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CALIFORNIA NATURAL RESOURCES AGENCY

California Energy Commission

Clean Transportation Program

FINAL PROJECT REPORT

Hydrogenics Advanced Fuel Cell Vehicle Technology Demonstration for Drayage Truck

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Prepared by: Cummins Electrified Power NA Inc.

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PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program. The statute authorizes the California Energy Commission (CEC) to develop and deploy alternative and renewable fuels and advanced transportation technologies to help attain the state's climate change policies. Assembly Bill 8 (Perea, Chapter 401, Statutes of 2013) reauthorizes the Clean Transportation Program through January 1, 2024, and specifies that the CEC allocate up to $20 million per year (or up to 20 percent of each fiscal year's funds) in funding for hydrogen station development until at least 100 stations are operational.

The Clean Transportation Program has an annual budget of about $100 million and provides financial support for projects that:

- Reduce California's use and dependence on petroleum transportation fuels and increase the use of alternative and renewable fuels and advanced vehicle technologies.
- Produce sustainable alternative and renewable low-carbon fuels in California.
- Expand alternative fueling infrastructure and fueling stations.
- Improve the efficiency, performance, and market viability of alternative light-, medium-, and heavy-duty vehicle technologies.
- Retrofit medium- and heavy-duty on-road and nonroad vehicle fleets to alternative technologies or fuel use.
- Expand the alternative fueling infrastructure available to existing fleets, public transit, and transportation corridors.
- Establish workforce-training programs and conduct public outreach on the benefits of alternative transportation fuels and vehicle technologies.

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-14-605 to cost share the field demonstration of truck technologies that may become commercially available in California. In response to PON-14-605, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards June 18, 2015 and the agreement was executed as ARV-15-002 on August 1, 2015.

ABSTRACT

This final report documents the design, build, integration and testing of Hydrogenics USA, Inc.'s advanced hydrogen fuel cell propulsion system for heavy-duty vehicles under the California Energy Commission agreement number ARV-15-002. The goals of this project were to demonstrate the technical viability of an advanced hydrogen fuel cell propulsion system in a Class 8 drayage truck and to reduce greenhouse gas emissions during the demonstration period.

Despite facing challenges, the project successfully demonstrated the technical and commercial viability of hydrogen fuel cell propulsion technology purposely designed and developed for Class 8 drayage trucks. It demonstrated a simplified integration and development process of an advanced fuel cell propulsion system into a Class 8 drayage truck. Funding from the California Energy Commission was a critical enabler to the overall success of Hydrogenics Corporation. By selecting Hydrogenics, the California Energy Commission's grant review process provided a valuable third-party evaluation of its business model for Cummins Inc.'s due diligence prior to its acquisition of the company in 2019.

As one of the first fully functioning heavy-duty fuel cell trucks ever built in California, the Hydrogenics Advanced Fuel Cell Vehicle represents a meaningful step in the hydrogen fuel cell industry. For Cummins Inc., it is an important building block in becoming a leader in fuel cell powertrains for heavy-duty mobility applications.

Keywords: Cummins Inc., Cummins, Cummins New Power, Hydrogenics Corporation, Hydrogenics USA, Inc., Hydrogenics, hydrogen, fuel cell, fuel cell electric vehicle

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TABLE OF CONTENTS

Page

Preface....................................i
Abstract....................................iii
Table of Contents....................................v
List of Figures....................................vi
List of Tables....................................vii
Executive Summary....................................1
CHAPTER 1: Project Overview....................................3
Hydrogenics USA, Inc.....................................3
Cummins Inc. and the New Power Segment....................................4
Project Description....................................6
Statement of Work Summary....................................8
Project Goals and Objectives....................................8
CHAPTER 2: Fuel Cell Truck Design....................................10
System Specifications....................................10
Fuel Cell Propulsion System Layout....................................11
Fuel Cell Power System....................................12
Power Electronics Module....................................15
Drive Motor....................................17
Hydrogen Fuel Storage....................................18
Battery Energy Storage....................................19
Electric Accessories System....................................20
Driver Interface and Control....................................22
Fuel Cell Truck Architecture....................................24
High Voltage Safety Interlock....................................27
Failure Mode and Effects Analysis....................................27
CHAPTER 3: Fuel Cell Truck Build, Integration and Testing....................................29
Fuel Cell Truck Build and Integration Process....................................29
Performance Testing and Validation....................................36
Vehicle Upgrades....................................37
Vehicle Performance Simulation....................................40
Vehicle Testing and Validation....................................40
Noise Testing....................................43
Fuel Economy Evaluation....................................44
CHAPTER 4: Conclusion....................................45
Project Success....................................45
Lessons Learned....................................46

Next Steps 46
Glossary 47

LIST OF FIGURES

Page

Figure 1: Hydrogenics' Fuel Cell Manufacturing Line (Left) And Electrolyser Installation in Bécancour, Canada (Right) 3
Figure 2: Cummins New Power Journey 4
Figure 3: Cummins Turnkey Fuel Cell and Electrified Power Systems 5
Figure 4: Cummins New Power Capabilities Map 6
Figure 5: Model Year 2018 Freightliner Cascadia Truck Platform (left) and Hydrogenics Celerity Plus Fuel Cell Power System (right) 10
Figure 6: Hydrogenics Advanced Fuel Cell Vehicle Major Components Layout 12
Figure 7: Hydrogenics Celerity Plus Technical Specifications 14
Figure 8: Hydrogenics Celerity Plus Subassembly Design and Details 15
Figure 9: Hydrogenics Celerity Plus Subassembly Installed in Truck Engine Bay 15
Figure 10: Power Electronics Module Design 16
Figure 11: Power Electronics Module Installed on Truck 17
Figure 12: Drive Motor Truck Chassis Integration Design 17
Figure 13: Hydrogen Fuel Storage System from Agility Fuel Systems 18
Figure 14: Hydrogen Fuel Storage System Installed on Truck 18
Figure 15: ACTIA High Volt Battery Enclosures (left) and System Architecture (right) 19
Figure 16: ACTIA High Volt Battery Modules Installed on Truck 19
Figure 17: Auxiliary Inverters Configuration 20
Figure 18: Power Steering Assembly 21
Figure 19: Cabin Air Conditioning System 21
Figure 20: Air Compressor Assembly 22
Figure 21: Fuel Cell Coolant Pump 22
Figure 22: Driver Interface and Controls Layout 23
Figure 23: Freightliner Instrument Cluster 23
Figure 24: Hydrogenics Digital Cluster Display 24
Figure 25: High Voltage Bus Power Flow 25
Figure 26: Hydrogenics Advanced Fuel Cell Vehicle High Level System Architecture 26
Figure 27: Freightliner Cascadia Glider Delivery and Inspection 29
Figure 28: Battery Chiller Installation (left) and Fuel Cell Cradle Preparation (right) 30
Figure 29: Hydrogenics Celerity Plus Subassembly Installation 31
Figure 30: Hydrogen Tank System Installation 32
Figure 31: Drive Motor and Drive Shaft Installation 32
Figure 32: High Voltage Battery Bracket Installation 33
Figure 33: Aerodynamic Fairings (left) and Air Compressor Installation (right) 33

Figure 34: Power Electronics Module Build, Testing and Installation 34
Figure 35: High Voltage Battery Packs Installation 35
Figure 36: Completed Hydrogenics Advanced Fuel Cell Vehicle 35
Figure 37: Hydrogenics Advanced Fuel Cell Vehicle Commissioning 36
Figure 38: Hydrogenics Advanced Fuel Cell Vehicle First Drive 36
Figure 39: Original High Voltage Battery Pack Design (left) and with Crash Protection Bracket (middle and right)..37
Figure 40: Original Location of the Hydrogen Pressure Release Device Ports.........................39
Figure 41: New Location of the Hydrogen Pressure Release Device Ports 39
Figure 42: Parking Lot Testing 40
Figure 43: Bobtail Road Testing 41
Figure 44: Unloaded/Loaded Trailer Road Testing 41
Figure 45: Refueling Testing 42
Figure 46: Grade Testing 42
Figure 47: The Hydrogenics Advanced Fuel Cell Vehicle...45

LIST OF TABLES

Page

Table 1: Hydrogenics Advanced Fuel Cell Vehicle Specifications 11
Table 2: Hydrogenics Celerity Plus Technical Features and Benefits 13
Table 3: Failure Mode and Effects Analysis Severity, Occurrence and Detection Scoring Sheet 28
Table 4: Vehicle Weight Before/After Front Axle Upgrade 38
Table 5: Noise Testing Results 44

EXECUTIVE SUMMARY

In order to demonstrate advanced truck technologies that may become commercially available in California, Hydrogenics USA, Inc. proposed to the California Energy Commission to demonstrate the technical and market viability of an advanced zero-emission hydrogen fuel cell propulsion technology purposely designed and developed for medium- and heavy-duty mobility applications. This proposed advanced propulsion technology was to expedite commercialization of hydrogen fuel cell medium and heavy-duty commercial vehicles by significantly reducing development, integration and production cost of building fuel cell hybrid vehicles. The requested California Energy Commission funding was to be matched by Hydrogenics USA, Inc.'s funding to integrate the proposed advanced fuel cell propulsion technology into a Class 8 drayage truck and demonstrate it in real-world drayage operation.

