performance

Component Selection and Packaging
- Initial packaging complete
- Major components identified

System Architecture Layouts
- Interactions between major components identified
- HV architecture and hydrogen infrastructure solidified

Figure 3: Vehicle Simulation Study



Hydrogen Consumption Analysis

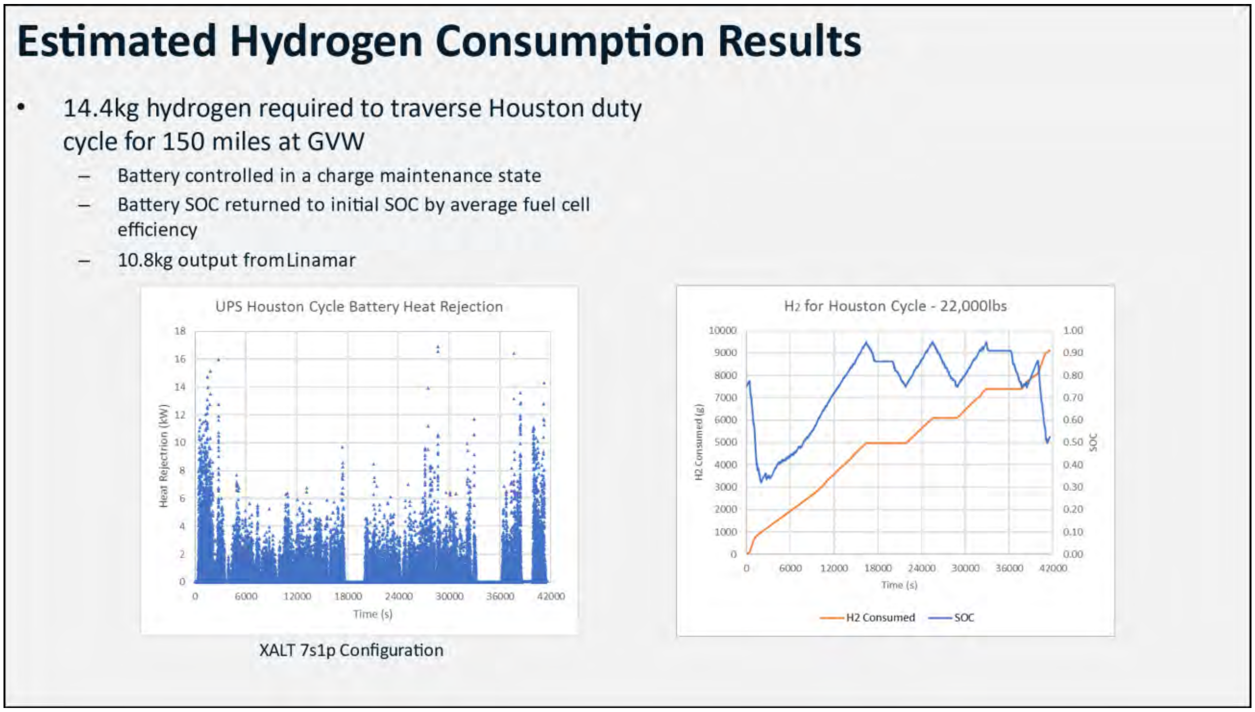
H2 capacity for 150 mile target

Assumptions

- Use UPS Houston drive cycle
- Vehicle parameters as provided by Linamar
  - Drag Coeff: 0.606
  - Frontal Area: 6.5 m^2
  - Rolling Resistance: 0.01
  - Tire OD: 0.796m
  - GVW, model weight: 22000lbs
  - FDR: 12:1
  - DC-DC and Line Losses: 93.6%
- Total equivalent rotational inertia typical of class 5 EV's: 35kgm^2
- 5kW average motoring accessory load
- Fuel cell operating states gathered from Ballard HD85 Performance Table
  - Use minimum beginning of life performance
  - 4 operating states chosen – Idle, efficiency, continuous power, peak power
  - Simple logic based on SOC and power draw used to determine fuel cell state

Note: 8% of the Houston drive cycle (at above conditions) is expected to exceed the motor output. Vehicle will operate at motor limited performance for 21 minutes of the 4.5 hour cycle

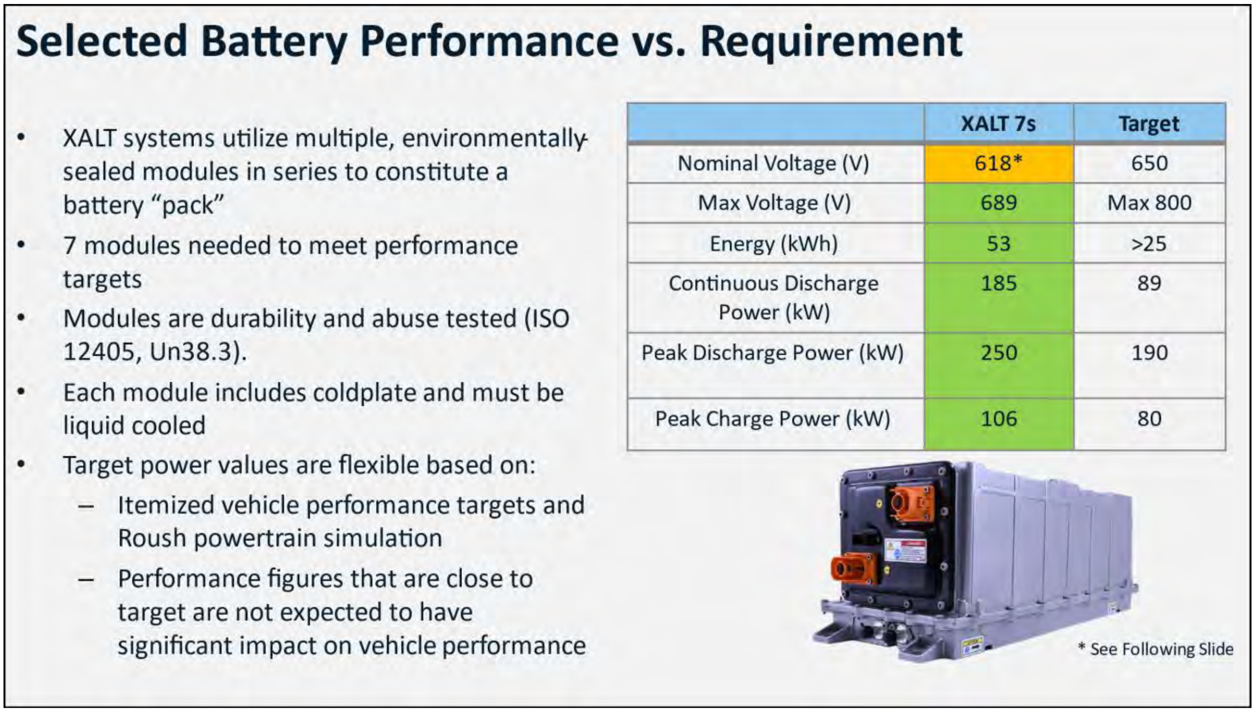
Figure 4: Hydrogen Consumption Analysis Assumptions



Estimated Hydrogen Consumption Results

- 14.4kg hydrogen required to traverse Houston duty cycle for 150 miles at GVW
  - Battery controlled in a charge maintenance state
  - Battery SOC returned to initial SOC by average fuel cell efficiency
  - 10.8kg output from Linamar

Figure 5: Hydrogen Consumption Modeling



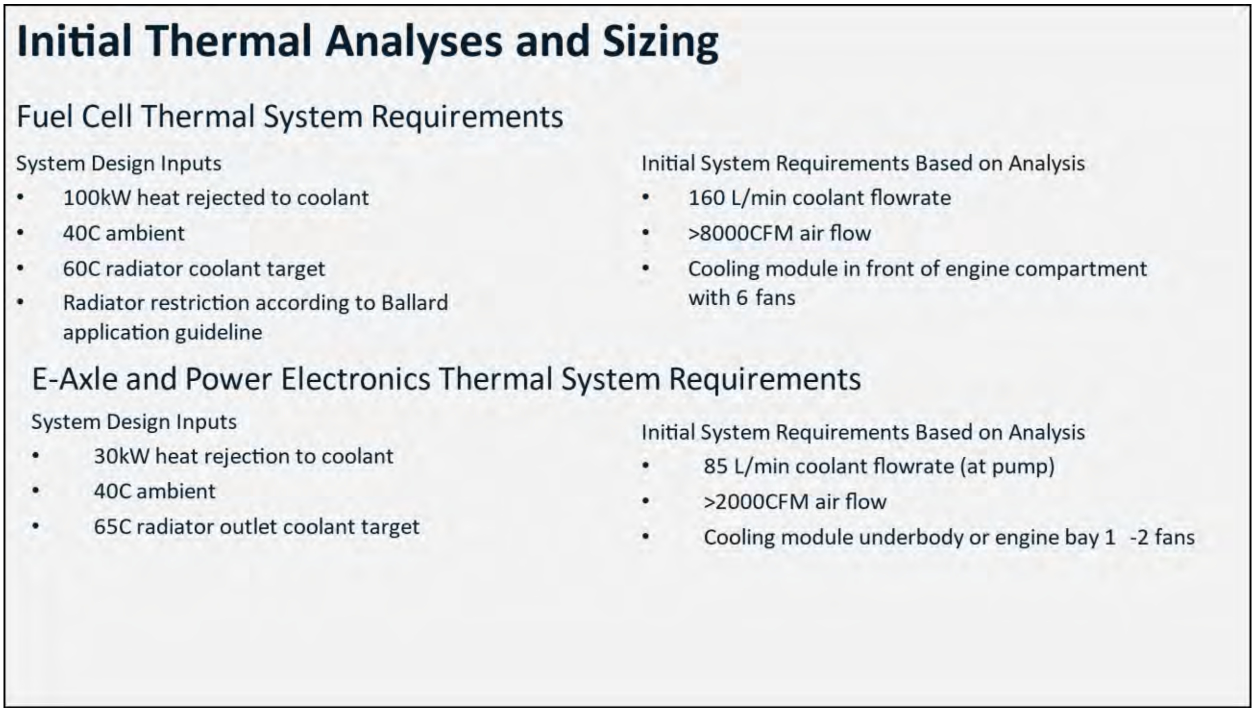
Selected Battery Performance vs. Requirement

- XALT systems utilize multiple, environmentally sealed modules in series to constitute a battery "pack"
- 7 modules needed to meet performance targets
- Modules are durability and abuse tested (ISO 12405, Un38.3).
- Each module includes coldplate and must be liquid cooled
- Target power values are flexible based on:
    - Itemized vehicle performance targets and Roush powertrain simulation
    - Performance figures that are close to target are not expected to have significant impact on vehicle performance

	XALT 7s	Target
Nominal Voltage (V)	618*	650
Max Voltage (V)	689	Max 800
Energy (kWh)	53	>25
Continuous Discharge Power (kW)	185	89
Peak Discharge Power (kW)	250	190
Peak Charge Power (kW)	106	80

* See Following Slide

Figure 6: Battery Selection and Sizing



Initial Thermal Analyses and Sizing

Fuel Cell Thermal System Requirements

System Design Inputs

- 100kW heat rejected to coolant
- 40C ambient
- 60C radiator coolant target
- Radiator restriction according to Ballard application guideline

Initial System Requirements Based on Analysis

- 160 L/min coolant flowrate
- >8000CFM air flow
- Cooling module in front of engine compartment with 6 fans

E-Axle and Power Electronics Thermal System Requirements

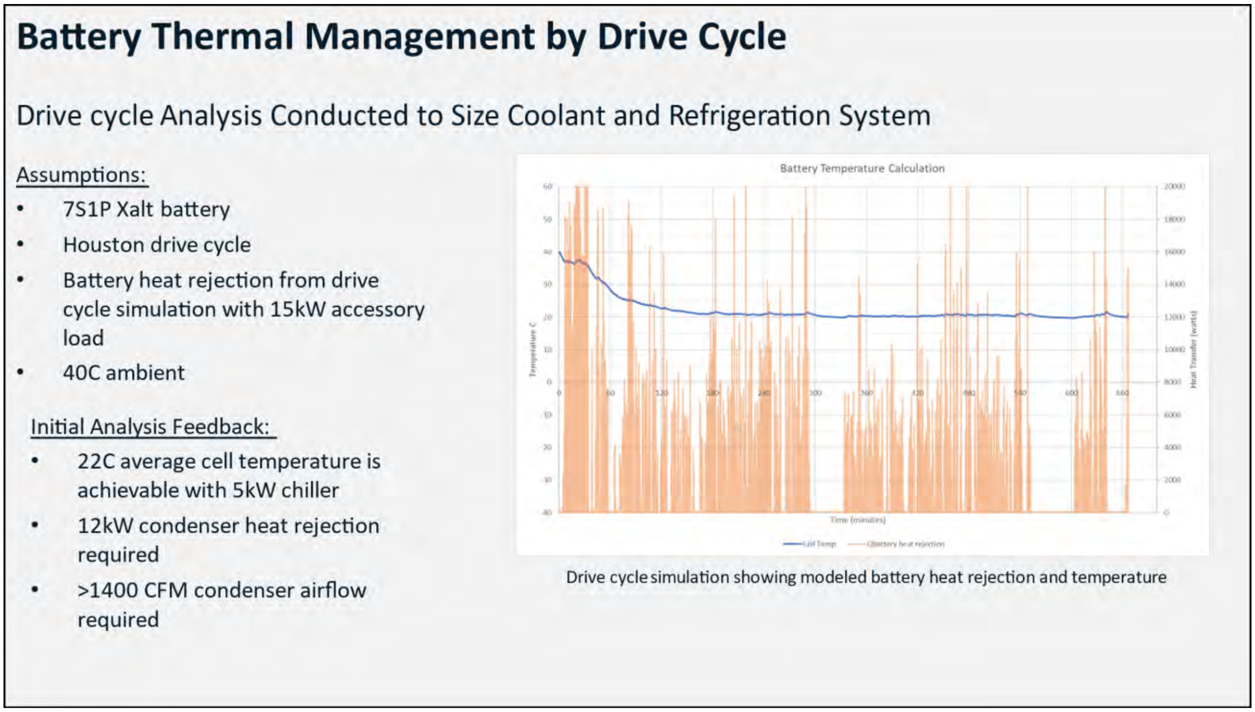
System Design Inputs

- 30kW heat rejection to coolant
- 40C ambient
- 65C radiator outlet coolant target

Initial System Requirements Based on Analysis

- 85 L/min coolant flowrate (at pump)
- >2000CFM air flow
- Cooling module underbody or engine bay 1 -2 fans

Figure 7: Thermal Management System Sizing by Components



Battery Thermal Management by Drive Cycle

Drive cycle Analysis Conducted to Size Coolant and Refrigeration System

Assumptions:

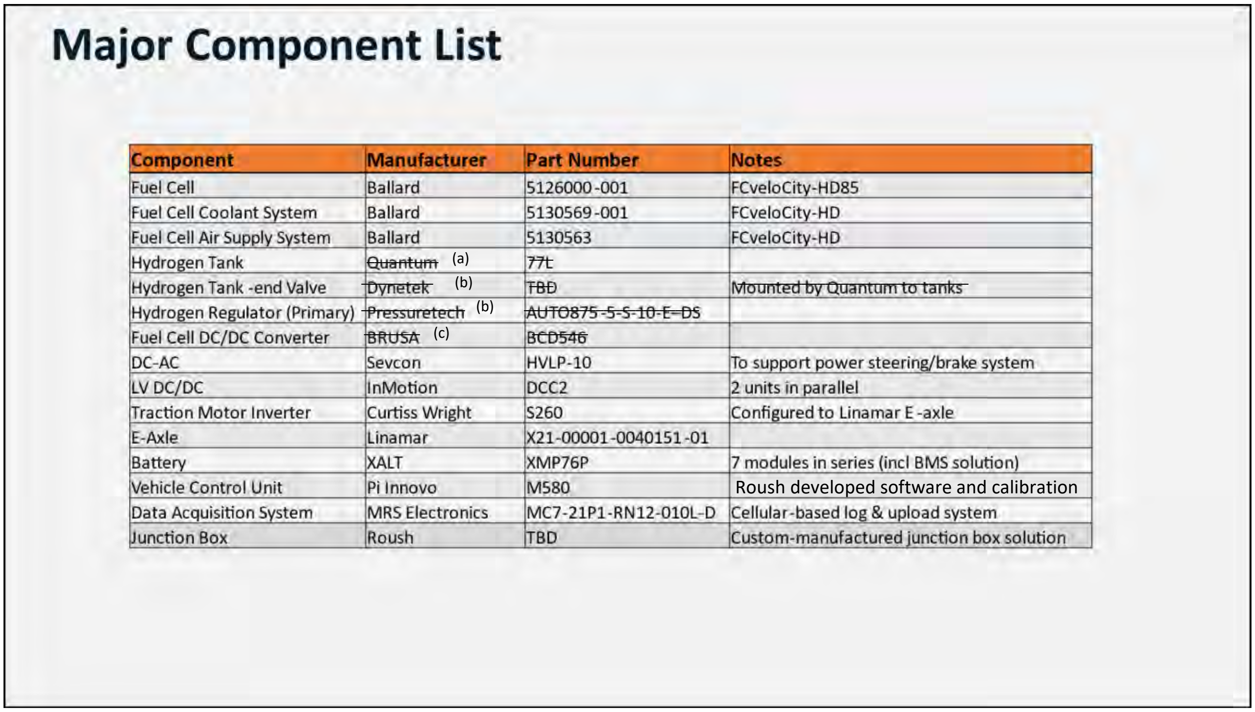
- 7S1P Xalt battery
- Houston drive cycle
- Battery heat rejection from drive cycle simulation with 15kW accessory load
- 40C ambient

Initial Analysis Feedback:

- 22C average cell temperature is achievable with 5kW chiller
- 12kW condenser heat rejection required
- >1400 CFM condenser airflow required

Drive cycle simulation showing modeled battery heat rejection and temperature

Figure 8: Thermal Management System Sizing by Drive Cycle



Major Component List

Component	Manufacturer	Part Number	Notes
Fuel Cell	Ballard	5126000-001	FCveloCity-HD85
Fuel Cell Coolant System	Ballard	5130569-001	FCveloCity-HD
Fuel Cell Air Supply System	Ballard	5130563	FCveloCity-HD
Hydrogen Tank	~~Quantum~~ (a)	~~77L~~	
Hydrogen Tank -end Valve	~~Dynetek~~ (b)	~~TBD~~	~~Mounted by Quantum to tanks~~
Hydrogen Regulator (Primary)	~~Pressuretech~~ (b)	~~AUTO875-5-S-10-E-DS~~	
Fuel Cell DC/DC Converter	~~BRUSA~~ (c)	~~BCD546~~	
DC-AC	Sevcon	HVLP-10	To support power steering/brake system
LV DC/DC	InMotion	DCC2	2 units in parallel
Traction Motor Inverter	Curtiss Wright	S260	Configured to Linamar E-axle
E-Axle	Linamar	X21-00001-0040151-01	
Battery	XALT	XMP76P	7 modules in series (incl BMS solution)
Vehicle Control Unit	Pi Innovo	M580	Roush developed software and calibration
Data Acquisition System	MRS Electronics	MC7-21P1-RN12-010L-D	Cellular-based log & upload system
Junction Box	Roush	TBD	Custom-manufactured junction box solution

Figure 9: Major Components at Preliminary Design Review

The vehicle design report was generated with a hydrogen storage system supplied by Quantum that featured five hydrogen cylinders. The Project Team discovered that the Quantum hydrogen cylinders would extend below the vehicle body skirt, which UPS determined would not be acceptable. The Project Team worked cooperatively with cylinder supplier, Worthington (now known as Luxfer), on a 700 bar (10,000 psi) cylinder solution that met the project requirements. Due to the tank supplier change, OMB supplied the tank valves and a custom designed hydrogen regulator to step down from the tank pressure to the inlet of the Ballard fuel cell. The DC/DC converter supplier was changed to Tame Power. Major components are shown in Figure 9 and Figure 10.