The project was kicked off in August 2015 but faced a series of challenges typical in this early phase of the fuel cell industry. Despite facing challenges, the project successfully demonstrated the technical and commercial viability of hydrogen fuel cell propulsion technology purposely designed and developed for Class 8 drayage trucks. It demonstrated a simplified integration and development process of an advanced fuel cell propulsion system into a Class 8 drayage truck. Funding from the California Energy Commission was a critical enabler to the overall success of Hydrogenics Corporation. By selecting Hydrogenics USA Inc., which is the U.S. business entity of Hydrogenics Corporation, the California Energy Commission's grant review process provided a valuable third-party evaluation of its business model for Cummins Inc.'s due diligence prior to its acquisition of the company in 2019. As one of the first fully functioning heavy-duty fuel cell trucks ever built in California, the Hydrogenics Advanced Fuel Cell Vehicle represents a meaningful step in the hydrogen fuel cell industry. For Cummins Inc., it is an important building block in becoming a leader in fuel cell powertrains for heavy-duty mobility applications.

Going forward, Cummins Inc. is involved in several projects pursuing its most up-to-date heavy-duty fuel cell powertrain architecture and design which incorporates the key learnings from this project and leapfrogs incremental design improvements on a powertrain architecture and design originally developed in 2015. Cummins Inc.'s latest generation architecture and design bring forward a state of the art fuel cell powertrain that 1) is customized, tested and optimized for regional haul and port applications, 2) can demonstrate the market viability of advanced zero emission fuel cell drive system technology in a heavy-duty truck and 3) accelerates the mass market penetration of heavy-duty hydrogen fuel cell trucks.

CHAPTER 1: Project Overview

Hydrogenics USA, Inc.

Hydrogenics Corporation (Hydrogenics) was founded in 1995 as a developer and manufacturer of hydrogen generation and fuel cell products based on water electrolysis and proton exchange membrane technology. Hydrogenics quickly grew as a market leader for the design and manufacture of industrial and commercial fuel cell and hydrogen production technologies, having supplied over 2,000 fuel cells and realized over 600 electrolyzer installations in 100 countries (Figure 1). Hydrogenics USA, Inc. (Hydrogenics USA) in Carlsbad was Hydrogenics' production facility and sales office in California.

Figure 1: Hydrogenics' Fuel Cell Manufacturing Line (Left) And Electrolyser Installation in Bécancour, Canada (Right)

Source: Cummins Inc.

In September 2019, Cummins Inc. (Cummins) closed on its acquisition of Hydrogenics, another step forward as Cummins continues to invest in a broad range of clean, fuel-efficient and high-performing products and technologies that deliver value to its customers. Hydrogenics provides Cummins with a unique collection of IP and technology for its fuel cell portfolio, a proven team and a long track record of commercial success in a technology that is beginning to accelerate. The acquisition accelerates Cummins' ability to further innovate and scale hydrogen fuel cell technologies across a range of commercial markets. Owning both fuel cell and hydrogen generation from electrolysis capabilities will enable the company to offer a full, differentiated hydrogen solution, from start to finish, seamlessly integrated for customers.

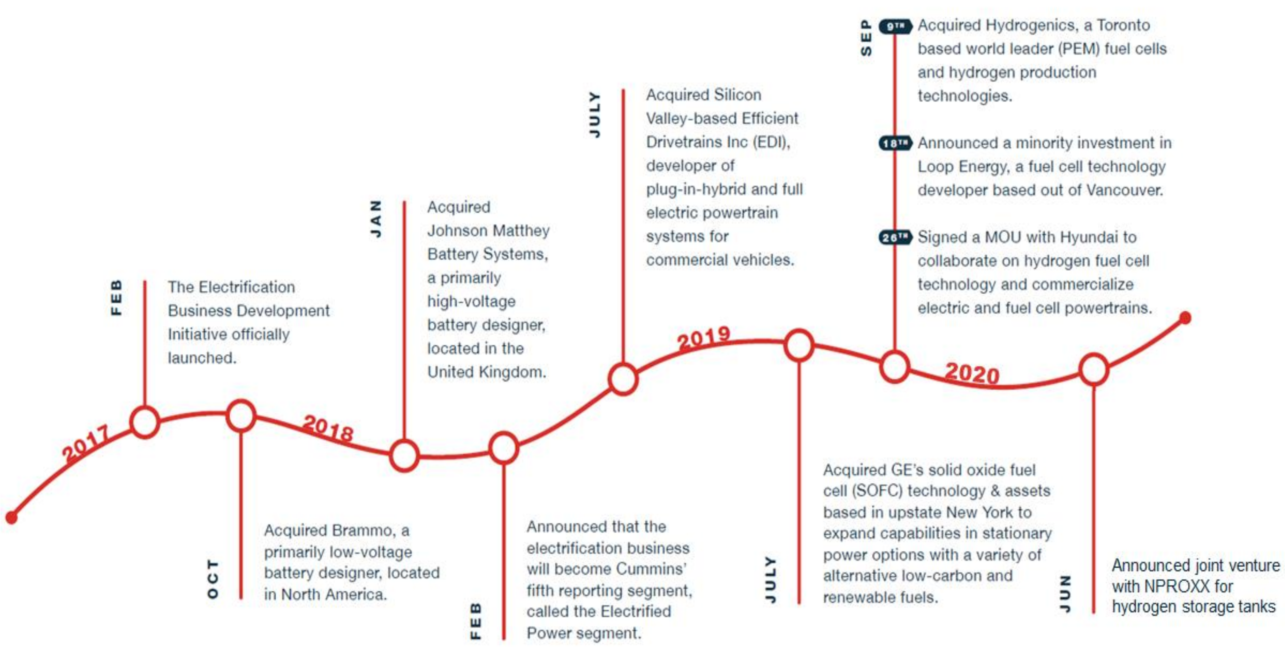
Hydrogenics' facilities as well as its employees were integrated into Cummins' fifth business segment, New Power, and since the acquisition of Hydrogenics, Cummins has dedicated a significant number of resources and capital to expand its operation in California.

Cummins Inc. and the New Power Segment

Cummins, a global power leader, is a corporation of complementary business units that design, manufacture, distribute and service a broad portfolio of power solutions. The company's products range from diesel and natural gas engines to hybrid, electric and fuel cell platforms, as well as related technologies, including battery systems, fuel systems, controls, air handling, filtration, emission solutions and electrical power generation systems. Cummins' vision is innovating for its customers to power their success. Cummins does this by investing in a range of technologies from diesel and natural gas internal combustion engines to fully electric and fuel cell solutions.

Cummins' expertise in alternative power technologies is rooted in over 20 years of research, development, and strategic partnerships. Since 2017, Cummins has significantly ramped up its capabilities to offer a full, differentiated electrified power solution, from start to finish, seamlessly integrated for customers (Figure 2). New Power is Cummins' fifth business segment, focused on electrified power and fuel cell and hydrogen technologies. Cummins works together to design and manufacture alternative power sources, including electrified power, fuel cell and hydrogen technologies. Applications include school buses, transit buses, light commercial vehicles, medium duty trucks, trains, off-highway applications as well as hydrogen production technologies.

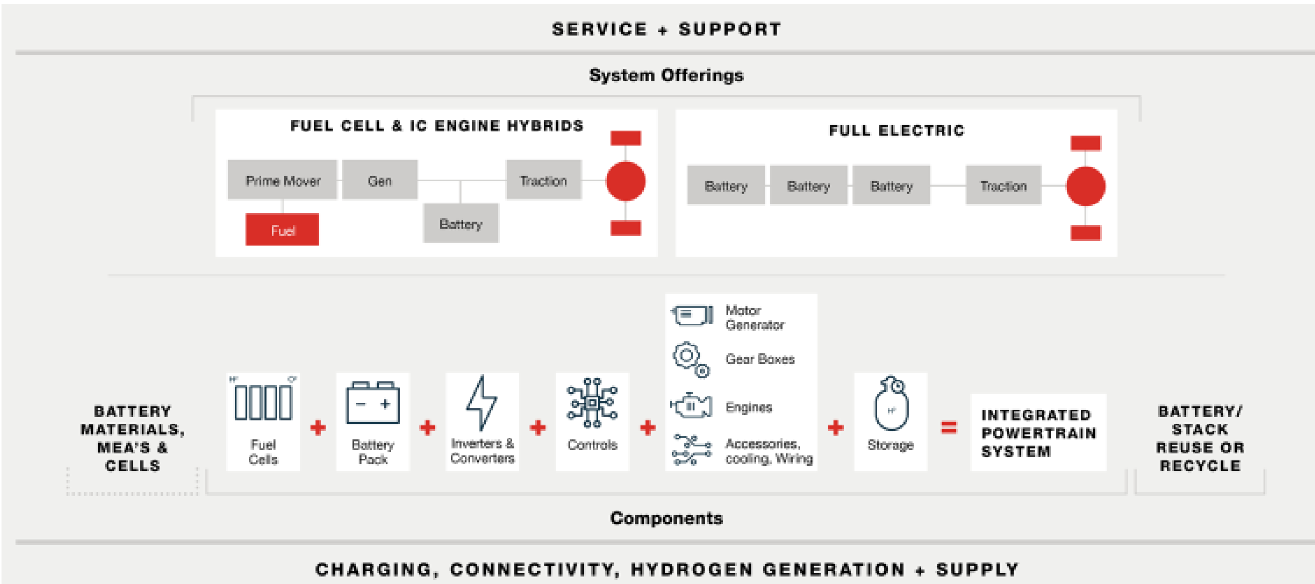
Figure 2: Cummins New Power Journey



Source: Cummins Inc.

Cummins New Power provides a portfolio of electrified, fuel cell and hydrogen power solutions, as well as some of the most critical components that have the largest impact on performance, quality and cost to deliver the most value to its customers (Figure 3).

Figure 3: Cummins Turnkey Fuel Cell and Electrified Power Systems



Source: Cummins Inc.

Cummins New Power organization spans the globe with major operations in North America, Europe and Asia. In the United States, Cummins New Power's footprint is rooted in Columbus, IN and in California, where facilities in Milpitas and West Sacramento provide 48,000 square foot for system development, vehicle integration and low volume production.

Figure 4: Cummins New Power Capabilities Map

Source: Cummins Inc.

Cummins has a 100-year-long track record of delivering leading power solutions. Notable technology commercialization successes include:

- More than 80,000 Cummins Westport six to 12-liter spark-ignited automotive natural gas engines in service worldwide today in commercial transportation application.
- Over 500 electrolyzer installations around the world, including the world's largest electrolyser system (20 Megawatt) in Canada for Air Liquide.
- More than 400 electric school buses, powered by a Cummins fully electric drivetrain, have been ordered to date from Blue Bird Corporation, a school bus manufacturer.
- Over 200 buses equipped with fuel cell power modules from Hydrogenics are in operation in China including transit buses with Yutong and Foton.
- Partnership with GILLIG LLC to integrate the Cummins electrified powertrain with the proven Low Floor platform bringing the most advanced zero-emission bus to the market.
- A 10-year agreement to supply Alstom Transport with hydrogen fuel cell systems for regional commuter trains.

Project Description

In order to enhance market acceptance of advanced vehicle technologies that will lead to vehicle production and commercialization, reduce greenhouse gas emissions, and reduce petroleum use, Hydrogenics USA proposed to the CEC to demonstrate the technical and market viability of an advanced zero-emission hydrogen fuel cell propulsion technology purposely designed and developed for medium- and heavy-duty mobility application. This proposed advanced propulsion technology was to expedite commercialization of hydrogen fuel cell medium and heavy-duty commercial vehicles by significantly reducing development, integration and production cost of building fuel cell hybrid vehicles.

The requested CEC funding was to be matched by Hydrogenics' funding to integrate the proposed advanced fuel cell propulsion technology into a Class 8 drayage truck and demonstrate it in real-world drayage operation.

The project was kicked off in August 2015 but faced a series of challenges typical in the earlier phase of the fuel cell industry:

- Longer than expected contract negotiations with ACTIA and Siemens, the two major subcontractors, delayed the start of the design work. The ACTIA agreement was executed in August 2016 and Siemens' agreement was executed in December 2016.
- A technology integration site in California was to be secured to build the truck. Delays in finding a suitable site and executing a lease limited truck design and build activities in California. A lease was signed in October 2016 and Hydrogenics USA established itself at 2870 Whiptail Loop, Carlsbad, CA 92010 in March 2017.
- Lack of engineering and technician resources limited truck design and build activities in California. An engineer and a technician were added to the Hydrogenics USA team in the second quarter of 2019 to support vehicle commissioning and testing.
- Limited engineering resources and changes in personnel and vendors delayed the design and build of the high voltage battery from ACTIA. It was delivered to Hydrogenics in the second quarter of 2018.
- The Hydrogenics team is specialized in the design and manufacture of fuel cell products and faced a steep learning curve with electric powertrain design and integration activities. This led to additional delays in completing the build and commissioning of the truck which was done in the second half of 2019.
- The decision to integrate the fuel cell propulsion system on a glider (without a VIN) instead of a completed truck introduced administrative challenges with the California Department of Motor Vehicles, California Department of Transportation and California Highway Patrol. Hydrogenics had to be set up as a truck manufacturer, capable of issuing VINs and the truck had to meet additional requirements and pass state inspections before being allowed to drive on the road.
- Upon Cummins' acquisition of Hydrogenics, the Hydrogenics USA organization was integrated into Cummins and this led to additional delays as both organizations worked on integration activities.
- Shortly after Cummins' acquisition of Hydrogenics, the responsibility to complete the project was passed on to Cummins Electrified Power NA Inc., a wholly owned subsidiary of Cummins with operations in California. Several system upgrades were required to bring the Hydrogenics Advanced Fuel Cell Vehicle up to Cummins' standard of performance and safety.
- Repeated issues with the Celerity Plus fuel cell power system and the ACTIA high voltage battery ultimately prevented the demonstration in real-world drayage operation.

Despite facing these challenges, Hydrogenics built one of the first advanced fuel cell Class 8 trucks and captured several critical learnings that are advancing Cummins' product design today. The funding from the CEC was a critical enabler for advancing hydrogen and fuel cells in the heavy-duty truck market and helped Hydrogenics position itself to be acquired by Cummins. Looking forward, Cummins is using this project as a building block for its next generation heavy-duty fuel cell electric powertrains and is committing significant resources in California to bring its fuel cell technologies to market.

Statement of Work Summary

Project Goals and Objectives

The goals of this project were to demonstrate the technical viability of an advanced hydrogen fuel cell propulsion system in a Class 8 drayage truck and to reduce greenhouse gas during the demonstration period.

The objectives of this project were to:

- Demonstrate a simplified technology integration and development process of the proposed fuel cell propulsion system into a Class 8 drayage truck.
- Conduct field demonstration to verify the performance of the proposed propulsion technology and to collect performance data.
- Document the build process of the demonstrated truck.

Tasks and Key Deliverables

The project was broken down into the following four tasks which each included several key deliverables.

Task 1: Administration

The goals of this task were to attend a kick-off meeting, critical project review meetings and the final meeting, as well as providing monthly progress reports and the final report, and lastly to identify and obtain matching funds, required permits, and execute subcontracts. This task included several formal and informal deliverables that were provided to the Commission Agreement Manager throughout the project.

Task 2: Technology Integration Site; Design and Procure

The goal of this task was to secure a technology integration site where the truck would be built and review the project plan, develop and design truck specifications and systems, procure components, and conduct performance and safety analysis. The key deliverables were a copy of the facility lease agreement and a summary report containing relevant design and procurement information.

Task 3: Build, Integrate, and Ship

The goal of this task was to manufacture, build, integrate, and ship the fuel cell truck to the fleet demonstrator. The key deliverable was a summary report with photographs.

Task 4: Demonstration, Data Collection and Analysis

The goals of this task were to train personnel, demonstrate the truck, and collect operational data from the project, to analyze that data for economic and environmental effects, and to include the data and analysis in the Final Report. The key deliverable was the data collection information and analysis to be included in the final report.

CHAPTER 2:
Fuel Cell Truck Design

The advanced fuel cell propulsion technology is a result of a joint development between Hydrogenics and Siemens to advance commercialization of fuel cell hybrid heavy-duty commercial vehicles by significantly reducing development and integration cost of building fuel cell hybrid vehicles. This advanced zero-emission propulsion technology developed by Hydrogenics is named Celerity Plus – the first fuel cell power system purposely designed, developed and dedicated for medium- and heavy-duty commercial vehicles and is pre-tested and pre-interfaced to an electric hybrid drive provided by Siemens.

The advanced fuel cell propulsion technology was integrated by Hydrogenics with technical support from Siemens regarding the powertrain tuning. The scope was to electrify an existing Freightliner glider truck with the top of the line technology available in order to deliver a truck designed around a specific mission.

System Specifications

The Hydrogenics Advanced Fuel Cell Vehicle is based on a Model Year 2018 Freightliner Cascadia truck platform depicted in Figure 5. It is a hybrid electric vehicle, blending power from a 92 kilowatt-hour (kWh) high voltage battery and the 60 kilowatt (kW) Hydrogenics Celerity Plus fuel cell power system. The Celerity Plus operates as a range extender running as required to sustain the battery charge, further extending the vehicle range.

Figure 5: Model Year 2018 Freightliner Cascadia Truck Platform (left) and Hydrogenics Celerity Plus Fuel Cell Power System (right)

Source: Cummins Inc.

Specifications of the Hydrogenics Advanced Fuel Cell Vehicle are summarized in Table 1 below.