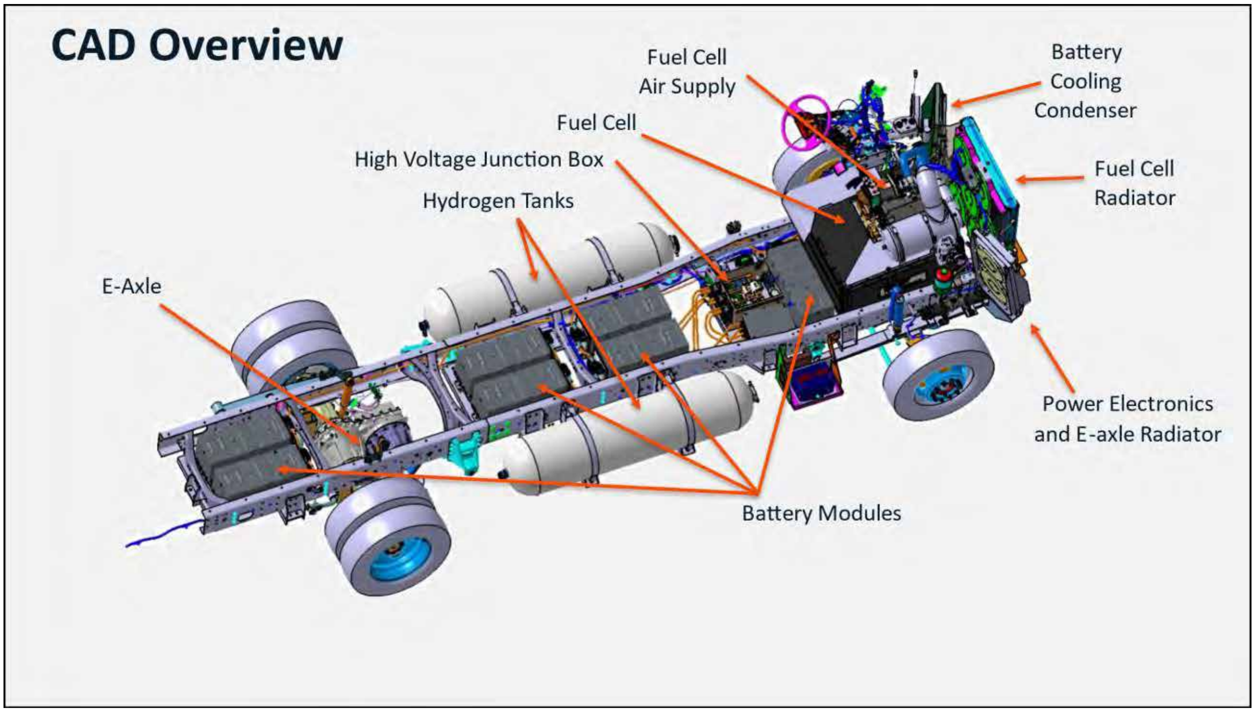


Figure 10: PDR CAD Model

Following completion of the PDR, Linamar and Roush incorporated feedback from CTE, UPS, and CARB into the final design and analysis. Key points summarized from the Final Design Report (FDR) include the data presented in the PDR and confirmation of the following:

1. Analysis by Roush, with better data fidelity and more sophisticated software analysis, showed the vehicle targets could be met.
2. The analysis confirmed that 15 kg hydrogen onboard would be adequate for the targeted range.
3. The analysis concluded that a minimum 25 kWh battery was required. The selected XALT system carried additional capacity (53 kWh) in order to meet the drive system voltage requirement.
4. The packaging of main items was completed using selected suppliers' components and subsystems.

Procurement and Subsystem Build

With the design phase completed, the next tasks were procurement, build, and delivery of major systems including hydrogen storage systems, high voltage battery modules, power distribution systems, traction drive eAxles, hydrogen fuel cells, thermal systems, vehicle control units, and the four vehicles for conversion to FCDVs.

CTE led the procurement of four Ford F-59 stripped chassis (Figure 11) in 2019. Peach State Ford (located in Atlanta, GA) supplied the chassis, and Morgan Olson set the UPS P100 step van bodies. The new gasoline powertrain content was subsequently removed (Figure 12) by Roush and sold to a thirdparty organization to offset the cost overage of the procured chassis. With the de-contented trucks in place at Roush, work began on modifications for the installation of fuel cell drivetrain components (Figure 13 - Figure 17) at their facility in Detroit, Michigan.

Figure 11: F-59 Stripped Chassis with Internal Combustion Engine components

Figure 12: Gasoline ICE and Related Components for Resale

Figure 13: De-Contented F-59 Chassis Showing Fuel Cell and Hydrogen Tank Saddles (WIP)

Figure 14: Hydrogen Tanks and Battery Modules on F-59 chassis

Figure 15: High Voltage Junction Box

Figure 16: Hydrogen Tank Showing OMB Valve

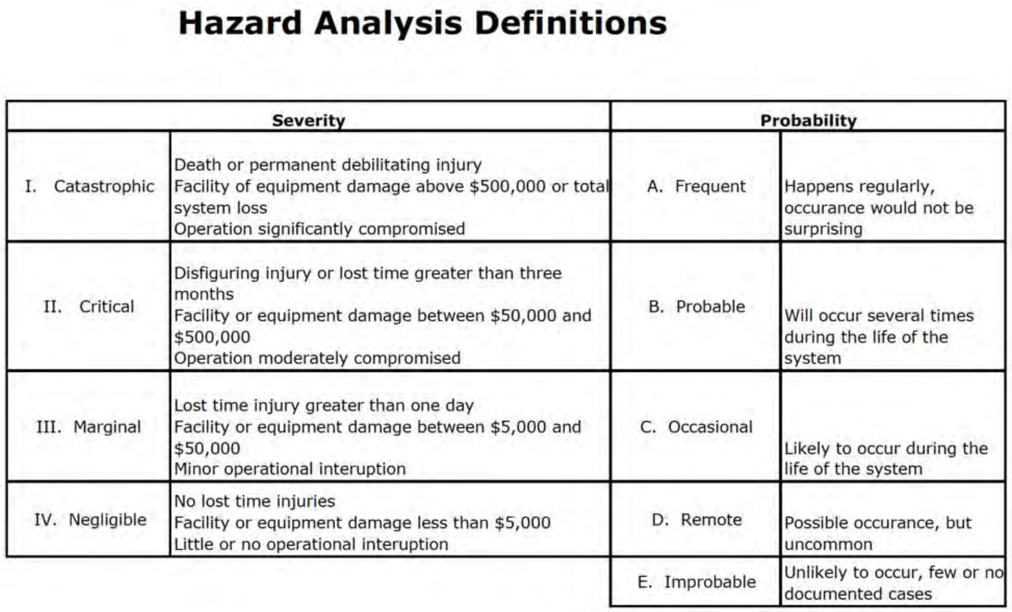
Figure 17: Fuel Cell with Air Handling System

Safety Planning

CTE organized and conducted a system safety planning meeting at the Linamar and Roush facilities in Detroit in Q3 of 2019. The purpose of the meeting was to conduct a Functional Hazard Analysis (FHA) and address any other safety considerations with the full Project Team. The Project Team conducted a project-level assessment to identify and supplement the individual equipment providers' safety plans, Failure Modes and Effects Analysis (FMEA), and Hazard and Operability studies (HAZOP). The review focused on the unique aspects of the vehicles that pose a safety risk, including reviews of hydrogen detection systems, hydrogen venting, high voltage safety systems, and operator training requirements.

The safety hazards were codified into a single document that summarized and evaluated the hazards, mitigations, and related action items that were subsequently implemented. See Appendix D for the final FHA.

The Project Team determined the Mitigation Risk Index (MRI) of each hazard using the severity and probability definitions shown in Figure 18.

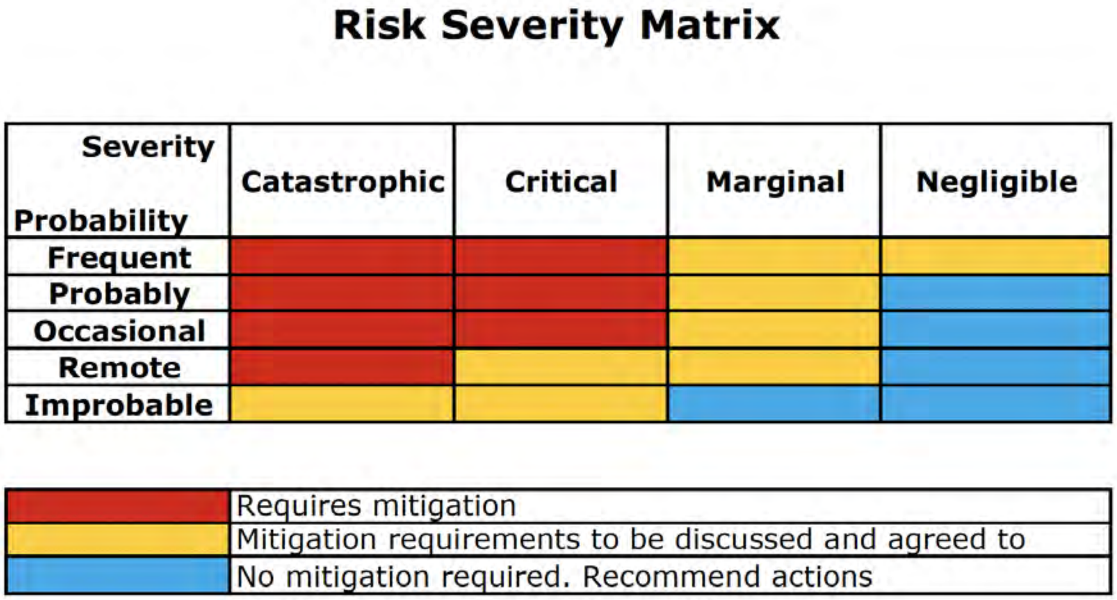


Hazard Analysis Definitions

Severity		Probability	
I. Catastrophic	Death or permanent debilitating injury Facility of equipment damage above $500,000 or total system loss Operation significantly compromised	A. Frequent	Happens regularly, occurance would not be surprising
II. Critical	Disfiguring injury or lost time greater than three months Facility or equipment damage between $50,000 and $500,000 Operation moderately compromised	B. Probable	Will occur several times during the life of the system
III. Marginal	Lost time injury greater than one day Facility or equipment damage between $5,000 and $50,000 Minor operational interuption	C. Occasional	Likely to occur during the life of the system
IV. Negligible	No lost time injuries Facility or equipment damage less than $5,000 Little or no operational interuption	D. Remote	Possible occurance, but uncommon
		E. Improbable	Unlikely to occur, few or no documented cases

Figure 18: Hazard Analysis Definitions

Using the MRI and the Risk Severity Matrix in Figure 19, the Project Team determined if a hazard required further risk mitigation.



Risk Severity Matrix

Severity / Probability	Catastrophic	Critical	Marginal	Negligible
Frequent	🟥	🟥	🟨	🟨
Probably	🟥	🟥	🟨	🟦
Occasional	🟥	🟥	🟨	🟦
Remote	🟥	🟨	🟨	🟦
Improbable	🟨	🟨	🟦	🟦

🟥	Requires mitigation
🟨	Mitigation requirements to be discussed and agreed to
🟦	No mitigation required. Recommend actions

Figure 19: Risk Severity Matrix

Vehicle Assembly and Integration

Roush performed vehicle assembly and integration from Q3 of 2019 to Q4 of 2020 using the major components supplied by Ballard (fuel cell) and Linamar (eAxle, inverter, batteries, hydrogen storage). Additionally, Roush developed the vehicle control system and revised the instrument panel to display hydrogen fuel level and other EV related parameters in place of engine speed and gasoline fuel level.

In mid-March 2020, the project team began assessing impacts due to COVID-19. On March 26, 2020, the Michigan governor issued a shelter-in-place order that shut down operations at Roush and Linamar until May 15, 2020. Many suppliers and subcontractors also shut down.

Roush encountered contract issues with the initial supplier of HV DC/DC converter. As a result, Roush changed the DC/DC design to a solution by Tame Power, which involved using two DC/DC converters in parallel to meet power conversion requirements without sacrificing efficiency. These converters required a 12-week lead time for procurement and were delivered late in Q2 of 2020.

For the purposes of this report, each of the four vehicles will be referenced by the last three digits of their trust number, as issued by the State of California: Truck 184, Truck 185, Truck 186, and Truck 187.

In September 2020, the first of four vehicles, Truck 186, was considered mechanically complete, including all subsystems installed, electrical connections made, and capable of self-propulsion (Figure 20 and Figure 21). Roush began calibration development on Truck 186 but experienced a critical failure in the DC/DC converter system, which required the return and repair of the system by Tame Power in France. Troubleshooting the root cause and repairing the DC/DC converters continued through Q1 of 2021 (see *Demonstration Readiness* section for further details).

Figure 20: Front View Showing eAxle System, FC, and Battery Condenser Radiators

Figure 21: UPS P100 Truck Body Reinstalled on the Finished Chassis

The DC/DC converter issue on Truck 186 was resolved and fuel cell commissioning activities began in June 2021. In July 2021, Roush worked to incrementally increase fuel cell power output and resolved some minor issues with software and wire harnesses throughout the process. By the end of July 2021, the fuel cell on Truck 186 operated up to 80 kW of power but had an issue with high hydrogen concentration measurements in the exhaust, which was eventually traced to faulty hydrogen sensors that had sat in storage for too long. After multiple attempts to repair, the faulty sensors were replaced in Q1 of 2022.

In November 2021, Roush reported smoke detection events that were causing the fuel cell to shut down mid-drive. According to Ballard, this had not been observed often in their fuel cells, but they have had issues with ionization smoke detectors in the past. Truck 186 was initially equipped with an optical detector. However, because there were problems with this optical detector, it was removed and replaced with an ionization detector instead. Roush continued troubleshooting through December 2021 and found that the root cause of the smoke detector events was condensation in the ventilation box where the smoke detector was housed. Roush worked with Ballard during Q1 of 2022 to redesign and install new ventilation boxes, prevent future water accumulation and condensation, and remedy the smoke detector events.

Test and Validation

Once vehicle integration was completed, Roush began powertrain and fuel cell consumption testing. Roush tested the vehicles on two types of drive cycles: mixed and start-stop. The mixed cycle contained a combination of normal city and highway driving, whereas the start/stop drive cycle consisted of repetitive stop-and-go driving to simulate the delivery of packages. Roush tested each of these drive cycles under different weight conditions: unloaded and loaded. The weight of the loaded condition was 21,000 lbs. This was the maximum weight that could be achieved with weight mats. For reference, the vehicle has a GVWR of 22,000 lbs. The weight of the unloaded condition was the curb weight of the vehicle, 13,500 lbs.

The test was conducted in Q1 of 2022. Based on the test results, summarized in Table 1 and Table 2, Roush reported that the in-service range would likely fall between the loaded start-stop cycle range and the unloaded mixed drive cycle range, depending on the route, cargo weight, and driver habits. The test indicated that the Project Team should target a range of 150 miles for the fleet.

Table 1: UPS FCDV Test Range Summary

Cycle	**Unloaded**	**Loaded**
Mixed	268 miles	142 miles
Start Stop	168 miles	88 miles

Table 2: UPS FCDV Test Efficiency Summary

Cycle	**Unloaded**	**Loaded**
Mixed	17.87 mi/kg	9.46 mi/kg
Start Stop	11.23 mi/kg	5.87 mi/kg

Shipping and Acceptance

Truck 186 was shipped to the UPS Customer Center in West Sacramento, CA on March 30, 2022 (Figure 22). Truck 187 was shipped on June 23, 2022, and Truck 184 was shipped on August 19, 2022. However, Truck 185 was held at Roush until November 2023. The reason for this being that the Project Team wanted to do parallel troubleshooting during the early part of the demonstration. Approximately one month into the deployment of the three trucks (Truck 186, 187, and 184) at West Sacramento, Roush would ship the fourth truck (Truck 185) to UPS.