Table 1: Hydrogenics Advanced Fuel Cell Vehicle Specifications

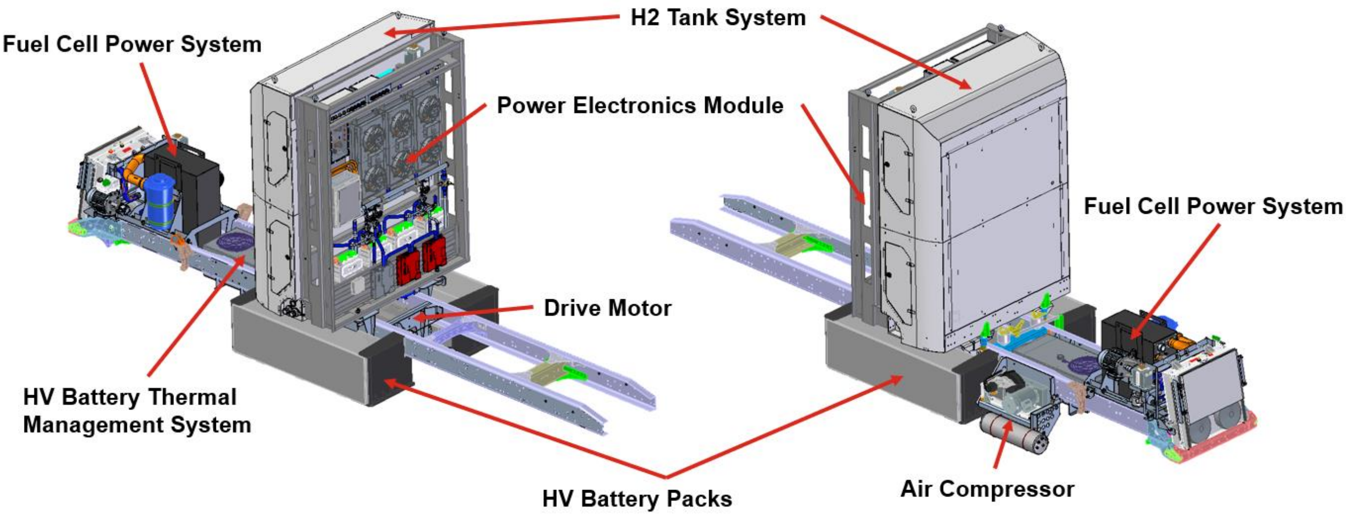
Attribute	**Specification/Description**
Base Vehicle	Freightliner Cascadia P3 Glider 2018
Truck Length	316”
Truck Height	157”
Truck Width	100”
GCWR	82,000 pounds (lbs)
Total Weight	26,040 lbs
Front Axle Weight	12,860 lbs
Rear Axle Weight	13,180 lbs
Traction Motor	Dual Siemens Permanent Electromagnetic Motor 320 kW (400 kW peak), 3,000 Nm (4000 Nm peak)
Transmission	Direct Drive
Hydrogen Fuel Cell	Hydrogenic Celerity Plus Fuel Cell Power System Rated: 60 kW
High Volt Battery	Actia 92 kWh Lithium Titanate Battery
Hydrogen Storage	Agility 32.6 kg @ 5,000 pounds per square inch (350 bar)
Max Vehicle Speed	65 mph
Estimated Range	150-200 miles
Gradeability	6% @ 30mph
Startability	15%

Source: Cummins Inc.

Fuel Cell Propulsion System Layout

The advanced fuel cell propulsion technology consists of the following subsystems: Fuel Cell Power System, Power Electronics Module, Drive Motor, Hydrogen Fuel Storage, Battery Energy Storage, Electric Accessories System, and Driver Interface and Control. Figure 6 below shows the layout and placement of these main subsystems and components of the truck chassis.

Figure 6: Hydrogenics Advanced Fuel Cell Vehicle Major Components Layout



Source: Cummins Inc.

Each of the subsystems is described in more details below:

Fuel Cell Power System

The Celerity Plus is an "all-in" fuel cell power system with the following technical features and benefits for accelerating commercialization of fuel cell powered medium and heavy-duty vehicles (**Error! Reference source not found.** and Figure 7).

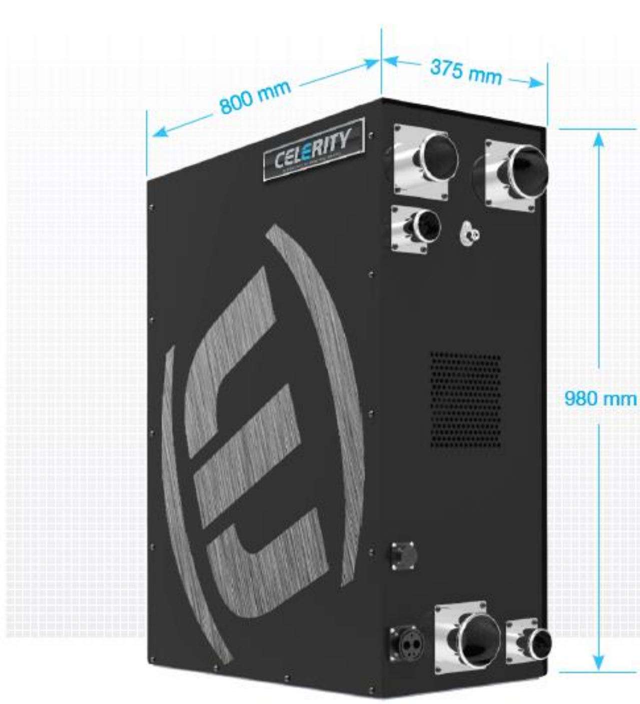
Table 2: Hydrogenics Celerity Plus Technical Features and Benefits

Innovative Features	Commercialization Benefits
Optimal configuration for voltage and current: flexible modularity in 60kw	• Reliable power performance for MHD drive cycle that commercial vehicles can rely on • Low stack current that further improves system efficiency. • Compact modularity enables easy installation as a single unit for range extension or multiple units for prime power and thus simplifies design process for power.
Optimal configuration in dimensions to be easily installed in the engine bay of a commercial truck.	• Minimize/eliminate the time and effort spent on modifying the truck chassis and frame rail to fit the fuel cell power system and thus shorten development and production time and cost of a fuel cell powered vehicle • Easier to access, remove and to maintain and thus lower the maintenance time and cost for vehicle operators • Lower development cost, capital cost of vehicle and lower maintenance cost lead to lower TCO of a fuel cell powered vehicle => more affordable for commercialization
Celerity is a highly integrated system with all major components packages into an IP-rated enclosure, including an advanced cold-weather package, achieving storage capacity at -40°C and system start-up at -10°C. Also included is reverse current protection and a fully integrated air delivery blower to provide optimum oxygen flow for low-pressure stack operation.	• Minimize/eliminate the time and effort for integrating peripheral components around the fuel cell power module which are usually required for other fuel cell power modules that are currently available in the market.

Source: Cummins Inc.

Figure 7: Hydrogenics Celerity Plus Technical Specifications

Net Power	60 kW
Performance	
Operating DC Voltage Range	300 to 640 V
Operating current	0 to 200 A
Physical	
Weight (dry)	275 kg
Length x Width x Height (mm)	800 x 375 x 980
Fuel	Hydrogen (Commercial grade per ISO/TS 14687-2:2008(E))
Oxidant	Air
Coolant	
Deionized Water	100%
Ethylene Glycol/Deionized Water	60/40%
Operating Conditions	
Coolant Outlet Temperature	45 – 65 °C
Hydrogen Supply Pressure	515 – 790 kPa
Air Supply Pressure	Ambient
Additional Features	
Control interface	CANbus J1939
Enclosure	IP-rated

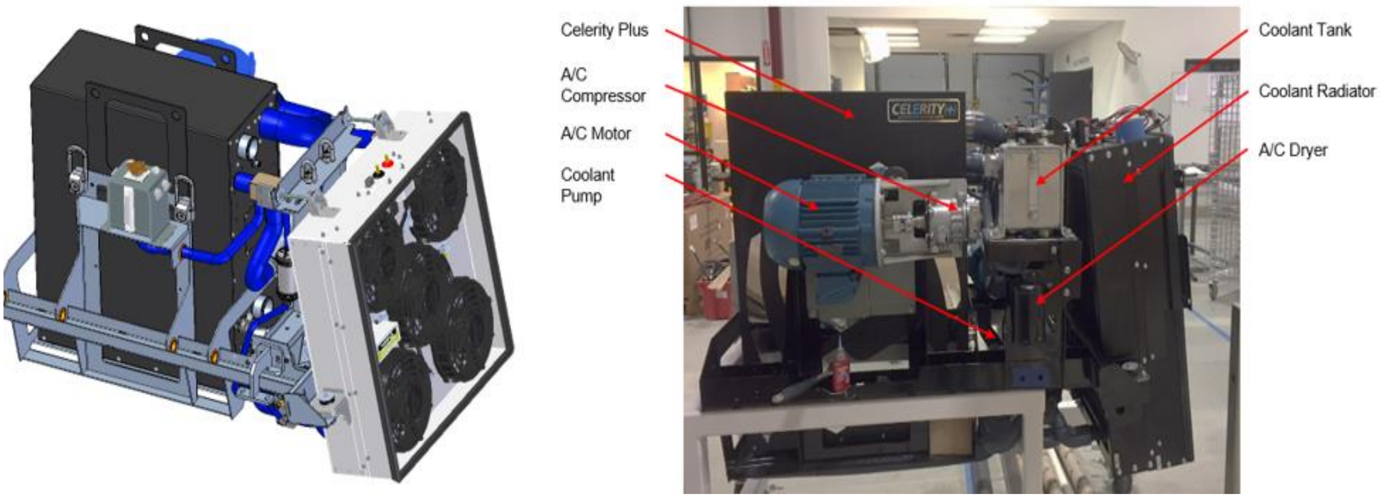


Source: Cummins Inc.

The Celerity Plus fuel cell system is mounted in a sub frame assembly that is under the conventional engine hood of the truck (Figure 8 and Figure 9). Components installed on the subassembly include:

- Fuel cell assembly (coolant pump, radiator, tank, piping, air intake system and exhaust),
- Power steering assembly (tank, motor, pump and hoses),
- Air conditioning assembly (motor, compressor, dryer, condenser and hoses),
- Coolant loop connection to cabin,
- Heater heat exchanger.

Figure 8: Hydrogenics Celerity Plus Subassembly Design and Details



Source: Cummins Inc.