Figure 22: Truck 186 Leaving Detroit on March 30, 2022

Figure 23: FCDV On Site in West Sacramento, January 2024

Task 3 Demonstration Readiness

Demonstration planning began early in the project, shortly after the CARB agreement was executed. The tasks to ensure demonstration readiness required extensive coordination among the Project Team. As part of demonstration readiness, the team performed the following activities:

1. Coordinated the hydrogen fuel supply
2. Developed vehicle O&M manuals
3. Developed a maintenance support plan
4. Completed vehicle operation and maintenance training
5. Underwent an extensive safety audit
6. Conducted on-site validation and system shakedown

Coordinating Hydrogen Fuel Supply and Demonstration Location

The project did not contract hydrogen infrastructure under this grant. However, prior to the project award, CTE discussed utilizing hydrogen fueling stations in Ontario, CA with StratosFuel and Shell. Both StratosFuel and Shell provided letters of commitment to the project.

The StratosFuel station was located at 1850 E. Holt Boulevard in Ontario, CA and was able fill at both 350 and 700 bar. The design and construction of this renewable hydrogen station were funded by the California Energy Commission, and the station opened for retail sales on March 29, 2018.

Additionally, in September 2018, Shell received notice of a proposed award from CARB to build a 1,000 kg/day hydrogen fueling station at the TravelCenters of America fueling center, located at 4265 E. Guasti Road in Ontario, only 2.4 miles from the Ontario UPS facility. The station would be built to accommodate trucks refueling at both 350 bar and 700 bar and was scheduled to open in 2020, very nearly the same time that UPS intended to deploy the FCDVs. In their letter of commitment, Shell stated that there would be sufficient capacity to support the daily fueling needs of the project.

Throughout 2019, CTE continued to monitor the reliability of the StratosFuel station and the progress of the Shell station. The Shell station was expected to be completed by September 2020, but the opening of the station continued to be delayed.

CTE began exploring potential backup demonstration locations as a risk mitigation measure due to the potential overutilization of the Shell station in Ontario given the multiple vehicle deployments at a single UPS center. CTE and UPS had identified several options for the backup demonstration location including West Sacramento based on fuel availability, fuel proximity to operations, local staff hydrogen familiarity, and operator enthusiasm.

In November 2020, CTE met with representatives from Iwatani to discuss the feasibility of deploying the vehicles at a public hydrogen fueling station in West Sacramento, CA. Iwatani expressed interest in providing fuel for the project, and the UPS West Sacramento facility was enthusiastic about hydrogen technologies. The Iwatani West Sacramento hydrogen fueling station is far from other publicly available hydrogen fueling stations. As a result, light-duty fuel cell vehicle customers in the Sacramento area rely heavily on Iwatani for their hydrogen fuel. The high traffic at this station underscores its critical role in supporting the local fuel cell vehicle infrastructure and ensuring the viability of hydrogen-powered transportation in the region.

In early 2021, the Project Team decided to move the demonstration to the West Sacramento UPS center. The UPS operators had received FCDV operations training, through a different ZANZEFF program, and were familiar with the technology. The chief concern with the relocation was the reliability and uptime of the West Sacramento Iwatani fueling station as the station was primarily designed for light-duty vehicles with smaller hydrogen capacities.

Throughout 2022 and 2023, the Project Team fueled at the Iwatani station intermittently. As the Project Team came closer to beginning the demonstration, CTE coordinated with UPS and Iwatani to determine the optimal fueling window for all parties. To accommodate the demand of the light-duty fuel cell vehicle customers, the Project Team decided to fuel during off-peak hours, from 8:00 pm to 11:00 pm.

Manuals Development

In August 2020, Roush began developing the vehicle operation manual. The manual provides operational instructions, cautions, and guidelines for the safe operation of the UPS FCDVs. Roush published the first iteration of the manual on April 22, 2022. However, during the UPS Safety Review period, Roush updated the manual to clarify the fueling procedure language and added images. The final version of the vehicle operation manual was released on March 3, 2023.

During the demonstration of the FCDVs, UPS would not be responsible for performing corrective maintenance on the vehicles. However, the Project Team developed and distributed maintenance, installation, and service manuals for fuel cell, the high voltage battery system, and the eAxle, for reference.

Project Support Process

In 2021 the Project Team developed a process flow for issue identification and resolution during the demonstration, including main and backup points of contact for each partner. UPS mechanics were trained on basic preventative maintenance for the vehicles and provided details such as timestamps of problems to Roush, Linamar, and Ballard for remote diagnostics. The process was used throughout the demonstration to support the identification and resolution of various vehicle problems (Figure 24).

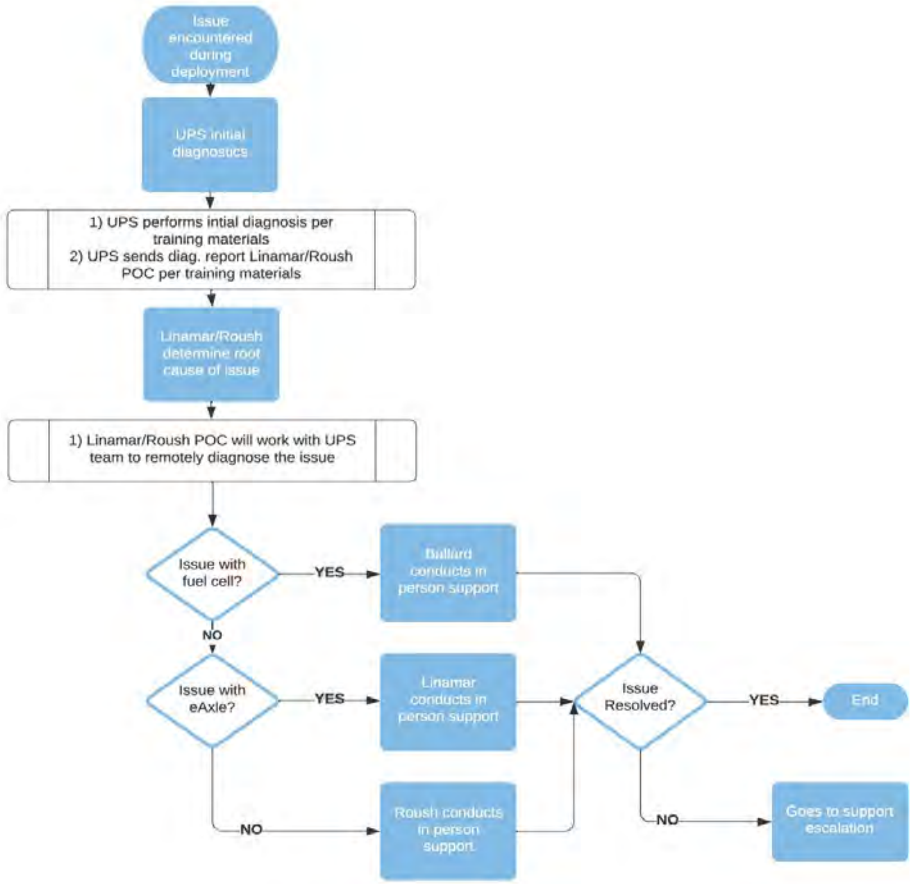


Figure 24: The Maintenance Support Process

Facilities Modifications for Hydrogen Safety

As discussed in the *Coordinating Hydrogen Fuel Supply and Demonstration Location* section of this report, the Project Team demonstration location was moved to the UPS distribution facility in West Sacramento, CA. This depot already had a robust gaseous detection system in place for the safe operation and maintenance of the CNG fleet. As a result, minimal upgrades would be required to make the garage compliant with local, state, and industry standards for safe hydrogen vehicle operation and maintenance.

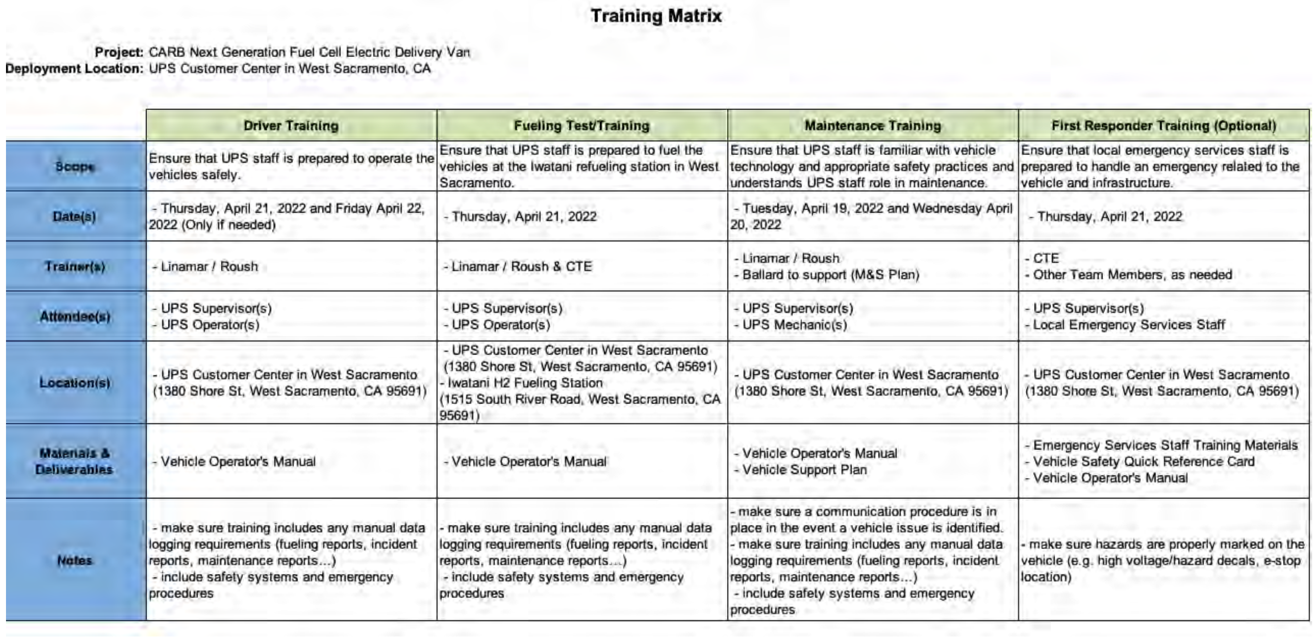
In June 2021, CTE contracted with Wilkins Process Optimization (WPO) to ensure that the maintenance bays were compliant with hydrogen safety codes and regulations. WPO used the following codes and standards to assess compliance:

- OSHA Standards 1926.407 and 1926.449
- NFPA Publications 2, 55, and 70
- NEC Articles 500 to 506
- 29 CFR 1910.399
- CBC Section 1.11.2.4.69

In August 2021 WPO completed the facility audit. WPO concluded that the UPS parking garages did not require any special safety equipment beyond what is required for traditional fuels. No changes were recommended for the package loading areas. However, WPO recommended installing hydrogen gas detection sensors in repair garages and following defueling requirements for any work on high voltage or hydrogen systems. UPS installed hydrogen gas sensors at the facility in 2022.

Training

Before vehicles entered service, the Project Team conducted operations, maintenance, and safety training across all critical job functions (supervisors, drivers, and mechanics) at UPS. UPS staff were educated not only on how the novel vehicle systems work but also on necessary safety considerations. Considerations included high voltage (clearly identified via hi-vis orange cabling) associated with the electric propulsion system and high pressure (clearly identified via stainless steel tubing) associated with the hydrogen fuel systems. Under no circumstances were UPS staff expected to perform maintenance or service activities on these systems. Training also covered fueling at the West Sacramento Iwatani station, including safety systems and emergency procedures. First responders were also invited to learn about the vehicles and infrastructure hazards and mitigations. The project training matrix is included below (Figure 25).



Training Matrix

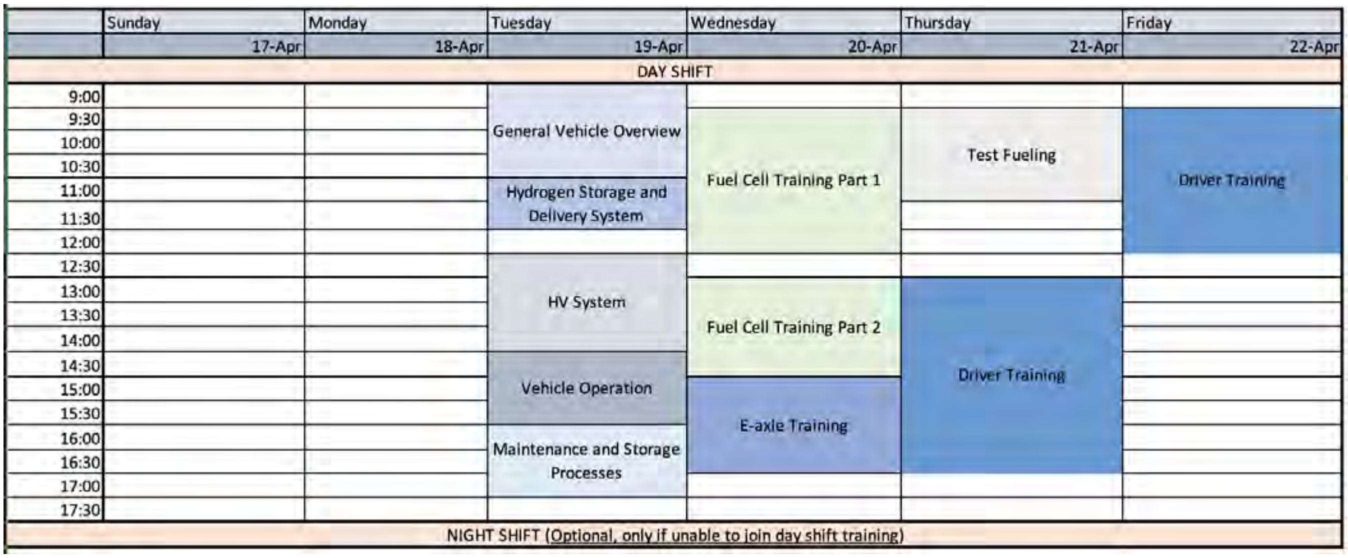
Project: CARB Next Generation Fuel Cell Electric Delivery Van
Deployment Location: UPS Customer Center in West Sacramento, CA

	Driver Training	Fueling Test/Training	Maintenance Training	First Responder Training (Optional)
Scope	Ensure that UPS staff is prepared to operate the vehicles safely.	Ensure that UPS staff is prepared to fuel the vehicles at the Iwatani refueling station in West Sacramento.	Ensure that UPS staff is familiar with vehicle technology and appropriate safety practices and understands UPS staff role in maintenance.	Ensure that local emergency services staff is prepared to handle an emergency related to the vehicle and infrastructure.
Date(s)	- Thursday, April 21, 2022 and Friday April 22, 2022 (Only if needed)	- Thursday, April 21, 2022	- Tuesday, April 19, 2022 and Wednesday April 20, 2022	- Thursday, April 21, 2022
Trainer(s)	- Linamar / Roush	- Linamar / Roush & CTE	- Linamar / Roush - Ballard to support (M&S Plan)	- CTE - Other Team Members, as needed
Attendee(s)	- UPS Supervisor(s) - UPS Operator(s)	- UPS Supervisor(s) - UPS Operator(s)	- UPS Supervisor(s) - UPS Mechanic(s)	- UPS Supervisor(s) - Local Emergency Services Staff
Location(s)	- UPS Customer Center in West Sacramento (1380 Shore St, West Sacramento, CA 95691)	- UPS Customer Center in West Sacramento (1380 Shore St, West Sacramento, CA 95691) - Iwatani H2 Fueling Station (1515 South River Road, West Sacramento, CA 95691)	- UPS Customer Center in West Sacramento (1380 Shore St, West Sacramento, CA 95691)	- UPS Customer Center in West Sacramento (1380 Shore St, West Sacramento, CA 95691)
Materials & Deliverables	- Vehicle Operator's Manual	- Vehicle Operator's Manual	- Vehicle Operator's Manual - Vehicle Support Plan	- Emergency Services Staff Training Materials - Vehicle Safety Quick Reference Card - Vehicle Operator's Manual
Notes	- make sure training includes any manual data logging requirements (fueling reports, incident reports, maintenance reports...) - include safety systems and emergency procedures	- make sure training includes any manual data logging requirements (fueling reports, incident reports, maintenance reports...) - include safety systems and emergency procedures	- make sure a communication procedure is in place in the event a vehicle issue is identified. - make sure training includes any manual data logging requirements (fueling reports, incident reports, maintenance reports...) - include safety systems and emergency procedures	- make sure hazards are properly marked on the vehicle (e.g. high voltage/hazard decals, e-stop location)

Figure 25: Project Training Matrix

UPS requested that the Project Team provide a 30-day notice prior to training to prepare personnel and allow for necessary changes to their daily operations. Training was originally scheduled for the week of September 20, 2021, but due to vehicle development and delivery delays (described in the *Vehicle Design and Build* section), training was delayed until the week of April 19, 2022.

The training schedule is provided below (Figure 26). Roush led the General Vehicle Overview, Hydrogen Storage and Delivery Systems, HV Systems, Vehicle Operation, and Maintenance and Storage Processes training sessions. Ballard led Fuel Cell Training, Linamar led the eAxle training, and CTE led the test fueling. Roush and Linamar both took trainees on test drives. Training was successfully completed by April 22, 2022.



	Sunday	Monday	Tuesday	Wednesday	Thursday	Friday
	17-Apr	18-Apr	19-Apr	20-Apr	21-Apr	22-Apr
DAY SHIFT						
9:00			General Vehicle Overview			
9:30				Fuel Cell Training Part 1	Test Fueling	Driver Training
10:00						
10:30						
11:00			Hydrogen Storage and Delivery System			
11:30						
12:00						
12:30			HV System			
13:00				Fuel Cell Training Part 2	Driver Training	
13:30						
14:00						
14:30			Vehicle Operation			
15:00				E-axle Training		
15:30						
16:00			Maintenance and Storage Processes			
16:30						
17:00						
17:30						
NIGHT SHIFT (Optional, only if unable to join day shift training)						

Figure 26: Project Training Schedule

During the safety review in 2023, UPS and their insurance provider informed the Project Team that the April 2022 training did not have a consistent and repeatable framework that could pass a legal discovery process in the unlikely scenario of a hydrogen event requiring an investigation. UPS requested that the Project Team conduct another vehicle operation and maintenance training session and provide more thorough documentation of training. UPS required their insurance carrier to approve the plan for subsequent training and associated documentation.

However, since the training task and associated milestone payments were expended for the April 2022 training, funding was not available for additional training. The Project Team consolidated the training schedule, reduced the scope, and reallocated funds from the demonstration budget to cover the cost of additional training.

The Project Team revised all training material and developed detailed training sign-off sheets to document the transfer of knowledge to UPS operators. The training plan and all associated documentation were approved by UPS' insurance carrier in August 2023. However, contracting, coordinating, updating, and developing the new material for additional training caused a significant strain on the project administration budget.

The additional training was completed January 16 - 19, 2024. CTE, Ballard, Linamar, and Roush led the in-person training. UPS and their insurance carrier were also in attendance. There were fifteen UPS automotive personnel trained (see Figure 28).

Drivers expressed satisfaction with the performance of the vans and responded positively to the training. Overall, the training was successful, and UPS personnel were adequately prepared to operate the vehicles in the demonstration.

Figure 27: Additional Training in January 2024.

Figure 28: Training Session at UPS West Sacramento

Figure 29: Hydrogen Refueling Training at Iwatani Hydrogen Station

UPS Safety Report

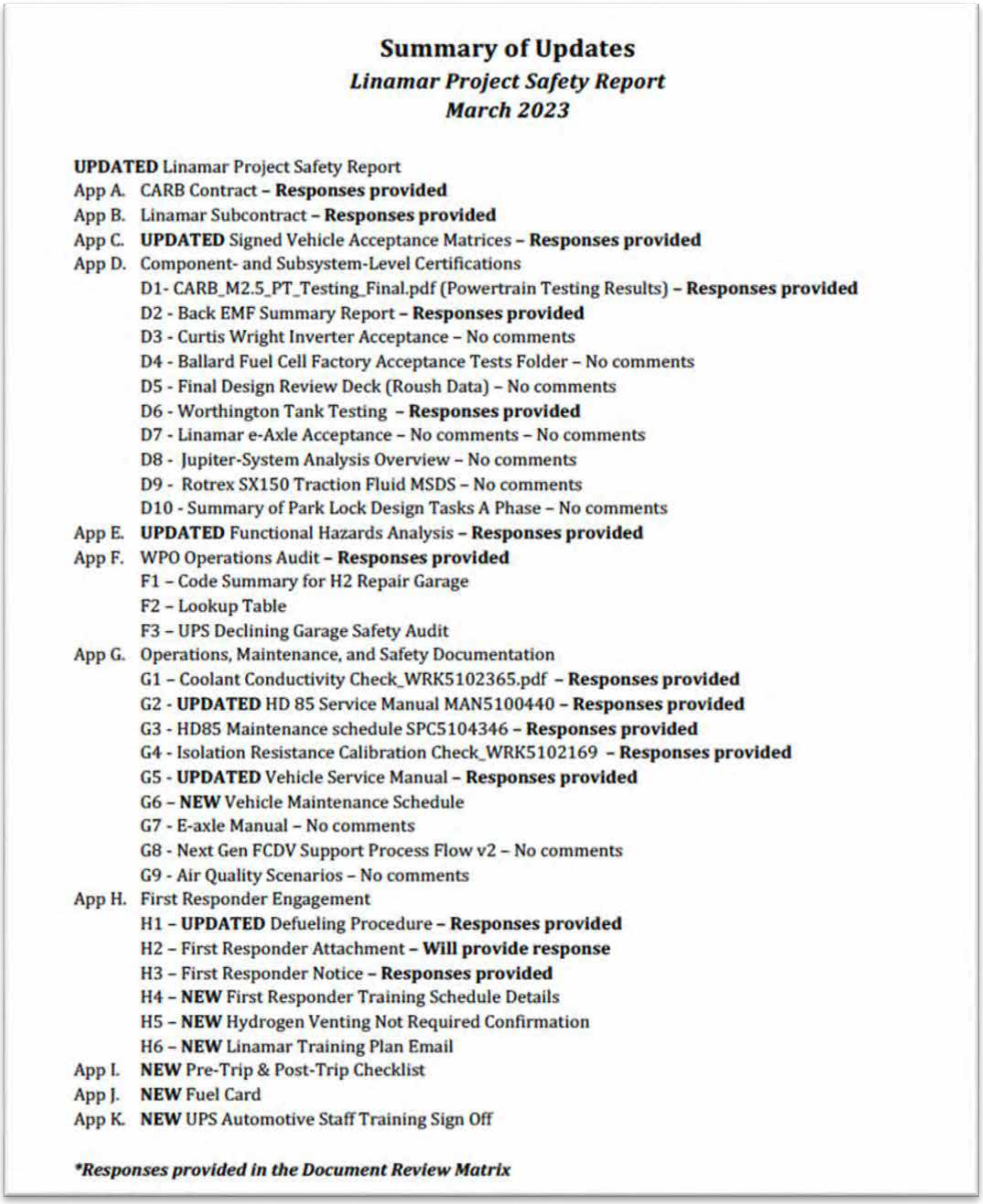
At the inception of the project, safety was prioritized and codified into the project scope of work and CARB contract. The Project Team defined the operational requirements to create the vehicle performance specifications. The vehicle was designed to maximize the utility of proven, off-the-shelf components in order to mitigate technical risk and maximize project safety. Each of the major vehicle subsystems was tested and certified according to the subsystem provider's best practices for safety and quality.

From the vehicle specifications, the Project Team developed an acceptance plan to ensure proper performance metrics and safety standards were met during test and demonstration. The acceptance plan identified all relevant codes and standards at the system and component levels, as well as operational requirements defined by UPS. Of particular relevance, maintenance and service activities were delineated so that UPS would not be responsible for maintaining or servicing the high voltage or high pressure (hydrogen) systems.

When Truck 186 was delivered to West Sacramento in April 2022, UPS engaged their insurer to conduct a safety audit on the vehicles. The FCDVs could not be put into service until UPS's insurer completed a comprehensive safety audit. CTE developed a Project Safety Report, a robust document that summarizes all project-level assessments. The appendix of the report includes more than thirty files detailing tests, certifications, confirmations, and approval.

The Project Team worked with the insurer to develop this Project Safety Report. The original report was submitted to UPS in August 2022. However, the Project Team published four iterations before receiving approval from UPS to deploy the FCDVs. Please see the latest iteration summary of the Project Safety Report in Appendix C.

The insurer responded to the August 2022 Project Safety Report with a matrix of comments. Some of these comments required documentation from component manufacturers and approval from the local Authority Having Jurisdiction (AHJ) at the West Sacramento Fire Department. CTE addressed each comment and submitted the first revision to UPS on October 20, 2022. Over the next three months, the Project Team awaited feedback. In January 2023, the insurer provided additional feedback, and by the end of March 2023, CTE responded to each comment, and provided new or additional documentation, as requested (see Figure 30).



Summary of Updates
Linamar Project Safety Report
March 2023

UPDATED Linamar Project Safety Report
App A. CARB Contract **– Responses provided**
App B. Linamar Subcontract **– Responses provided**
App C. **UPDATED** Signed Vehicle Acceptance Matrices **– Responses provided**
App D. Component- and Subsystem-Level Certifications
    D1- CARB_M2.5_PT_Testing_Final.pdf (Powertrain Testing Results) **– Responses provided**
    D2 - Back EMF Summary Report **– Responses provided**
    D3 - Curtis Wright Inverter Acceptance – No comments
    D4 - Ballard Fuel Cell Factory Acceptance Tests Folder – No comments
    D5 - Final Design Review Deck (Roush Data) – No comments
    D6 - Worthington Tank Testing **– Responses provided**
    D7 - Linamar e-Axle Acceptance – No comments – No comments
    D8 - Jupiter-System Analysis Overview – No comments
    D9 - Rotrex SX150 Traction Fluid MSDS – No comments
    D10 - Summary of Park Lock Design Tasks A Phase – No comments
App E. **UPDATED** Functional Hazards Analysis **– Responses provided**
App F. WPO Operations Audit **– Responses provided**
    F1 – Code Summary for H2 Repair Garage
    F2 – Lookup Table
    F3 – UPS Declining Garage Safety Audit
App G. Operations, Maintenance, and Safety Documentation
    G1 – Coolant Conductivity Check_WRK5102365.pdf **– Responses provided**
    G2 - **UPDATED** HD 85 Service Manual MAN5100440 **– Responses provided**
    G3 - HD85 Maintenance schedule SPC5104346 **– Responses provided**
    G4 - Isolation Resistance Calibration Check_WRK5102169 **– Responses provided**
    G5 - **UPDATED** Vehicle Service Manual **– Responses provided**
    G6 – **NEW** Vehicle Maintenance Schedule
    G7 - E-axle Manual – No comments
    G8 - Next Gen FCDV Support Process Flow v2 – No comments
    G9 - Air Quality Scenarios – No comments
App H. First Responder Engagement
    H1 – **UPDATED** Defueling Procedure **– Responses provided**
    H2 – First Responder Attachment **– Will provide response**
    H3 – First Responder Notice **– Responses provided**
    H4 – **NEW** First Responder Training Schedule Details
    H5 – **NEW** Hydrogen Venting Not Required Confirmation
    H6 – **NEW** Linamar Training Plan Email
App I. **NEW** Pre-Trip & Post-Trip Checklist
App J. **NEW** Fuel Card
App K. **NEW** UPS Automotive Staff Training Sign Off

Responses provided in the Document Review Matrix

Figure 30: Summary of Updates to the Project Safety Report

One month later, CTE received another round of comments from the insurer and throughout May 2023, CTE worked with the Project Team to resolve the comments. Between June and August 2023, CTE pushed UPS and their insurance carrier to approve the Project Safety Report. On August 24, 2023, UPS approved the Project Safety Report cleared the vehicles for service.

The UPS safety audit resulted in a delay of over a year, and the development of the Project Safety Report significantly strained the project budget. However, the Project Team considers the Project Safety Report to be one of the greatest achievements of this program. The insurer's high level of engagement required the Project Team to develop a comprehensive set of documents that can be leveraged for the development of future FCDVs.

On-Site Validation and System Shakedown

In order to validate vehicle systems operation, each vehicle underwent two separate commissioning processes: one for the base electric vehicle propulsion system, and one for the hydrogen fuel cell range extender system. Both processes generated a commissioning document for each vehicle that detailed the methodologies and provided a sign-off on each major component. All commissioning was completed prior to vehicle shipment.

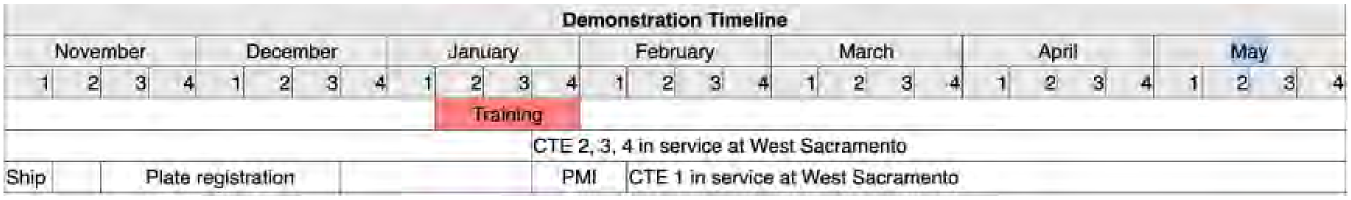
After the vehicles (Trucks 184, 185, 186, 187) were delivered to UPS and upon completion of the safety audit, UPS conducted preventative maintenance inspections (PMIs) to ensure the package cars were in good working condition and to identify and address any potential issues before they escalated into major problems. These inspections were crucial for maintaining the safety, reliability, and efficiency of the fleet.

Defective items requiring replacement were identified during the inspections that occurred during May and June 2023 on the three vehicles delivered to UPS first (Trucks 184, 186, and 187). Issues included items such as missing hazardous material posters and required documentation that needed to accompany the vehicle to missing parts or parts requiring repair.

Task 4 Vehicle Deployment and Operations

FCDV Operations and Support

The original intent was to deploy the FCDV's for 12 months beginning in 2020 in Ontario, CA. However, the events previously described caused the Project Team to relocate the demonstration to West Sacramento, CA and the limited remaining budget required the team to shorten the demonstration period to three months in 2024. The revised demonstration schedule is shown below in Figure 31.



Demonstration Timeline

November				December				January				February				March				April				May			
1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4	1	2	3	4
									Training																		
											CTE 2, 3, 4 in service at West Sacramento																
Ship		Plate registration									PMI		CTE 1 in service at West Sacramento														

Figure 31: Demonstration Timeline in 2023-2024

Repair Issues and Support

Prior to the February 2024 deployment, the four FCDVs were experiencing varying degrees of issues that required corrective maintenance. While onsite for training and shakedown in January 2024, Roush, Linamar, and Ballard documented issues that required repair. Throughout February 2024, the Project Team determined how to resolve, and the resolutions are shown on issue log below in Table 3**.** The complete issue log can be found in Appendix A.

Table 3: Vehicle Issues and Resolutions

Issue	**Resolution**
Missing fans	UPS installed fans.
Low-hanging high voltage lines beneath vehicle	Linamar/Roush affirmed these cables are safe for demonstration because they are not the lowest item in the system. Additionally, some loop/droop is needed for axle movement, especially if placed on a frame hoist.
Low hanging coolant lines beneath vehicle	Linamar/Roush affirmed this is a low risk to operation as-is. The lines are not able to be easily rerouted. If a coolant line is damaged it is a similar risk as with conventional powertrain radiator coolant hose issues. The eAxle has motor and oil sump temperature sensing and will protect the powertrain.
Program roll back assist control for parking on hills	Linamar/Roush recommended no actions for safe demonstration due to the rollback mitigations below: 1) Inverter function is not implemented and would require validation of a new feature 2) F-59 chassis vintage does not support ABS activation for hill hold with TRW brake system 3) UPS driver training and SOP has drivers applying manual parking brake at all vehicle stop conditions (stop light, stop sign, etc.)
Zip ties holding the fuel cell	Linamar/Roush do not see this as a major issue for evaluation vehicles but addressed specific cable tie locations of concern with UPS.
D.I. filter on fuel cells due to vehicles being stationary	Coolant systems on all trucks were circulated and checked with conductivity meters and all were within acceptable range. Truck 187 had D.I. filter replaced.
Rear wheel well H2 tank and sensor potentially exposed to flying road debris	Linamar/Roush see this as a very low probability risk. Roush fabricated and installed a deflector sheet attached to the wheel well liner.
Water intrusion from hood around HV connections that were not rated for wet environments due to missing weather stripping	Rubber seals were installed on the leading edge of drip channels for all vehicles except truck 185 which is not operational due to an electrical short in the 12V fuse box.
Plugs missing on drip channel	Aluminum pop rivets were installed in holes on the firewall side of the drip channel.
24V connections located inside passenger-side step are held shut by rubber tabs	Per SAE guidelines, 24V are not considered HV and do not require additional safety precautions therefore rubber strap is sufficient for LV connections. UPS agreed this was not an issue. All low voltage items are under step.
Set regeneration at level 3 as default due to driver preference	Roush flashed all 4 SCMs with the update to set regeneration at level 3.
HV electrical lines are intermingled with other components that might be encountered during standard maintenance by UPS.	No action taken because training identified all orange wires are high voltage and to be avoided.
Fluid on wiring from leaks from auto lube and hoses	All wires are TXL wire and fluid resistant which is standard automotive wire. The connectors are all individually sealed automotive military standard Deutsch connectors. Roush/Linamar affirm issue can be closed with regard to oil and water.
Wires should be butterfly strapped	The UPS preference for use of butterfly retention straps was understood by Roush/Linamar but not viewed as a requirement for evaluation vehicles; no action was taken.
Potential chaffing on wires tie-strapped to shock tower	The shock tower does not move, so this location was considered a valid attachment point.