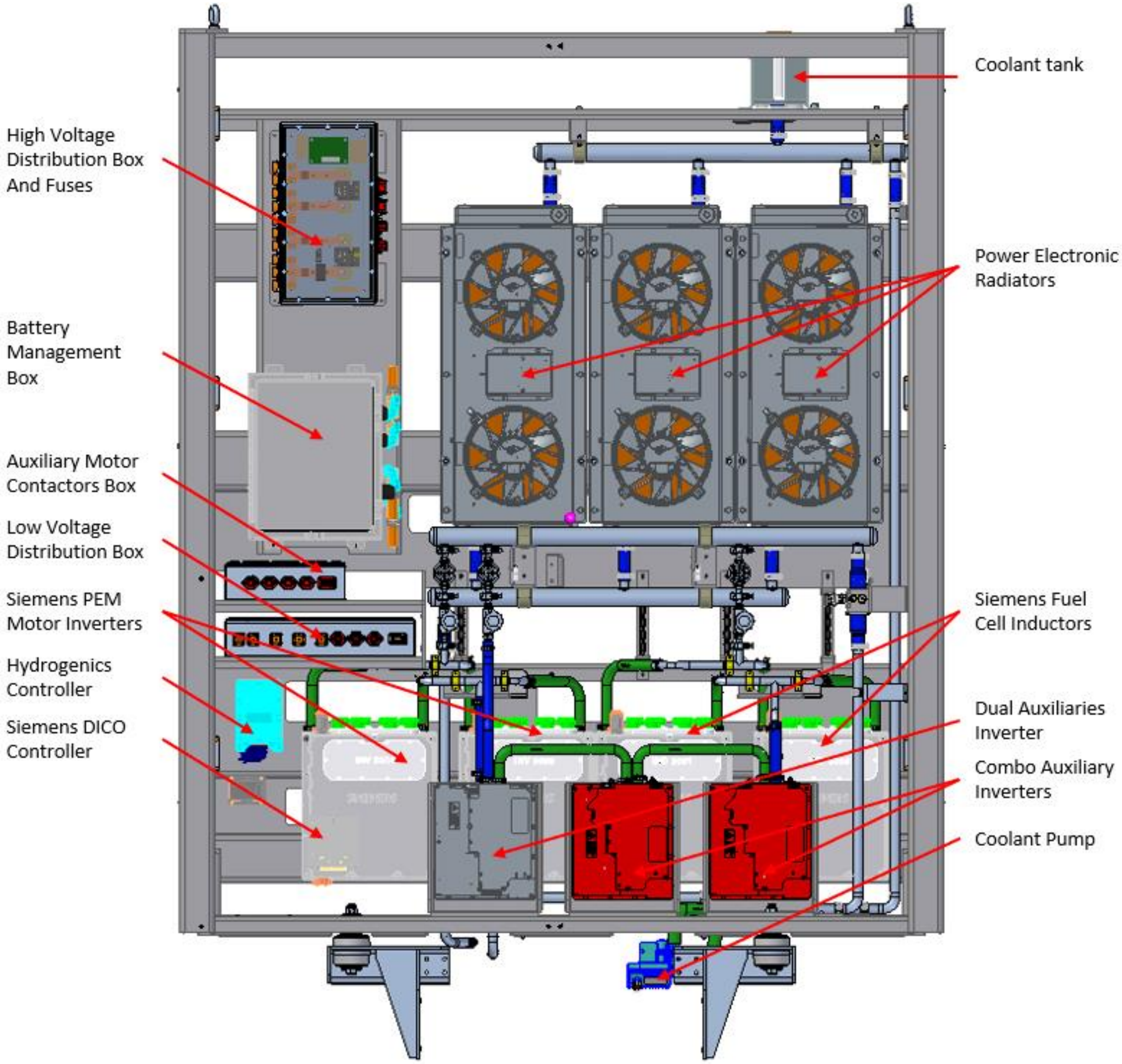
Figure 9: Hydrogenics Celerity Plus Subassembly Installed in Truck Engine Bay

Source: Cummins Inc.

Power Electronics Module

The basic Siemens drive system consists of high efficiency liquid cooled Siemens inverters, inductor, drive motor, auxiliary inverters, control unit and power cables. Apart from the traction motor, the basic system is packaged in the vertical power electronic cradle installed behind the cabin (Figure 10 and Figure 11). The entire module is built, wired and pre-tested as a subassembly before being installed on the truck. The high voltage battery packs are connected directly to the high voltage electrical bus, and the Celerity Plus fuel cell power system interfaces to the power electronics assembly through a direct connection with the Siemens inductors, positioned at the bottom right of the power electronics module.

Figure 10: Power Electronics Module Design



Source: Cummins Inc.

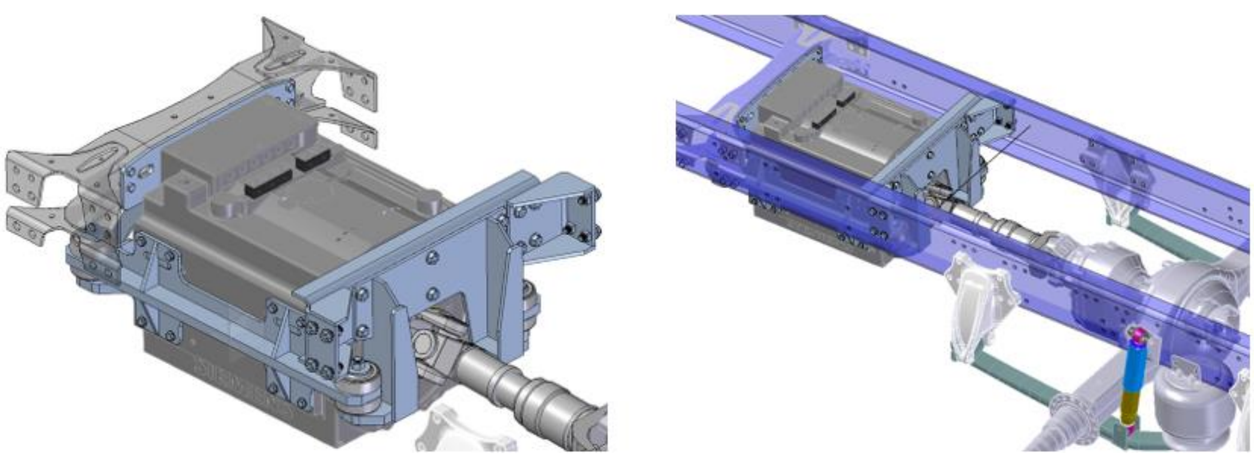
Figure 11: Power Electronics Module Installed on Truck

Source: Cummins Inc.

Drive Motor

The Siemens system is a traction motor with two permanent magnet synchronous type motors in one housing. Due to the motor's size, torque and speed, the traction motor is mounted directly on the rear axle differential without a gearbox. Its function is to convert the electrical power from the fuel cell and battery system through the inverters into mechanical power with the required torque and speed range to propel the truck. Figure 12 below shows the drive motor installation and direct connection to the differential.

Figure 12: Drive Motor Truck Chassis Integration Design



Source: Cummins Inc.

Hydrogen Fuel Storage

The hydrogen fuel storage system was built by Agility Fuel Systems, a leading company in mobile application gas storage systems (Figure 13). The hydrogen fuel storage system for this project utilizes seven carbon fiber Type 4 high-pressure cylinders, with a total capacity of 32.6 kg at 350 bar (5000 pounds per square inch) enough to support a 150-200 miles range depending on driving conditions.

Figure 13: Hydrogen Fuel Storage System from Agility Fuel Systems

Source: Cummins Inc.

The hydrogen fuel storage system is installed between the cab and power electronics module. The fueling port and interface is located on the driver side (Figure 14)

Figure 14: Hydrogen Fuel Storage System Installed on Truck

Source: Cummins Inc.

Battery Energy Storage

The Hydrogenics Advanced Fuel Cell Vehicle is equipped with two 46 kWh lithium titanate high voltage (600 Volt Direct Current) nominal) battery modules from ACTIA mounted in an environmentally sealed enclosure (Figure 15 and Figure 16). The battery system consists of two battery packs in parallel and one control case (Power System Manager) with a Chief Master (Figure 15). From the user standpoint the battery system behaves like a single battery. Electrical connections from the battery system to the vehicle are through the Power System Manager module. Cooling for the battery packs is provided by a chiller controlled by the Chief Master.

Figure 15: ACTIA High Volt Battery Enclosures (left) and System Architecture (right)

Source: Cummins Inc.

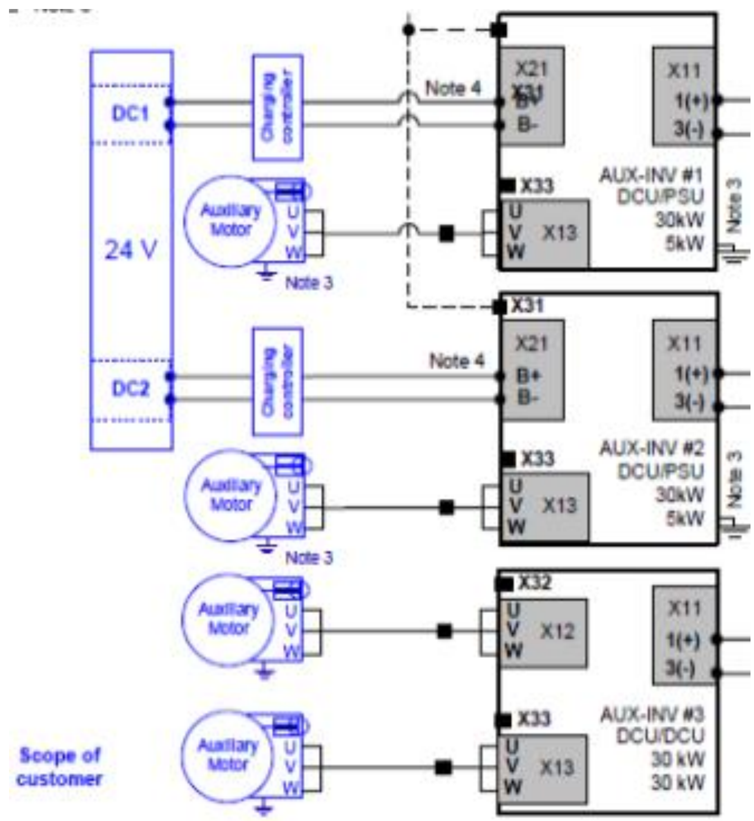
Figure 16: ACTIA High Volt Battery Modules Installed on Truck

Source: Cummins Inc.