HV wiring at hard angles	Wiring was rerouted on identified concern. There are strain reliefs at the connectors on both sides.
Multiple internal fuel cell fault codes related to errant fuel cell current transducer measurements (19703, 518, 404, 5017, 304)	Truck 185 had a number of faults related to the current transducer. Truck 185’s radiator was removed, reinstalled, and refilled. The fuel cell concern on 185 was closed. Truck 185 had an electrical short in the 12V fuse box and was not operational. Water intrusion to the fuel cell coolant module harness likely shorted out the board which was replaced. The harness bulkhead connector was removed, the damaged wire was cut out, and connections were soldered and repaired. Truck 185 required a new fuse box and review to return to operational status. All other trucks were cleared of faults and operational.
Non-operational cabin heaters	Linamar/Roush confirmed all heaters had failed and suspected all trucks had the same issue: high voltage on the 350V bus led to failure, not water intrusion. They confirmed that high voltage from the fuel cell shut down sequence overloaded the heaters. Replacements were needed, but the high shutdown voltage was still a concern. Because the demonstration was occurring in California in the spring, Linamar/Roush recommended running the trucks without cabin heaters for the demonstration.
Bottom rubber mat protection from radiator back unsecured	All trucks reviewed and reinstalled.
Missing SEVCON controller for fuel cell water pump	Linamar/Roush found the SEVCON and installed it on truck 184. Trucks 185, 186, and 187 were sealed.
UPS "Fuel Cell Vehicle" sticker on the van exterior missing	UPS had labels and installed them.
Hydrogen hazard labeling missing on van exterior	Linamar installed labeling in three locations plus the fuel port on all trucks.
Hydrogen controller (HCM) borrowed from Truck 185 for Truck 187	Roush/Linamar returned the controller to 185 from 187. They confirmed all trucks had HCMs installed and were fully operational.
Fuel cell shut down mid-drive with 6918 fault code indicating integrator current draw low	Ballard described this as an inadequate load from the BDC to maintain the requested fuel cell power. A software fix was implemented for this known issue on truck 184.
Fuel cell locks out due to voltage above expected range at shutdown	Ballard and Roush determined that the fuel cell voltage spike at shutdown is managed by Ballard via their preheating module. This module was removed from the truck build due to space constraints and no functional need for deployment in California. The issue was reviewed and approved by all parties (Roush, Linamar, Ballard) at that time (ca. 2019). The team learned during this troubleshooting period that the module had a secondary function for voltage management. Roush, Linamar, and Ballard determined that all other components on the circuit are safe at the high voltage because the first solution of a software fix was not able to manage the voltage spike. Therefore, Roush increased the shutdown threshold, and all faults are clear. There were no operational concerns for the demonstration.
Fuel cell fault 1118	A feature of the ground fault monitor (GFM) on all truck fuel cells was disabled to prevent conflict with the external ground fault monitor.
Hydrogen tank rock guards missing on truck 185	Guards were reinstalled.

In-service operation was delayed until the vehicle issues in Table 3 were resolved. The Project Team spent February and March 2024 determining the root cause, required actions, acceptable risks, parts, and costs needed to resolve each issue. A site-visit was scheduled for April 2024 to execute all repairs. Linamar generously covered the cost of the repairs since the project did not have budget remaining for vehicle remediation. UPS replaced cabin heaters, installed cabin fans, and applied appropriate external lettering to the fleet.

Between April 1 - 4, 2024, Linamar, Roush, and Ballard traveled to the UPS facility in West Sacramento to execute all repairs. The trip was successful and trucks 186 and 187 were ready to be entered into package delivery service. However, Truck 184 had issues with hydrogen refueling and Truck 185 was not operational. See Table 4 for the status of the vehicles at the conclusion of the April 2024 remediation trip.

Table 4: Vehicle Status Summary as of April 2024

Vehicle No.	Status	Registration
184	Fueling communication issues	Complete
185	Not operational	Not registered
186	Operational	Complete
187	Operational	Complete

Given the limited time remaining in the demonstration, the Project Team decided to prioritize the remediation of the three functioning vehicles and not attempt further repairs on Truck 185. Spare parts from Truck 185 were used to support the functioning vehicles.

Deployment

On April 18, 2024, OEMs provided official sign off on all repairs acknowledging that the Trucks 184, 186, and 187 were acceptable to operate. However, on April 25, 2024, no vehicles had been deployed and UPS explained that they needed internal approval to deploy the functioning vehicles (Trucks 184, 186, and 187). UPS received approval, and Trucks 186 and 187were deployed into package delivery service on May 9, 2024. However, there were various issues that caused the vehicles to go in and out of service throughout May 2024.

Issue 1: Dashboard Cluster Issue

Truck 184 was not deployed due to a fuel cell indicator light on the dashboard cluster, indicating a fuel cell fault. Ballard determined that the indicator light was triggered by an automatic maintenance reminder, based on hours in service. The quickest fix was a software reflash because Ballard had removed the maintenance reminder in its latest production software release. However, a Ballard technician was required on-site to perform the software update. Truck 184 was taken out of service until the issue was resolved. On May 22, 2024, the fuel cell indicator light appeared on the dashboard of Truck 186, causing it to be pulled from service. On May 27, 2024, a Ballard technician came to the UPS facility to update the fuel cell software on Trucks 184, and 186, resolving the fuel cell indicator light issue.

On April 30, 2024, Truck 186 was able to fuel; however, UPS fuelers noticed that the fuel gauge was not properly working. Roush worked with UPS and found that the root cause was a loose needle on the instrument cluster. The instrument cluster was replaced with the cluster from Truck 185 and the issue was resolved.

Lessons Learned: The prototype nature of the vehicles contributed to the implemented fault handling and operator feedback strategy. The team implemented a two-level indicator tell-tale strategy using amber for all non-critical warnings and red for critical issues requiring immediate attention. Select fuel cell warnings as well as general fuel cell reminders or maintenance information were combined in collaboration with the fuel cell supplier and displayed as either amber or red indicators to the vehicle operator. In the case of the instances noted above, a simple maintenance reminder was forcing the amber "H2" light to illuminate. Additionally, driver training instills strong discipline to not ignore any warning light and to protect the vehicle by not continuing operation for either amber or red indicators.

The issue with the fuel gage on Truck 186 was again a lesson learned for prototype vehicle development that is reusing standard OEM equipment. The OEM gage has a simple press fit of the indicator arrow on the gage post which after multiple disassembly/reassembly activities was loose and not being retained properly.

Recommendation for Future Users of the Technology: The team recommends future production-based implementations to use a full three tier driver information strategy that includes green/blue operational status items, amber for non-critical warnings and red for critical system issues. The team also recommends to not only blend the conventional OEM indicators but supplement the indicator lights with a more informative electronic information center providing more detailed and specific information. All faults and warnings cannot be treated equally forcing engineering team involvement to troubleshoot. Any reuse of OEM gages on the dashboard should also include a quality check for its condition and operation.

Issue 2: Refueling Issues

On April 4, 2024, the station was offline because the ESB (emergency stop button) had been actuated. Resetting the ESB requires a technician on-site and results in multiple hours of station downtime. Iwatani was working on improving their ESB remediation time, but the April 4, 2024, actuation prevented UPS from deploying the vehicles in service until the next day.

While fueling the trucks during the April 2024 repair trip, the UPS driver/refueler noticed that the dispenser display communicated "Please Wait" or "Dispenser error" messages which prevented the vehicles from fueling. Roush ultimately suspected a problem with the communication protocol between the vehicle and station was contributing to the problem. This was the case for Truck 184. In another instance, the fuel level was so low that the amount the Truck 187 requested from the station caused issues with the station software. All issues were resolved, and Trucks 184, 186, and 187 were successfully refueled by May 9, 2024.

During the demonstration, Iwatani upgraded their station capability to reduce the wait time between fills to 10 minutes and increase the limit per fueling sessions from 3 kg to 5 kg. On May 28, 2024, UPS noticed that station was only dispending 0.3 kg of hydrogen before requiring customers to wait approximately 20 minutes to fuel again. Iwatani confirmed that the station was shutting off due to temperature management problems at high temperatures during the summer. UPS attempted to fuel late at night when temperatures were cooler but were unsuccessful. See
Table 5 for record of fueling issues during April and May 2024.

Table 5: Iwatani Station Issue Log

Date	Truck	Notes
4/4/24		Station was shut down for e-stop
4/5/24	187	“Please Wait” message (8:39 pm PT)
4/5/24	187	9:30pm, station was e-stopped
4/6/24	187	“Please Wait” message (12:06 pm PT)
4/6/24	184	"Dispenser error" message shown, 9:42 pm (suspect issue with communication protocols)
4/29/24	184	"Please Wait" message at station
4/30/24	187	"Please Wait" message at station
5/28/24	184/186	Station limiting fills to ~0.3 kg due to temperature management
5/30/24	186	Station limiting fills to ~0.3 kg due to temperature management

Lessons Learned: Fueling events during the demonstration period illustrated a few different reliability issues to hydrogen fueling for commercial vehicle applications. First is the significantly larger hydrogen fill capacity each vehicle presents to the fueling station. The project vehicle capacity is 2-2.5x larger than the currently available passenger vehicle offerings. With a limited fuel supply to be managed at the public station, full fill ups of commercial vehicles place a strain on the nearby hydrogen passenger vehicle community. Further the available commercial vehicle capacity, when communicated to the station, may confuse the station logic – particularly if the updated software supporting commercial vehicles is not implemented at the hydrogen station and the fueling request is then denied. Additionally, if the tank pressure is too low during the initial pressure check of the fueling sequence the logic may conclude the nozzle is not connected to a vehicle and prevent fueling. Disabling the infrared communications between the truck and the station hydrogen dispenser allowed a fueling event to start, provided the tanks were not too depleted, but would be stopped at a prescribed limit either due to table fill calculations or artificial limitations per customer.

Recommendation for Future Users of the Technology: Commercial vehicle operations should strongly consider installing hydrogen refueling infrastructure within their own operation (“behind the fence” solutions) to ensure fuel availability. This private infrastructure would eliminate the reliance on the small public infrastructure that is dominantly configured for passenger automotive customers.

Issue 3: Loose Fuel Port

On May 20, 2024, the Project Team learned that the fuel fill port had come loose on Truck 187. Though this issue did not require Truck 187 to be removed from service, Roush recommended that UPS file a small notch into the fuel cap to address a working theory that trapped air beneath the cap was warming after fueling and the resultant pressure rise could dislodge the cap. UPS found that throwing a parcel onto the truck shook the vehicle enough to trigger the fuel cap sensor even after notching the cap but did not have further issues on route. UPS continued to operate the vehicle and the Project Team monitored the situation.

Lessons Learned: The hydrogen fuel fill assembly was selected as a complete commercially available unit that uses an o-ring around the cap to provide a seal from the environment (i.e. dust, water, etc.)

as well as a spring loaded ball detent to secure the cap in the closed position. Physical impact from package loading inside the vehicle as well as entrapped air building pressure behind the o-ring illustrated a lack of robustness to the design. Disturbances as noted as well as vibration from driving would be sufficient to trigger the limit switch into thinking the cap has become removed or dislodged.

Recommendation for Future Users of the Technology: Future production-based system designs need to include a better evaluation of the retention method for the enclosure and ensure a proper air vent is included. The team also recommends engineering a custom fuel door arrangement similar to a standard ICE vehicle. This custom door should also take into account different fueling nozzle designs versus the bayonet style that was used during this project.

Issue 4: HV System Fault

On May 29, 2024, a UPS driver went over a large bump while on a route, and the HV warning indicator on the dashboard cluster illuminated. As instructed, in the event of an HV system fault, only qualified service personnel should handle the vehicle until the cause of the fault is determined. As a result, the driver pulled over and Truck 187 was towed back to the UPS facility.

Roush worked to determine the root cause but was having difficulty because the fault decoding between the controller software and the decoding tool was not consistent; however, they suspected a low voltage connection problem broke the high voltage interlock loop, which would have allowed the vehicle to drive until it was keyed off at which point it would not be allowed to re-energize to prevent technician injury. Truck 187 was out of service for the remainder of the demonstration.

Lessons Learned: A complete root cause was not able to be completed on this vehicle. The shutdown occurred near the end of the planned demonstration period reducing available support time to troubleshoot. The inconsistent fault handling the team noted prevented further remote analysis. On-site support is needed to determine the actual problem condition.

Recommendation for Future Users of the Technology: Improve data logging, fault handling and diagnostic layers need to be implemented to allow the prototype truck fleet operator an understanding of what and where the trouble is in the system.

Issue 5: Data Logging

Roush installed data loggers that were powered by the low voltage batteries on the trucks. Signals were collected from the CAN bus and uploaded via local cellular service. However, the logger was unable to recover upload data automatically after entering a cell service dead area during a route. To resolve, UPS would power cycle the data logger by disconnecting the 12V battery. UPS moved the two working data loggers between vehicles (186 and 187) to ensure that working trucks (184, 186, and 187) had working data loggers while in service. As described above, only Truck 186 and 187were operated in delivery service with working loggers.

Lessons Learned: Data loggers were installed in these vehicles to provide the project partners with vehicle performance information beyond just having real time diagnostics. The data recorded is solely intended for real world usage feedback into the design and development into next generation product and not needed for general vehicle operation. The current data logger software doesn’t appear to have provisions which allow the data logger to reestablish contact when a cell signal is lost without fully cycling power. This lack of recovery was not previously known.

Recommendation for Future Users of the Technology: Future versions of the software for this data logger could be developed to improve communication robustness in operational areas with weak or no cellular service available. Alternatively, other data logger systems also employ dual SIM cards with different frequencies to improve connectivity. The team also recommends performing test drives through potential routes monitoring cell signal strength and connectivity before selecting the data logger type for demonstration purposes.

Data Report

Due to the issues described in the *Vehicle Deployment and Operations* section above, Trucks 186 and 187 were in regular package delivery until May 30, 2024. Truck 184 experienced various issues that rendered it out of service, and parts from Truck 185 were utilized to support functioning vehicles. As a result, the *Data Report* below captures and analyzes the performance of Truck 186 and Truck 187.

Vehicle and Equipment Specification

Propulsion System Specifications: Table 6 details key FCDV specifications. The van stores 15 kg of hydrogen at 700 bar and is capable of top speeds of 68 mph and 180 kW of peak power from the eAxle. The battery stores 53 kWh.

Table 6: FCDV Truck Specifications

FCDV Truck Specifications Ford F-59 178-inch chassis / Morgan Olson Walk-in Step Van (P100 Package Car)	
GVWR / GAWR / Curb	22,000 lbs / 15,000 lbs / 12,922 lbs
Target Range / Top Speed	150 miles / 68 mph
Fuel Cell	Ballard – FCvelocCity-HD85 / 85 kW net
Hydrogen Storage	2 tanks, Type 3, 700 bar, 15 kg total capacity
Battery System	53 kWh, 700 V XALT, 250 kW max
eAxle	Linamar Medium-Duty eAxle, helical gears
eAxle rating	180 kW peak / 130 kW continuous, 11,500 Nm

Vehicle Operation

Description of Daily Use of Vehicles: The package cars (186 and 187) were operated on short routes around West Sacramento for package delivery on weekdays during the day. The vehicles were typically refueled between 8:00 pm and 11:00 pm by a dedicated UPS refueler. See *Vehicle Deployment and Operations* section for more details.

Vehicle Usage: Table 7 and
Table 8 summarize package delivery operations for Truck 186 and Truck 187. Truck 186 operated between 2 and 13 hours per day during May for a total of 63 hours of in-service demonstration, completing stops between 10 and 160 times per day. Truck 187 was on-route for a total of 50 hours, between 4 and 10 hours each day and completed between 4 and 99 stops each day.

Table 7: Truck 186 Operations Summary

Truck 186 Operations Summary
Source: Linamar Data Collection

Date	Day of Week	Distance (miles)	Duration (hrs)	Number of Stops	Fuel Used (kg)	Notes
5/9/24	Thu	12.6	2.9	10	1.78	Battery was charged from 40% to 70% before departing
5/10/24	Fri	36.4	7.8	73	1.96	
5/13/24	Mon	24.7	3.8	31	0.95	
5/15/24	Wed	1.1	Not on routes			
5/16/24	Thu	34.7	4.0	53	2.03	
5/20/24	Mon	56.7	12.7	160	3.73	
5/21/24	Tue	18.0	4.4	11	1.13	
5/24/24	Fri	22.4	Bad data files			
5/28/24	Tue	51.8	9.0	141	2.99	
5/29/24	Wed	65.9	9.7	146	3.84	
5/30/24	Thu	43.7	8.8	150	2.55	

Table 8: Truck 187 Operations Summary

Truck 187 Operations Summary
Source: Linamar Data Collection

Date	Day of Week	Distance (miles)	Duration (hrs)	Number of Stops	Fuel Used (kg)	Notes
5/9/24	Thu	27.1	4.8	4	1.53	
5/21/24	Tue	23.0	8.0	65	1.78	Battery charged from 51% to 70% SOC
5/22/24	Wed	33.2	8.2	69	1.89	
5/23/24	Thu	37.4	9.7	99	2.43	
5/24/24	Fri	22.7	7.6	74	3.03	
5/28/24	Tue	23.4	5.1	8	0.58	
5/29/24	Wed	20.6	6.7	62	1.60	HV fault and towed home

GPS Data: Due to the short demonstration and UPS's desire to operate the vehicles on short routes, less than 50 miles, generally, close to the depot, without highway driving, and with trained drivers, there were only four viable routes, and only two routes that ended up being utilized regularly. Truck 186 drove a route south of the depot (Figure 32**,** tracts with scores from 10-60th percentiles on CalEnviroScreen4.0). Truck 187 drove routes into Midtown Sacramento (Figure 33, tracts with scores in the 60-70th percentiles on CalEnviroScreen4.0) and further east into Colonial Manor (Figure 34, tracts with scores in 60th-70th percentiles on CalEnviroScreen4.0). All GPS data can be found in the data files in Appendix E under parameters GPS_LATITUDE_DEG and GPS_LONGITUDE_DEG.

Figure 32: GPS Trace of Truck 186 May 30, 2024 Package Delivery Service

Figure 33: GPS Trace of Truck 187 May 21, 2024 Package Delivery Service

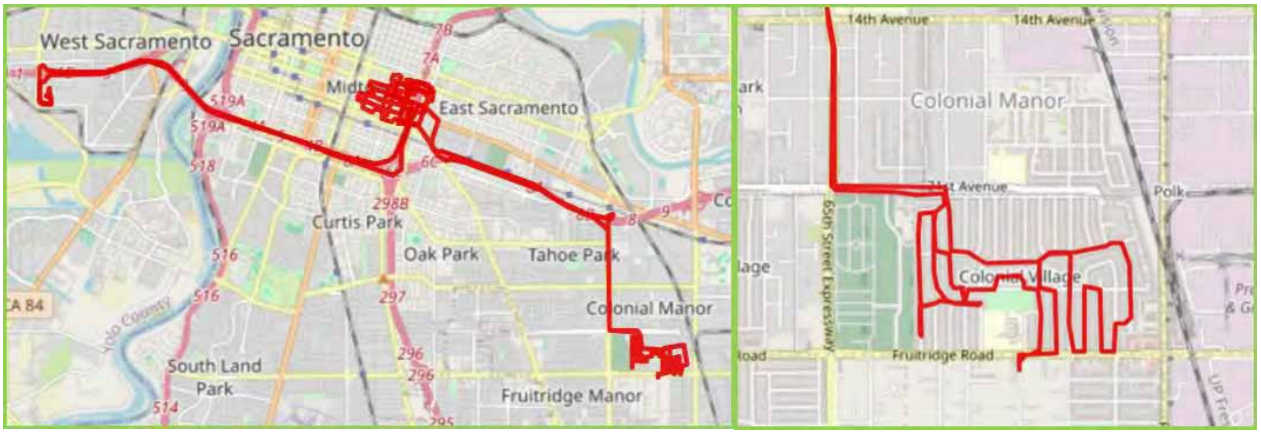


Figure 34: GPS Trace of Truck 187 May 23, 2024 Package Delivery Service

Origin and Destination: The vehicles operated out of the UPS West Sacramento Depot located at 1380 Shore Street West Sacramento, CA 95691. The routes targeted for deployment were 4D River City, 4B, 20H Sacramento Route on Harbor Side, 21A Sacramento Route.

Distance Traveled: The daily distance traveled in delivery service was between 12 and 65 miles for Truck 186 and between 20 and 40 miles for Truck 187 (Figure 35).

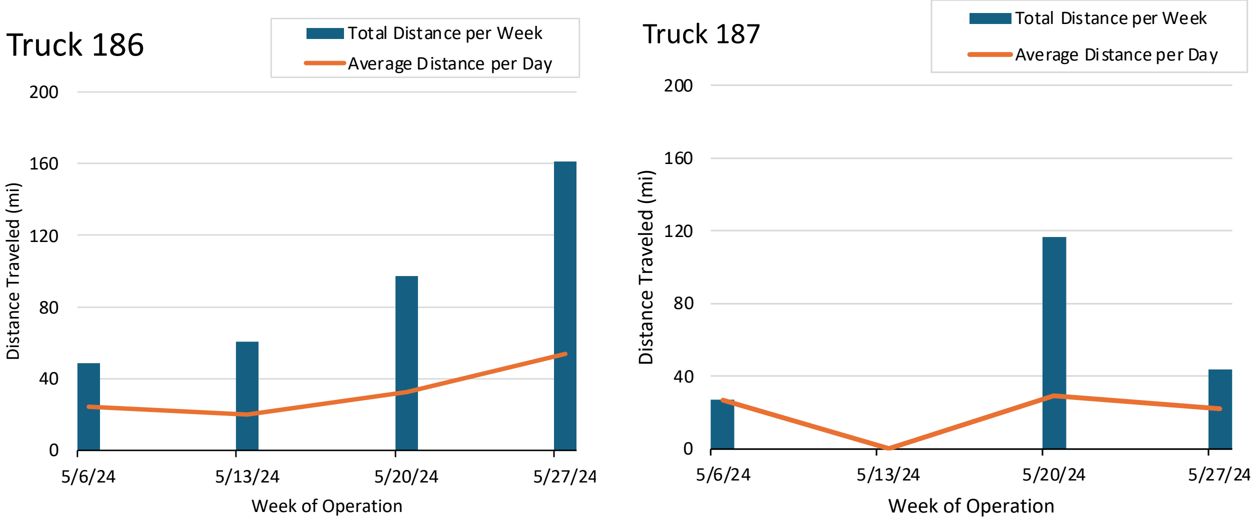
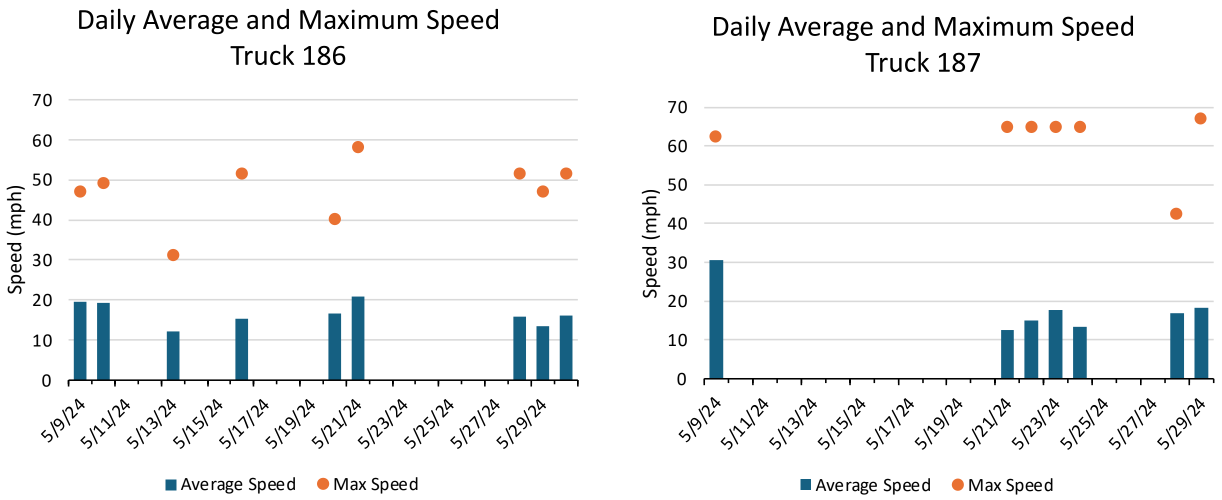


Figure 35: Weekly and Average Daily Distance Traveled

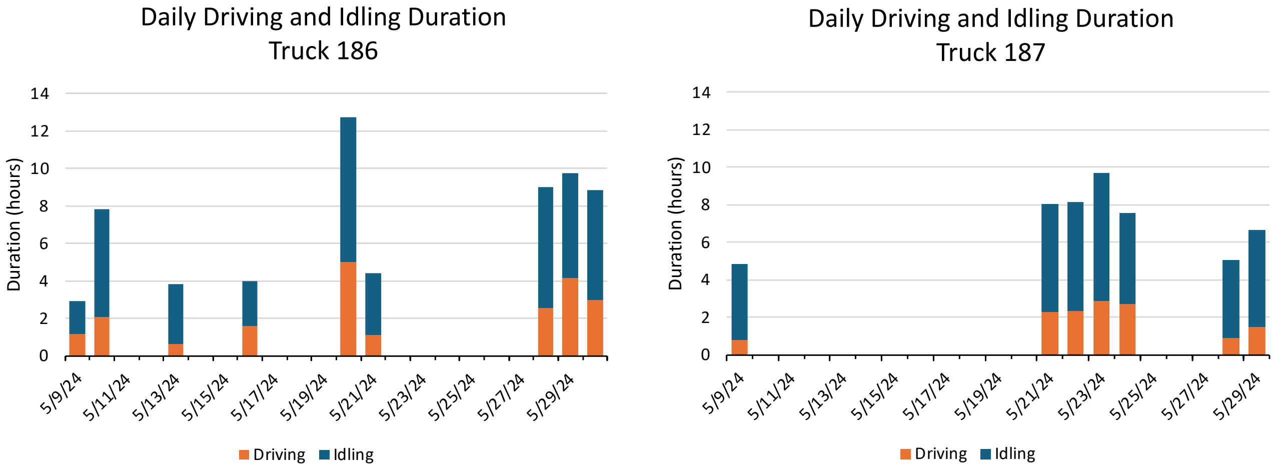
Average Speed: When driving on-route, the daily average vehicle speeds ranged between 12 mph and 20 mph for Truck 186, and between 12 mph and 30 mph for Truck 187. The daily maximum speed for the trucks was between 30 mph and 67 mph, with Truck 187 more often driving at highway speeds due to its routes. Figure 36 shows the daily average and daily maximum speed on route for Trucks 186 and 187.


Daily Average and Maximum Speed Truck 186

Daily Average and Maximum Speed Truck 187

Figure 36: Daily Average and Maximum Vehicle Speed

Idling: During package delivery service, the vehicles drive for a longer duration, then make frequent stops to deliver packages. This duty cycle leads to frequent idling. Truck 186 idled between 1 and 8 hours each day in service, and Truck 187 idled between 4 and 7 hours each day in service (Figure 37).


Daily Driving and Idling Duration Truck 186

Daily Driving and Idling Duration Truck 187

Figure 37: Daily Driving and Idling Duration

Weight of Load: The vehicles are rated for a maximum load of 7,000 lbs; specific daily package loads are not recorded by UPS.

Battery Degradation: The battery state of health (SOH) was captured over the demonstration by measurements of the capacitance and resistance of the battery as a percentage of the peak state of health. At the end of the demonstration, Truck 186 had 100% resistance SOH and 99.1% capacitance SOH, and Truck 187 had 100% resistance SOH and 98.8% capacitance SOH, indicating minimal degradation over the demonstration.

Vehicle Performance

Miles Between Road Calls: One road call was necessary during the demonstration for Truck 187 at odometer 1331 miles; see *FCDV Operations and Support* section for details.

Number of Road Stop Calls: One road call was necessary during the demonstration for Truck 187; see *FCDV Operations and Support* section for details.

Vehicle Availability: The delivery vans did not have maximum availability due to several maintenance problems before and during the demonstration as well as problems with hydrogen availability. See *FCDV Operations and Support* section for details.

Vehicle Zero-Emission Range: Using the total distance traveled by both trucks and the amount of fuel consumed for the duration of the demonstration, the calculated average economy is 16.4 mi/kg. By multiplying this value by 15 kg (on-board hydrogen storage capacity), the predicted range of the vehicles in parcel delivery service is 247 miles. This is 39 miles greater than the average simulated range of 205 miles, described in the *Test and Validation* section of this report (Figure 38). Note that the range on May 9, 2024 for Truck 186 is much lower due to the fuel cell being used to charge the HV battery from 40% to 70% before going on route for the day, resulting in fewer miles traveled.

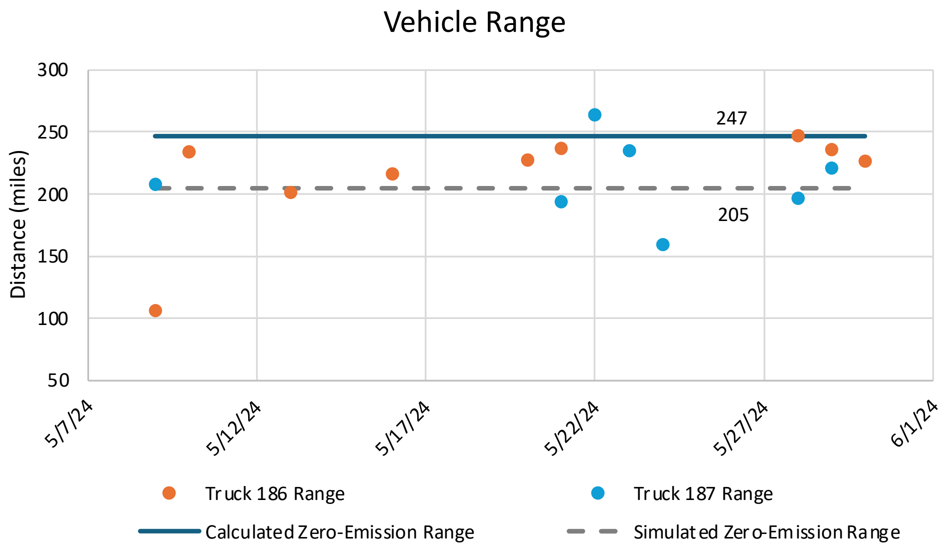


Figure 38: Vehicle Range Comparison

Fuel and Energy Consumption

Amount of Fuel, Date, and Fuel Price per Unit: The Project Team collected hydrogen fueling data from various sources. UPS provided receipts from fueling sessions at Iwatani. These receipts show the amount of fuel purchased, the price per kg of H2, and the total cost of each fueling session. However, UPS was unable to provide the Project Team with all receipts. As a result, the Hydrogen Purchased column in the table below captures only those fueling sessions where receipts were provided to the Project Team.

The vehicle hydrogen consumption was captured by Linamar. Linamar used the measured fuel flow rate to calculate the amount of hydrogen consumed by the vehicle. Iwatani confirmed the cost per unit at their station remained consistent throughout the demonstration period. The cost of hydrogen in West Sacramento was $29.99/kg over the course of the demonstration.

The fuel used over the course of the demonstration for package delivery service is summarized in Table 9. In total, Truck 186 consumed 20.7 kg of hydrogen and Truck 187 used 12.8 kg of hydrogen in package delivery service. Based on the receipts provided to the Project Team, UPS purchased 47.8 kg of hydrogen and spent $1,434.65 for the hydrogen fuel during the demonstration. Note the fuel purchase by UPS does not include all fueling sessions and some fuel was consumed in non-delivery service driving.

Table 9: Refueling Events and Fuel Consumption During Demonstration

Date	**Unit Price ($/kg)** *Source: Iwatani*	**Total Hydrogen Purchased (kg)** *Source: UPS Receipts*	**Cost of Fuel ($)** *Calculated*	**Hydrogen Consumed by 186 (kg)** *Source: Linamar Vehicle Data*	**Hydrogen Consumed by 187 (kg)** *Source: Linamar Vehicle Data*
5/3/24	$ 29.99	4.37	$ 130.94		
5/3/24	$ 29.99	1.25	$ 37.58		
5/3/24	$ 29.99	3.60	$ 107.84		
5/9/24	$ 29.99	4.84	$ 145.00	1.78	1.53
5/10/24	$ 29.99	0.41	$ 12.39	1.96	
5/13/24	$ 29.99	4.04	$ 121.16	0.95	
5/15/24	$ 29.99	0.61	$ 18.32		
5/16/24				2.03	
5/17/24	$ 29.99	4.84	$ 145.00		
5/17/24	$ 29.99	3.69	$ 110.72		
5/20/24				3.73	
5/21/24				1.13	1.78
5/22/24	$ 29.99	4.44	$ 133.25		1.89
5/22/24	$ 29.99	4.11	$ 123.20		
5/22/24	$ 29.99	0.43	$ 12.84		
5/23/24					2.43
5/24/24	$ 29.99	0.39	$ 11.73		3.03
5/24/24	$ 29.99	4.84	$ 145.00		
5/25/24	$ 29.99	0.38	$ 11.25		
5/25/24	$ 29.99	4.84	$ 145.00		
5/25/24	$ 29.99	0.39	$ 11.70		
5/28/24				2.99	0.58
5/29/24	$ 29.99	0.39	$ 11.73	3.84	1.60
5/30/24				2.55	

The estimated cumulative hydrogen fuel cost and calculated amount of hydrogen fuel purchased from the station is shown in Figure 39 and Figure 40.

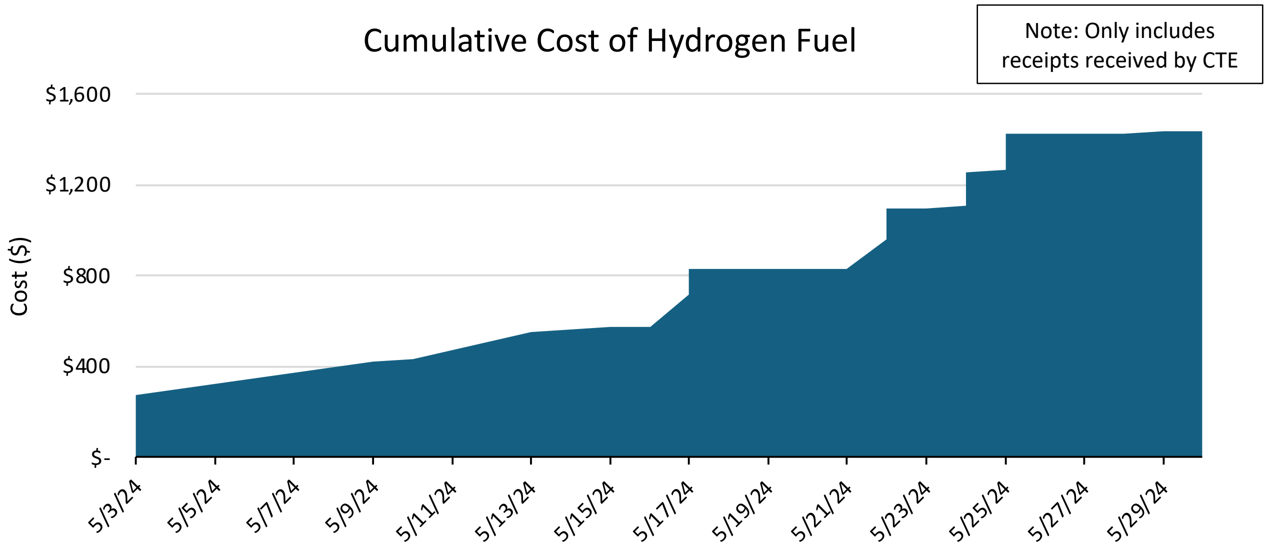


Figure 39: Cumulative Cost of Hydrogen Fuel

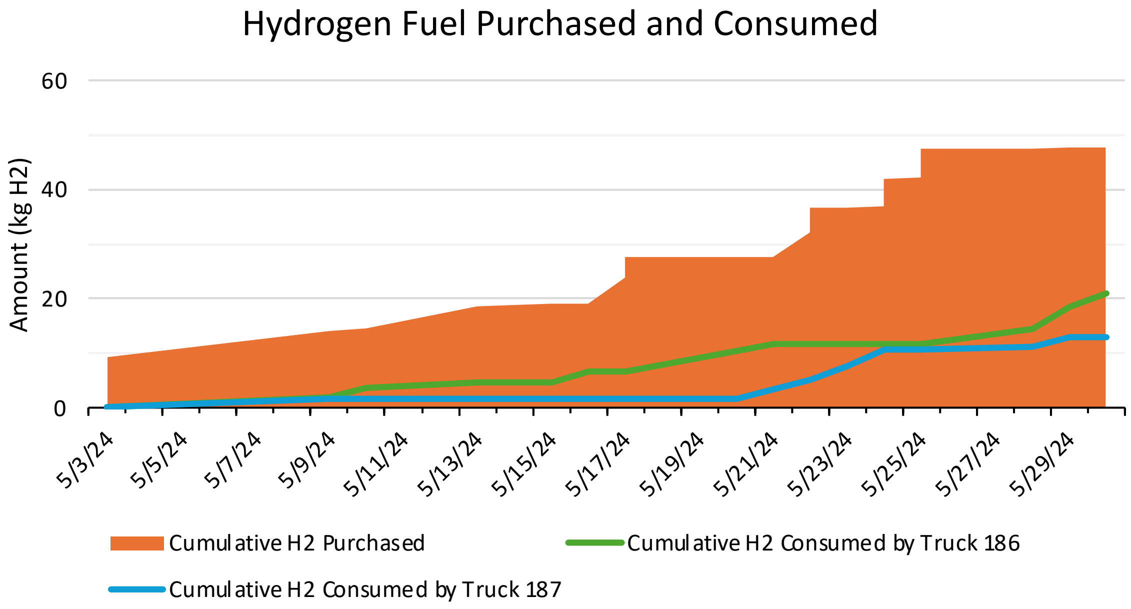


Figure 40: Cumulative Hydrogen Purchased and Consumed

State of Charge (SOC): During operation, the battery was charged by the fuel cell. The parameter that described this is labeled as BATT_Sys_SOC_String_Avg and was collected at a 1 Hz sampling rate. Please see Appendix E for the SOC data.