Electric Accessories System

The Siemens auxiliary inverters provide 230 Volt Alternating Current via a high voltage junction box to power accessory devices such as the power steering motor, air conditioning motor, air brake pneumatic systems compressor, and fuel cell coolant pump. The Hydrogenics Advanced Fuel Cell Vehicle has two types of auxiliary inverters: 1) motor inverters and 24 volt DC/DC converters and 2) Dual motor inverters. The 24 Volt Direct Current generated from the motor inverters is used to power the loads installed on the truck except for the Freightliner cabin which operates at 12 Volt Direct Current (Figure 17).

Figure 17: Auxiliary Inverters Configuration

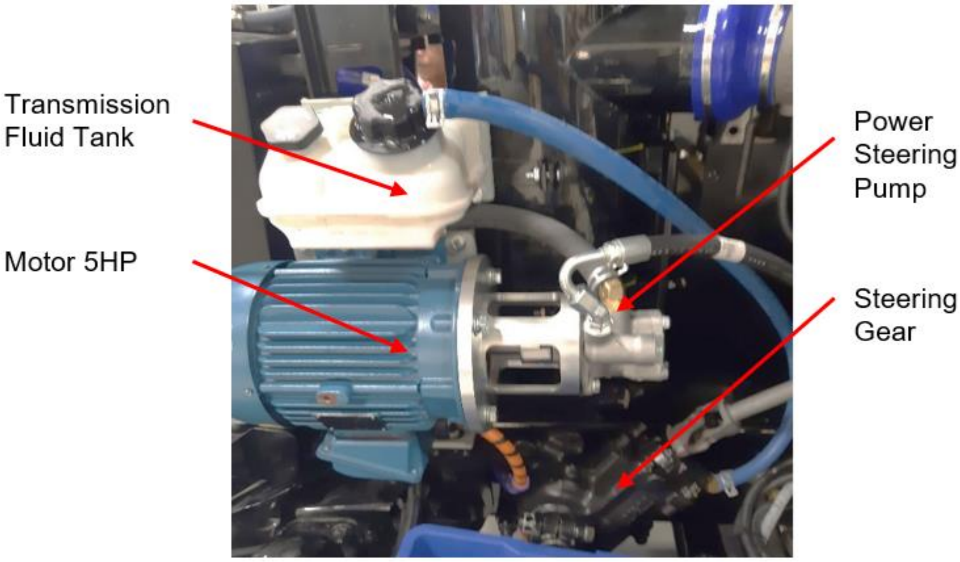


Source: Cummins Inc.

Power Steering Assembly

The power steering system is installed on the fuel cell subassembly frame and it is located on the roadside of the truck. The steering gear is the only component attached directly to the truck's frame (Figure 18).

Figure 18: Power Steering Assembly

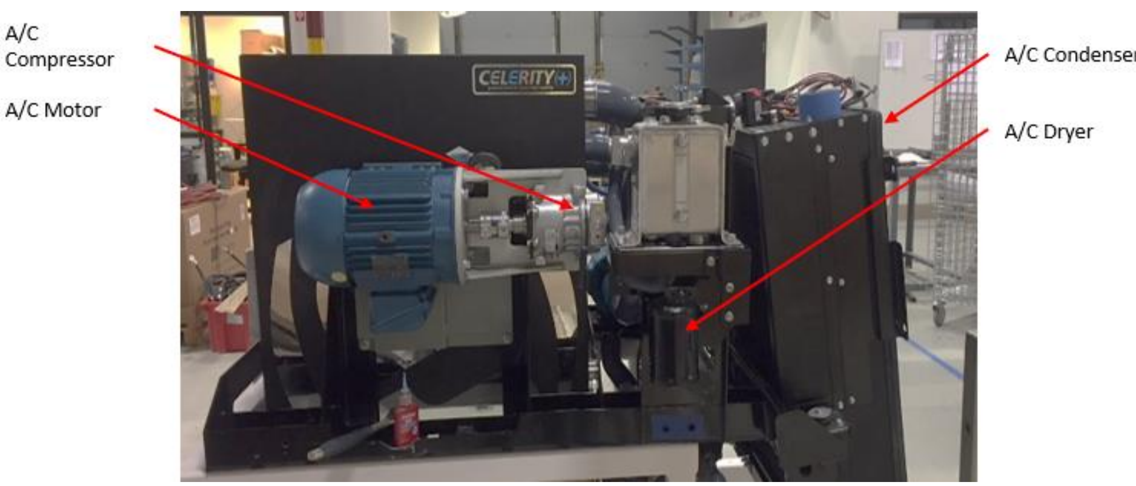


Source: Cummins Inc.

Cabin Air Conditioning System

The cabin air conditioning system is also installed on the fuel cell subassembly frame and it is located on the curbside of the truck. The assembly shown in Figure 19 is connected to the evaporator, which is part of the original cabin air conditioning system, and it is the only component attached to the chassis truck.

Figure 19: Cabin Air Conditioning System

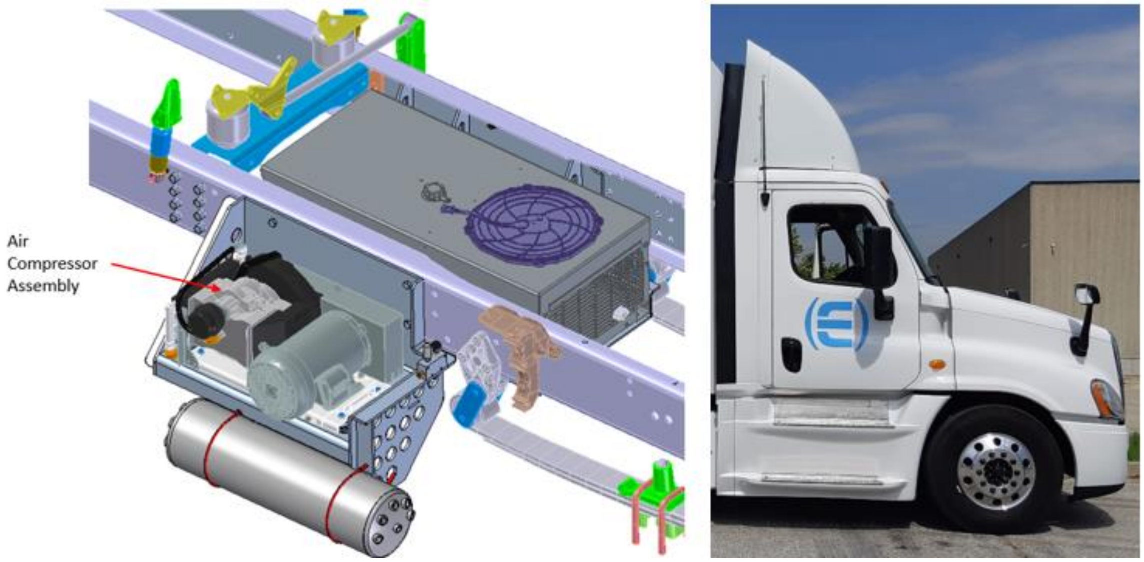


Source: Cummins Inc.

Air Compressor Assembly

The air compressor is installed on the curbside of the truck behind the passenger cabin access steps (Figure 20). The electric compressor substitutes the original compressor linked to the diesel engine to provide compressed air to the braking system.

Figure 20: Air Compressor Assembly

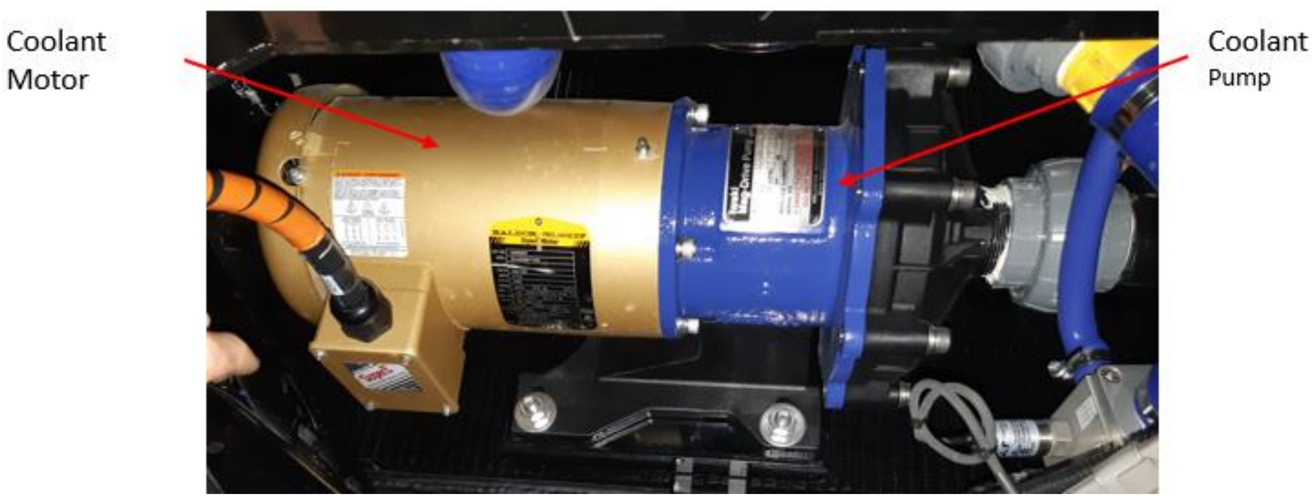


Source: Cummins Inc.

Fuel Cell Coolant Pump

The fuel cell pump is installed on the fuel cell subassembly frame and is located below the front radiator (Figure 21).

Figure 21: Fuel Cell Coolant Pump



Source: Cummins Inc.

Driver Interface and Control

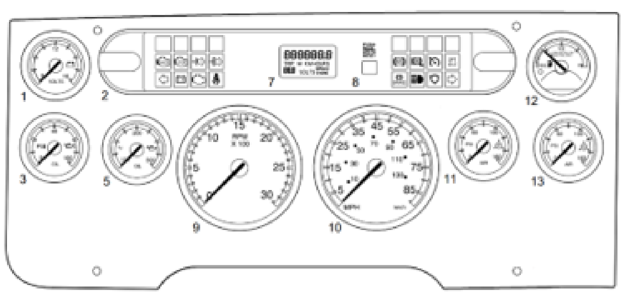
Driver vehicle interface and controls are shown below in Figure 22 and incorporate Freightliner's standard interface with an additional Hydrogenics digital cluster display. Signals such as throttle, brake, transmission gear shifter position are broadcasted to the main Electric Vehicle Control Unit to control the overall drive system functions of the vehicle. The driver would be familiar with the controls and operation of the vehicle because they are similar to a conventional truck and easier to operate than a conventional truck.

Figure 22: Driver Interface and Controls Layout

Source: Cummins Inc.

In addition, the Freightliner cluster provide the following information to the driver (Figure 23):

Figure 23: Freightliner Instrument Cluster



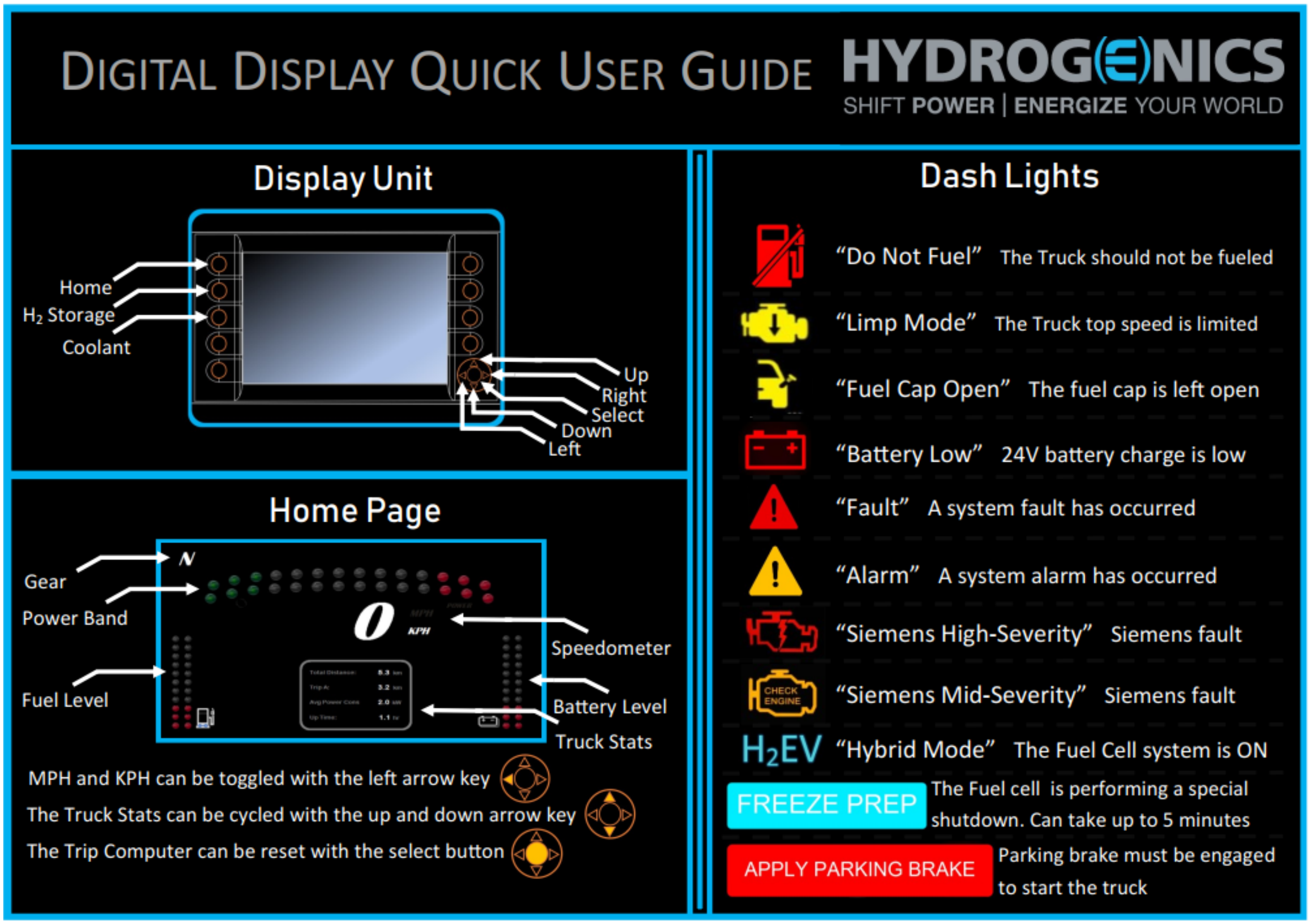
1) 12V battery voltage gauge
2) MIL, front light indicators and odometer
3) Fuel cell coolant pressure
5) Fuel cell coolant temperature
9) Drive motor RPM
10) Speedometer
11) Primary air pressure gauge
12) Hydrogen fuel level gauge
13) Secondary air pressure gauge

Source: Cummins Inc.

Hydrogenics Digital Cluster Display

An additional display is included to visualize information on the fuel cell propulsion system. These include standard metrics such as: vehicle speed, mileage and shifter position. It also includes information not supported by the original truck cluster such as: battery state of charge, hydrogen pressure levels, fuel cell status, coolant loop status, custom faults and alarms (Figure 24).

Figure 24: Hydrogenics Digital Cluster Display

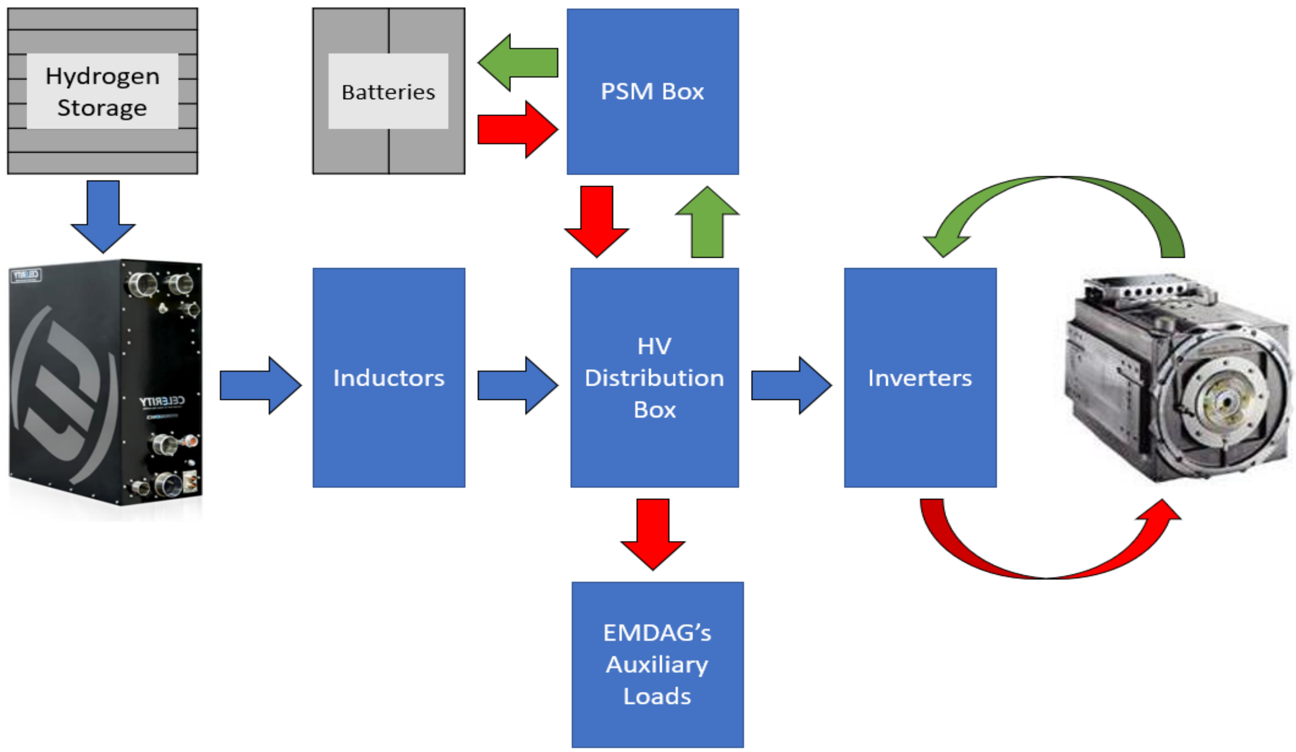


Source: Cummins Inc.