Refueling Time: According to the vehicle data loggers on Truck 186, the average fueling time during the demonstration was 16 minutes, and the average fill rate was 0.25 kg/min (Table 10).

Table 10: Truck 186 Fueling Summary

	Total Fuel Consumed (kg) *Source: Vehicle Data Logs*	**Fuel Fill Time (min)** *Source: Vehicle Data Logs*	**Fuel Fill Rate (kg/min)**
Average	3.37	15.90	0.23
Minimum	1.44	7.20	0.17
Maximum	4.70	28.28	0.34

According to the vehicle data loggers on Truck 187, the average fueling time during the demonstration was 27 minutes, and the average fill rate was 0.16 kg/min (Table 11).

Table 11: Truck 187 Fueling Summary

	Total Fuel Consumed (kg) *Source: Vehicle Data Logs*	**Fuel Fill Time (min)** *Source: Vehicle Data Logs*	**Fuel Fill Rate (kg/min)**
Average	4.29	26.85	0.16
Minimum	3.54	25.33	0.13
Maximum	4.86	28.00	0.19

Distance Traveled to Refuel: The distance traveled was 2.5 miles between the UPS Customer Center and the Iwatani West Sacramento Hydrogen Station located at 1515 S River Rd, West Sacramento, CA 95691 (Figure 41).

Figure 41: Truck 187 Refueling Route on May 17, 2024 from the UPS Facility to Iwatani Station

Refueling Source: The hydrogen at the Iwatani West Sacramento Hydrogen Station is supplied from the Linde-Praxair SMR facility in Ontario, CA via liquid delivery by Messer. The reported carbon intensity is 0 kg CO_2e/kg H_2. Iwatani uses a combination of Low Carbon Fuel Credit pathways to supply every Iwatani hydrogen station with hydrogen that has 0 carbon intensity and is 40% renewable.

Refueling Frequency: During the May 2024 demonstration, there were 18 refueling events recorded by UPS. See Table 9 for details. Note, not all fueling events were reported by UPS. Some refueling events occurred on the same day but are separate events due to quantity caps and wait times required at the station.

Fuel Economy and Energy Consumption: The fuel economy of Truck 186 was between 13.3 and 16.4 miles per kilogram, averaging approximately 15.2 miles per kilogram (see Figure 42, excluding May 9, 2024, see explanation below). UPS confirmed that the vehicles begin service at maximum weight, approximately 21,000 pounds, and gradually unload throughout the day. The average fuel economy of Truck 186 was 1.5 miles per kilogram better than the simulated fuel economy of 13.7 miles per kilogram for a loaded FCDV.

The worst fuel economy for Truck 186 occurred on May 9, 2024, the first day it was put into regular operation. Linamar reported that the fuel economy on this date was 7 miles per kilogram. This was because the battery was charged from 40% to 70% by the fuel cell before going on route, which significantly decreased fuel economy and increased energy consumption per mile.

The fuel economy of Truck 187 was between 10.6 and 17.6 miles per kilogram, averaging approximately 14.1 miles per kilogram (see Figure 42). The average fuel economy of Truck 187 was 0.4 miles per kilogram better than the simulated fuel economy of 13.7 miles per kilogram for a loaded FCDV. Truck 187's routes had more highway driving than Truck 186.

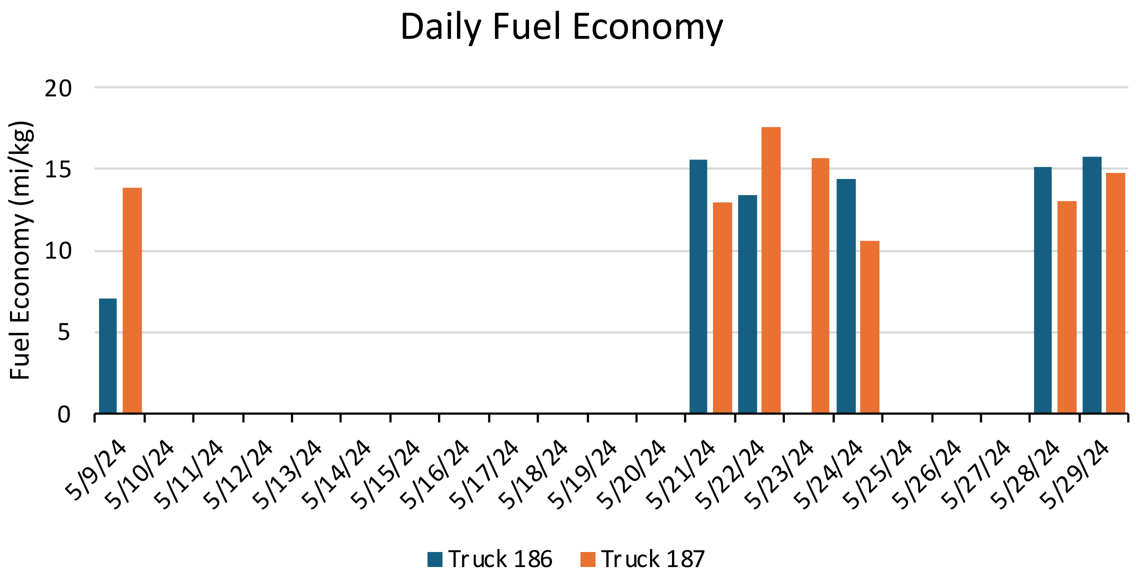


Figure 42: Daily Fuel Economy

On Truck 186, the energy consumption was typically between 4 and 10 kilowatt hours per mile. However, on May 9, 2024, the energy consumption was significantly higher, 45.1 kilowatt hours per mile (see Figure 43). As described above, this was because on May 9, 2024, the battery was charged from 40% to 70% by the fuel cell before going on route, which significantly decreased fuel economy and increased energy consumption per mile.

On Truck 187, the energy consumption per mile was between 3 and 10 kilowatt hours per mile. On May 21, 2024, Truck 187 had an energy consumption of 17.7 kilowatt hours per mile because the battery was charged from 52% to 70% SOC.

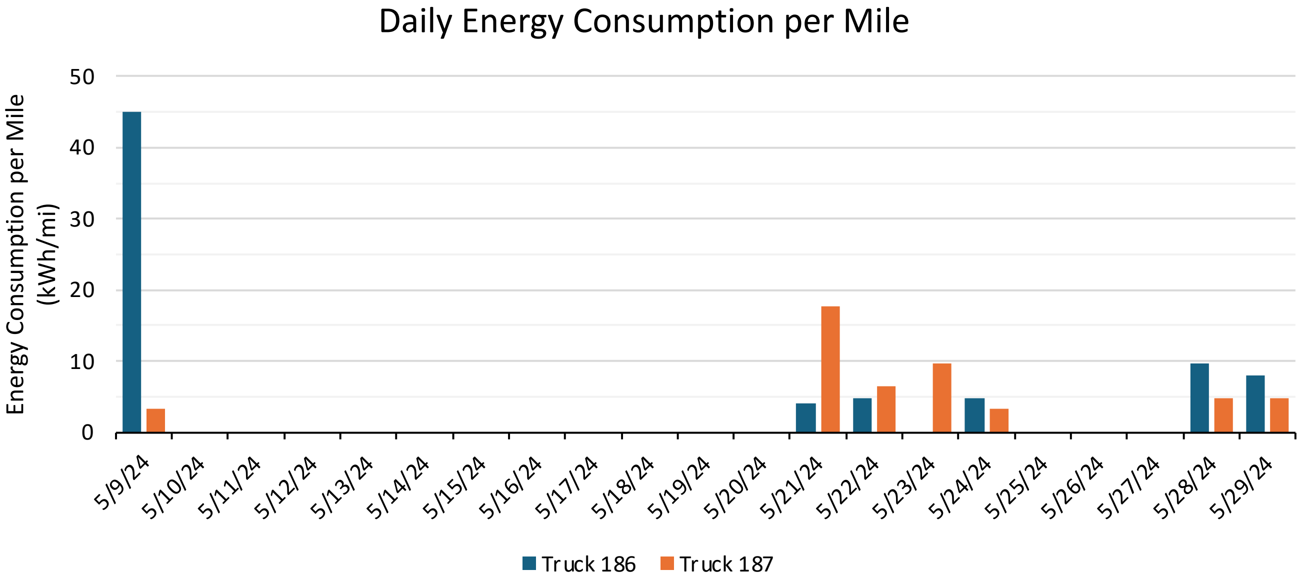


Figure 43: Energy Consumption per Mile

Fuel/Energy Consumption While Idling: To calculate the fuel consumption while idling, the fuel flow rate parameter (*hcmFlVolFlw* in slpm) was to be integrated over the time that the vehicle speed is zero miles per hour (i.e., when the motor torque request, parameter *Motor_TorqueRq*, is zero). Please see Appendix E for further information.

Service Calls

Date of Service Call, Description of Problem, and Repair: Service was completed by UPS mechanics on the baseline technology systems such as the vehicle body, cabin systems such as heating and fans, and low voltage battery replacements. All advanced technology systems services were completed by Ballard, Roush, or Linamar technicians and engineers. See *Repair Issues and Support* for details. The date, description of problem, repair performed, and parts replaced for demonstration repairs can be found in the Issue Log in Appendix A. The cost of UPS parts and labor is in Table 14.

Time Out of Service: As described in *Vehicle Deployment and Operations* section of this report, Trucks 184 and 185 were not put into regular service. Trucks 186 and 187 entered service in May 2024.

Service Response Time to New Trouble Call: The Project Team was responsive to calls from UPS about dashboard warning lights or questions about vehicle performance. Roush was available remotely and able to use remote data collection to diagnose issues and advise on solutions, particularly for refueling problems.

Safety

Description of any Accidents or Incidents: There were no safety incidents throughout the program.

Emissions Testing

The FCDVs operated for 113 hours and 555 miles over the demonstration, using 34 kg hydrogen. CTE compared the emissions of the FCDV to an equivalent diesel delivery van over 55 miles based on the

2023 AFLEET On Road Footprint[2] tool and emissions data from a diesel delivery van (see Methodology, Appendix B).

Overall, the FCDVs emitted 0 kg of greenhouse gasses (GHGs) from well to wheels (WTW). There are no tailpipe emissions from a FCDV, and the emissions from hydrogen production are certified to be zero by Iwatani. In comparison, the diesel delivery van emits 0.8 short tons WTW. The FCDVs saved 0.8 short tons of GHGs.

A diesel delivery van releases local harmful air pollutants. Deploying the FCDVs, which have no tailpipe air pollutants, saved 1.3 pounds of carbon monoxide (CO), 1.7 lbs of Nitrogen Oxides (NOx), 0.1 pounds of particulate matter under 10 micrometers (PM10), and 0.1 pounds of Volatile Organic Compounds (VOCs). These pollutants have a considerable health impact on the community (Table 12).

Table 12: Tailpipe Air Pollutants and WTW GHGs

		Tailpipe Air Pollutants (lbs)				
	WTW GHGs (short tons)	CO	NOx	PM10	VOC	SOx
FCDV	0	0	0	0	0	0
Diesel Delivery Van	0.8	1.3	1.7	0.1	0.1	0.01

While the upstream pollutants for the FCDVs are certified zero, the upstream pollutants for the diesel FCDV are shown in Table 13.

Table 13: Upstream Air Pollutants

	Upstream Air Pollutants (lbs)					
	CO	NOx	PM10	PM2.5	VOC	SOx
FCDV	0	0	0	0	0	0
Diesel Delivery Van	0.2	0.3	0.02	0.02	0.13	0.09

Please see the Emissions Calculations Methodology in Appendix B for details of calculations.

Fueling Infrastructure and Maintenance Infrastructure

Fueling Infrastructure: The fueling infrastructure utilized by the program was the Iwatani West Sacramento hydrogen station. Though it was not funded by the program, it served a critical role as the only open station in the Sacramento region. The station is supplied by liquid hydrogen delivery and dispenses hydrogen at 700 bar.[3] The fueling protocol is optimized for light-duty fueling, but it does have the ability to fill 10+ kg at slower fill rates. The modeled HyScape capacity is 394 kg/day with an average demand of 131 kg/day in 2024 (January 1, 2024 through May 30, 2024). Customers are requested to wait between 10 to 15 minutes between fueling to help maintain high reliability.

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[2] AFLEET 2023, Argonne National Laboratory

[3] Discussions with Iwatani personnel

Additional upgrades are planned for 2024 to improve back-to-back fueling capability. The hydrogen is 40% renewable with a carbon intensity of 0 kg CO_2e/kg H_2[4]. The average station uptime since late 2023 has been above 90%. Figure 44 below shows the station at 94% uptime for the week of May 18-24, 2024, according to the Hydrogen California website.[5] The blue line shows the station hydrogen inventory, and the red and green bars show the uptime of the station.

Figure 44: Iwatani Station Inventory and Uptime for May 18-24, 2024

Maintenance Infrastructure: UPS installed hydrogen gas detection sensors in the West Sacramento facility in 2022. Due to the robust CNG buildout, minimal maintenance facility upgrades were required.

Operating and Maintenance Costs

Detailed Maintenance Costs for Baseline and Advanced Technology Vehicles/Equipment, including Parts and Labor: UPS provided maintenance labor and parts expenses for the FCDVs (Table 14). Labor expenses are calculated at a rate of $125 per hour. The costs were relatively low because the OEMs provided most maintenance and support. The total costs for UPS maintenance and labor over the course of the program were $14,158.84, or $3,539.74 per truck.

Table 14: UPS Maintenance Costs for FCDVs

	2021			2022			2023			2024		
Unit	Lab. Hrs	Labor	Parts	Lab. Hrs	Labor	Parts	Lab. Hrs	Labor	Parts	Lab. Hrs	Labor	Parts
184	0.1	$12.50	$ -	3.57	$446.25	$ -	15.5	$1,940.00	$38.79	12.1	$1,516.25	$10.02
185	0.1	$12.50	$ -	-	$ -	$ -	0.6	$83.75	$ -	5.2	$655.00	$32.45
186	1.5	$195.00	$ -	3.62	$452.50	$ -	15.3	$1,916.25	$62.45	19.1	$2,391.25	$64.47
187	0.1	$12.50	$ -	-	$ -	$ -	12.9	$1,616.25	$62.42	19.7	$2,470.00	$168.24
Total	1.8	$232.50	$ -	7.19	$898.75	$ -	44.4	$5,556.25	$163.66	56.2	$7,032.50	$275.18
Program Total Labor:	$13,720.00			**Program Total Parts:**	$438.84			**Program Total Maintenance:**	$14,158.84			

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[4] According to Iwatani personnel
One kg of hydrogen has 120 MJ energy. (Department of Energy, Hydrogen Storage)
[5] Only one week at a time can be visualized. H2-CA - West Sacramento

O&M Costs for Facility Safety Systems Related to Hydrogen and Fuel Cells: Due to the robust CNG buildout at the West Sacramento maintenance facility, the upgrades required to prepare the facility for the FCDVs were minimal. In August 2021, WPO completed a facility safety audit to ensure that the maintenance bays were compliant with hydrogen safety codes and regulations. WPO concluded that the UPS parking garages do not require any special safety equipment beyond what is required for traditional fuels. No changes were recommended for the package loading areas. However, WPO recommended installing hydrogen gas detection sensors in repair garages and following defueling requirements for any work on high voltage or hydrogen systems.

In June 2021, UPS upgraded the garage sensors to monitor H2. UPS confirmed (via email) that the upgrade cost approximately $3,000. Please see the *Facilities Modifications for Hydrogen Safety* section of this report for further details.

User/Fleet Experience Survey

User/Fleet Experience of the Advanced Technology: Table 15 summarizes the results of the user survey with ratings from one to five. One being the worst rank, and five being the best rank. The users captured a variety of roles at UPS. Generally, the operators were very satisfied with the training they received and the vehicle safety. Vehicle uptime, operation and maintenance challenges, and the vehicles' ability to meet demand were some of the lowest ratings of the five users.

Table 15: User Survey Results

Experience with Vehicle	Mechanic	Fueler/Carwasher	Driver 1	Driver 2	Maintenance Technician	Average	Comments
Vehicle availability ("up time")	3	5	2	3	1	**2.8**	Driver 2 - Only marking low due to the starting time
Vehicle power and handling	4	5	2	4	3	**3.6**	Driver 2 - Vehicle handles one of the best I've driven
Vehicle's ability to meet demand (overall performance)	2	5	3	3	1	**2.8**	Driver 2 - start up and wait time if starting too fast is the only thing to really slow me down (45 sec to 1 min wait time)
Operations & Maintenance (O&M) challenges	2	5	1	NA	1	**2.25**	
Availability of service parts	2	5	1	NA	1	**2.25**	
Satisfaction with Project Team's reponse to service requests	3	5	3	5	3	**3.8**	Driver 2 - Every time I had a question I was met with a quick response Fueler 1 - Very satisifed with the project team
Vehicle safety	4	5	4	5	2	**4**	Drive 2 - Very Safe
Refueling difficulty	3	5	NA	NA	4	**4**	Fueler 1 - Fueling after 8 pm is good
Refueling reliability	3	5	NA	NA	4	**4**	
Training							
Satisfaction with instructor	4	5	5	5	5	**4.8**	Driver 2 - Felt very comfortable due to the knowledge I got before going on road.
Confidence in technology before training	3	5	4	5	3	**4**	Fueler 1 - Jon (UPS) has been very reliable and is there for me at any time of need
Confidence in technology after training	3	5	4	5	2	**3.8**	

Workforce Training Programs: As demonstrated by the user survey responses, the training sessions that took place were effective and helped users have confidence in the fuel cell technology. A total of 15 employees were trained. See *Training* section of this report for further detail.

Describe Insurance Policies: Please see the *Demonstration Readiness* section and *UPS Safety Report* section of this report for details about the involvement of UPS's insurer.

Vehicle Manufacturer Response/Service for Warranty Claims and/or Trouble Shooting: Linamar, Ballard, and Roush were responsive to troubleshooting needs before and during the demonstration and were able to perform remote diagnostics, guide UPS personnel through troubleshooting, and executed an extra site visit for repairs and support throughout the entire program. See *FCDV Operations and Support* section for further details.

Conclusion

The FCDV project demonstrated the build of four FCDVs using the standard Ford F-59 chassis, the Ballard FCvelocity™ fuel cell, and the Linamar eAxle. Unique design aspects included a new non-level package for the fuel cell to fit inside the chassis design. Despite cascading challenges from COVID-19 and supply chain problems causing delays in the build, the team delivered four vans to UPS for demonstration in West Sacramento, California. Overcoming hurdles with hydrogen availability in the region and ongoing maintenance challenges, two vans were demonstrated in package delivery service for a total of 113 hours and 555 miles, resulting in an average fuel economy of 16.4 miles per kilogram and a total estimated range of 247 miles, exceeding the target range of 125 miles and simulated range of 205 miles. This range meets the needs of the majority of UPS delivery routes. However, due to the high cost of hydrogen at public fueling stations, UPS will not continue to operate the vans.

The demonstration saved 0.8 tons of greenhouse gas emissions from well to wheels in fuel and operation compared to a diesel UPS van. There is no immediate plan for the commercialization of a fuel cell delivery van by the project partners, but the project provided important lessons including the need for resilient fuel supplies, committed operating partners, and thorough safety planning and education.

Recommendations

To ensure the successful adoption and implementation of FCDVs, several barriers must be overcome. The public perception of hydrogen remains a significant challenge, necessitating comprehensive education and safety training for end-users. Additionally, the current reliance on public hydrogen fueling stations has led to operational delays, highlighting the need for more mature and reliable fueling infrastructure. Finally, demonstrating the scalability of hydrogen technology is crucial for its adoption by large commercial fleet operators. The following recommendations aim to address the ways to overcome existing barriers to market adoption and allow for vehicle technology expansion:

Barrier 1: Hydrogen Safety Education

There are continual challenges with the public perception of hydrogen. For mass adoption of FCDVs, there must be a comprehensive structure in place to educate end-users about hydrogen. Though the Project Team engaged extensively in safety planning throughout the lifetime of the project, hydrogen safety and training should be a larger focus of funded projects.

UPS's insurer encouraged safety training and development of hydrogen safety documentation, which became the Project Team's main focus for an entire year, leading to significant project delays. Ultimately, the FCDV project succeeded in developing a comprehensive set of documents that can be leveraged for the development of future FCDV demonstrations. However, the additional hydrogen safety education work that took place during the one-year delay was not included in the project plan at the onset of the project.

To overcome this barrier and mitigate delays on future projects, technology development and demonstration projects must incorporate a greater emphasis on community engagement and hydrogen safety education into their scope of work. Elements from the project's Safety Plan, such as the training sign-off sheets, fueling cards, and training agenda, shall be used as a standard for training material on future projects.

Barrier 2: Utilizing Public Fueling Stations

Initially, the Project Team felt that an advantage for the FCDV project, and for the medium-duty market in general, was taking advantage of public fueling infrastructure. Mobile fueling infrastructure adds cost, time, and risk that can be justifiable for a temporary demonstration but detracts from the cost-reduction goals afforded by mass deployment. If an end-user does not invest in on-site fueling infrastructure, they are dependent upon public hydrogen fueling stations for their fueling needs; however, some public stations limit the fill pressure and amount of hydrogen available, which can be inconvenient for a medium-duty fuel cell vehicle operator trying to maximize zero-emission range.

Sourcing hydrogen fuel from a public fueling station was one of the barriers, among others, that prevented the vehicles from operating on a daily basis. Regular preventative maintenance for fuel cells requires the operator to run the full cell weekly, and with longer delays in fuel availability, the fuel cells may require more extensive maintenance to rehabilitate and reach full power.

Public hydrogen fueling infrastructure has not reached sufficient maturity to support regular delivery van operations. Demonstration projects need to plan for redundancy in fueling options, such as contracting a fuel provider. However, continued investments by state and federal agencies will improve the reliability of hydrogen in the coming years.

Another barrier to market adoption and vehicle technology expansion is low diesel fuel prices. As for-profit transportation companies, many medium- and heavy-duty truck operators are sensitive to fueling costs and will select technologies that allow their businesses to operate at the highest profit margins. A primary method of mitigating this risk is to encourage rapid and widespread deployment of hydrogen fueled vehicles through various vehicle deployment programs and relationships with hydrogen fuel providers (such as Iwatani, Shell, and Air Products). Increasing the volume of hydrogen use will help decrease fueling infrastructure and hydrogen production costs ensuring it is an economical alternative to diesel. The economics from the demonstration, concluded that this particular FCEV technology is not currently competitive with the incumbent technologies due to the high cost, the limited availability, and the limited supply of hydrogen fuel at public fueling stations. However, it is expected that the economics will improve in the future with the introduction of the DOE Hydrogen Hubs.

Barrier 3: Demonstrating at Scale

Large commercial fleet operators must have evidence of the scalability of a technology before incorporating it into their operations. To move class 6 FCDV's forward in the market, investing in large scale demonstrations are essential. The challenges of scaling battery electric charging infrastructure are becoming more apparent, but there is growing interest in scaling hydrogen infrastructure. Demonstrating hydrogen scalability provides confidence to commercial fleet operators and proves that a transition to a fleet of hydrogen vehicles is possible. As a result of this program, the Project Team continues to seek opportunities in the medium-duty FC vehicle space, where the technology can be demonstrated at a large-scale.

Commercialization and Future Development

Fuel-cell electric technology has the potential for widespread commercialization and significant transformation of the goods-movement industry while achieving reductions in GHG emissions by offsetting fossil fuel use. As the eAxle provider, Linamar feels there is great opportunity for electrification in the medium duty delivery van market and are positioned with a strong electrified powertrain solution to support future fuel cell opportunities. The FCDV project provided a strong launching point for the redesign, development and launching of a Medium Duty Class 6 eAxle. Linamar leveraged learnings from the initial project axles into a multi-year development of the now commercially available eMD15 eAxle. The eMD15 improves on the durability and performance from the initial axles used in the FCDVs and has launched into volume production. Linamar is eager to add additional customers to this axle program and provide adaptation support to different chassis and track widths.

The project provided experience and understanding of packaging fuel cell modules into very tight engine compartments due to the design constraints of the package car body and other subsystems. The compatibility of Ballard fuel cells was expanded through their learnings about non-level, or tilted, module installations, expanding their design space for more packaging options. They also learned new ways to configure exhaust and ventilation piping, as well as the importance of mounting locations for motor controllers relative to road water exposure. Ballard's latest fuel cell modules (FCmove™) overcome most of the difficulties encountered with integrating the FCvelocity™ module used in these trucks, integrating air and cooling systems into the same package as the fuel cell module while shrinking volumetric density by about one-third. Improving space utilization on the vehicle increases available range and efficiency. Integrating Ballard's latest fuel cells modules into medium duty FC vans should present little difficulty.

Broader Acceptance of Technology

Understanding the perspectives of both drivers and fleet operators is crucial for evaluating the effectiveness and practicality of the FCDVs. Feedback from vehicle operators revealed a general satisfaction with vehicle safety and handling, though issues such as long start times and maintenance challenges were noted. On the other hand, UPS, one of the key participants in the demonstration, chose not to continue using the trucks post-demonstration due to high operational costs, fueling challenges, and reliability concerns. These insights highlight significant areas for improvement as the market for hydrogen-powered vehicles evolves. Additionally, the broader market perspective underscores the ongoing challenges in scaling hydrogen infrastructure and the potential impact of new initiatives in the future. The following sections delve into these perspectives in more detail.

Driver Perspectives: Generally, the operators were very satisfied with the vehicle safety. Some were very pleased with the vehicle handling, with one operator saying it was the best van they had driven. Some had more mixed reviews on the handling, such as an issue with the long start time. The most negative aspects as seen by the users were the vehicle uptime, and operation and maintenance challenges. Given the limited demonstration, and the frequent repair and uptime challenges, this is not unexpected. Some of the vehicle integration aspects were not designed for a long demonstration, and this affected the uptime achieved. Factors outside of the project control such as fueling also contributed to the uptime issues.

Fleet Operator Perspective: UPS chose not to continue operating the trucks after the demonstration period ended due to the high cost of ownership in comparison to their baseline diesel vehicles. The cost of fuel at an average of $29.99/kg over the demonstration makes driving the trucks a large operating expense. Additionally, the uncertainty UPS faced when fueling the FCDVs made the operations challenging. There were multiple instances when UPS went to fuel the trucks at the West Sacramento station in April or May 2024, only to find the station shut down due to an ESB or temperature limitations. These factors meant that UPS could not be certain that the trucks would be able to fuel, and many times UPS managers had to sideline the vehicles the next day.

Broader Market Perspective: Hydrogen has already become more accepted and available since the inception of this project five years ago in 2019; however, as the 2023 CARB Annual Evaluation of Hydrogen Fuel Station Network Development shows, there are challenges in rapidly scaling up hydrogen stations, and the number of stations is not growing as quickly as previously projected.[6] This project was a demonstration of the problems arising from a major player, Shell, withdrawing from light-duty stations causing the number of stations in the Sacramento area to decrease from three to one. There is still a gap to close in the market for broad hydrogen adoption.

Community Impact

A major success of the FCDV project was the workforce development at the West Sacramento site. The Project Team conducted two trainings and ultimately 15 UPS employees were trained in driving, fueling, or maintaining the vans. A total of 150 employee hours of training were conducted. As demonstrated by the surveys and discussed above, employees involved with the project had positive perspectives. Experience with next-generation zero-emissions technology is a valuable skill, and the UPS mechanics who were closely supporting Roush, Ballard, and Linamar had many hands-on learning opportunities with the technology.

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[6] 2023 CARB Annual Evaluation of Fuel Cell Electric Vehicle Deployment

As shown in Figure 45, the UPS facility in West Sacramento is in an area with a CalEnviroScreen4.0 score of over 90%. The red circle indicates the location of the UPS customer center, and the areas with higher scores have greater environmental justice needs. West Sacramento has some of the worst air quality in the nation with high levels (98th percentile) of diesel emissions and particulate matter (PM2.5), contributing to public health problems such as asthma, respiratory and cardiac diseases, and cancer. [7] Several tracts in the area are above the 90th percentile nationally for asthma. [8] Additionally, the area has high freight traffic volume and transportation noise levels due to I-5[9,10]. Zero-emissions goods movement alleviates public health concerns like diesel pollutants and traffic noise that disproportionately affect the low-income and disadvantaged communities in the area where the FCDVs operated. The emissions reductions of the FCDVs and training for UPS personnel provided a benefit to the disadvantaged communities around the UPS facility.

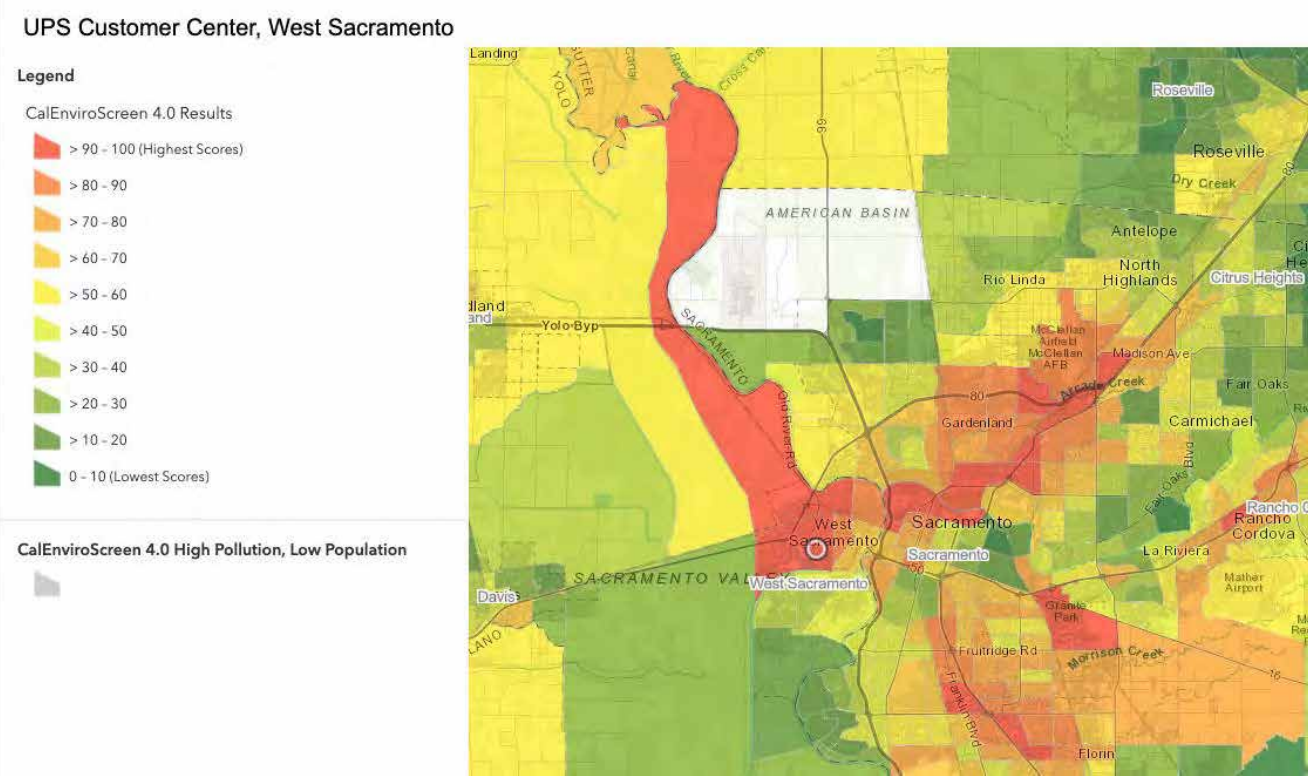

Figure 45: DAC Zones in West Sacramento According to CalEnviroScreen4.0[11]

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[7] Climate and Economic Justice Screening Tool

[8] Ibid.

[9] Freight Flows by Highway, Railway, and Waterway, Bureau of Transportation Statistics, 2018

[10] National Transportation Noise Map. Bureau of Transportation Statistics, 2018

[11] CalEnviroScreen 4.0 Results

Disclosures

Technology Showcases

1. Created and submitted a poster and booklet for the CARB LCT Symposium on March 24, 2020. CTE planned on attending but the symposium was canceled due to COVID-19.
2. On March 31, 2021, the Project Team distributed a press release about the program.
3. CTE attended CARB's Board hearing on October 24, 2019, to support the Low Carbon Transportation Poster Session that included a poster for this project.
4. On July 13, 2021, CTE staff traveled to Linamar's facility in Detroit where they were hosting the ride-alongs. Linamar drove CTE staff on public roads in EV-only mode.
5. On September 1, 2021, CTE attended the ACT Expo in Long Beach, California to support the project which was on display. The booth showcased Truck 184, the overall project status and objectives, and a 3D-printed models of Linamar's e-axle at various stages of development.
6. On September 24-26, 2021, UPS displayed a vehicle at the annual California Capital Airshow in Sacramento as shown in Figure 46. The vehicle generated significant interest from the public and provided project details by utilizing the same poster from the ACT Expo.

Figure 46: California Capital Airshow in Sacramento

7. CTE worked closely with the California Fuel Cell Partnership (CaFCP) and CARB to display the vehicle at the Hydrogen Village Event taking place at the State Capitol in Sacramento, California on April 6, 2022. This event was the largest outreach and public display of hydrogen and fuel cell technologies ever held at the State Capitol.

Appendix

All documents are included as attachments to this PDF

Appendix A: Vehicle Issue and Repair Logs
Appendix B: Emissions Estimate Methodology
Appendix C: Project Safety Report
Appendix D: Functional Hazard Analysis
Appendix E: Operational Data from Truck 186 and Truck 187
Appendix F: Project Management Plan