Fuel Cell Truck Architecture

Figure 25 below depicts the high voltage power flow architecture of the truck. The battery pack provides power for acceleration and all-electric operation, and energy recuperation from regenerative braking, thus improving overall system efficiency and providing benefits to mechanical brake service life. The Hydrogenics Celerity Plus fuel cell power system provides conversion of hydrogen energy up to 60 kW of fuel cell power.

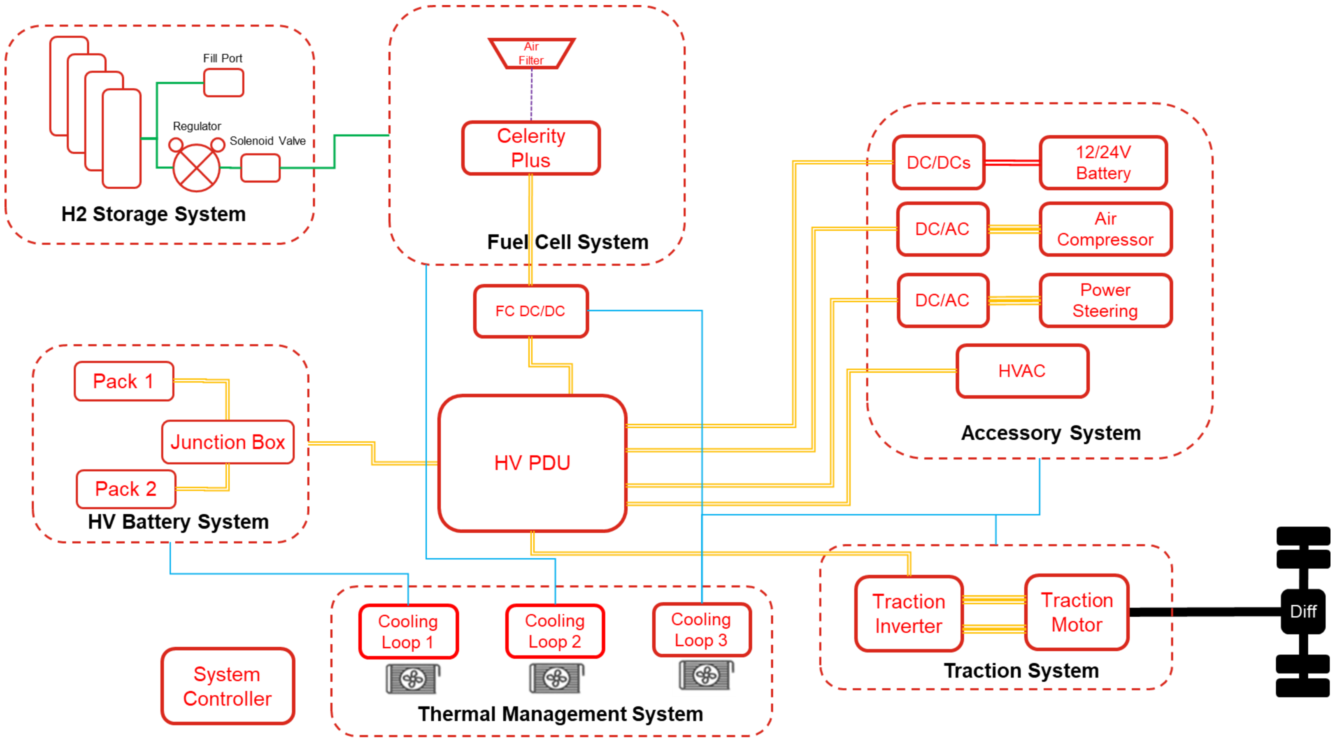
Figure 25: High Voltage Bus Power Flow



Source: Cummins Inc.

The high voltage architecture of the truck is depicted in **Figure *26*.** It shows how components of the high voltage system are connected to the main high voltage direct current power bus. In the Hydrogenics Advanced Fuel Cell Vehicle configuration, the high voltage battery pack is directly connected to the high voltage bus with contactors, pre-charge and circuit protection fusing; the Celerity Plus fuel cell power system is connected to the drive system via two Siemens inductors.

Figure 26: Hydrogenics Advanced Fuel Cell Vehicle High Level System Architecture



Source: Cummins

The air compressor, power steering motor, cabin air conditioning motor and fuel cell coolant pump are connected to the Siemens inverters via an auxiliary load contactor box. Two inverters provide the 24 Volt Direct Current power to the standard low voltage vehicle loads. Safety monitoring is performed by a high voltage ground fault detector, installed inside a battery enclosure, that constantly monitors if 600 Volt Direct Current is properly isolated from the chassis to avoid any injury.

The truck main supervisory control (Electric Vehicle Control Unit) takes vehicle drivers input from the vehicle CAN network including any multiplexed discrete signals, and processes into control commands to the powertrain via J1939 CAN communication protocol. The truck's overall vehicle controller handles all system functions from Key-On to Key-Off, and all modes of operation from system startup, run and shutdown.

The Hydrogenics Advanced Fuel Cell Vehicle has three different cooling loops in order to optimize performance of the different components: 1) fuel cell coolant loop, 2) high voltage batteries coolant loop, and 3) power electronics coolant loop. The fuel cell coolant loop is optimized around the fuel cell optimal thermal set point and pressure. It is also used to heat the cabin since it is connected to the original air conditioning system heat exchanger. The high voltage battery packs are cooled with a chiller and the coolant loop in order to keep the batteries at their optimum operating temperature. The power electronics coolant loop is cooling the Siemens drive components (inverters, inductors, drive motor, and other accessories).

High Voltage Safety Interlock

A High Voltage Safety Interlock was incorporated to the system to monitor its state and shut it down in case of an emergency. The High Voltage Safety Interlock is composed of a high voltage interlock circuit, an emergency shut down circuit and a high voltage isolation check safety mechanism.

The High Voltage Safety Interlock is designed to detect isolation issues and if the high voltage connectors within the high voltage interlock circuit become loose or are being opened improperly (during service for instance). In these cases, the High Voltage Safety Interlock will trigger the emergency shut down circuit to isolate the high voltage within the high voltage battery, thus maintaining a safe state until repaired. In addition, the truck is equipped with an inertia sensor that can detect serious impacts to the truck. In case of a crash, the inertia sensor will also trigger the emergency shut down circuit.

Lastly, ACTIA integrated a high voltage isolation measurement device into its high voltage batteries to continuously monitor battery isolation and trigger a system fault in case of isolation issues. In case of issue, the Electric Vehicle Control Unit reacts by sending a warning to the driver through the Hydrogenics Cluster Display and gradually limiting power to the wheels to allow the driver to safely pull over. Ultimately, the system is shut down until repaired.

Failure Mode and Effects Analysis

A system-level Failure Mode and Effects Analysis was conducted with a cross functional team of engineers from mechanical, electrical, controls, thermal and service to evaluate and mitigate the critical effects of failures within the various fuel cell truck propulsion subsystems.

A list of system, subsystems and major components functions, and all their associated failure modes was created. The potential effects of these failure modes, their potential causes and current mitigation mechanisms were then each reviewed, discussed and scored based on severity, occurrence and detection (**Error! Reference source not found.**). Lastly, the team generated a series of corrective and mitigating actions for the failure modes with the highest risk priority numbers that were implemented on the fuel cell truck.

Table 3: Failure Mode and Effects Analysis Severity, Occurrence and Detection Scoring Sheet

Project RD3008						
Project Model: CEC Drayage Truck						
Severity		**Occurrence**		**Detection**		
10	Major Injury/ Loss of Life	10	Will occur in early product life	10	Undetectable	
9	Hazardous Conditions	9	Likely mis-usage by customer	9	Very remote	
8	Minor Injury	8	Will occur at end of product life	8	Remote	Alarm/Detection during data analysis
7	Component/Equipment Damage	7	75% chance	7	Very low	Alarm/Detection during maintenance
6	Shutdown-Major Service required	6	25% chance	6	Low	Alarm/Detection during diagnostic mode
5	Shutdown-Minor Service required	5	10% chance	5	Moderate	Alarm/Detection during refueling
4	Shutdown-Can be restated without servicing	4	Unlikely mis-usage by customer	4	Moderately high	Alarm/Detection during startup
3	Major Nuisance	3	1% chance	3	High	Alarm/Detection during operation
2	Minor Nuisance	2	0.1% chance	2	Very high	
1	No discernable effect	1	0.01% chance	1	Almost certain	Shut down

Source: Cummins

CHAPTER 3: Fuel Cell Truck Build, Integration and Testing

This chapter reviews the assembly and integration, commissioning and testing of the Hydrogenics Advanced Fuel Cell Vehicle that was completed under Task 3 of the approved scope of work.

Fuel Cell Truck Build and Integration Process

The Hydrogenics Advanced Fuel Cell Vehicle was built by the Hydrogenics team in Canada following the major steps described below.

Step 1: Truck glider preparation and measurement verification

Upon reception of the truck glider, any unnecessary parts and components were removed, and dimensions were measured to verify that they corresponded to the CAD models of the Model Year 2018 Cascadia truck provided by Freightliner (Figure 27). The engineering and design package and documents of the fuel cell propulsion system were updated as required.

Figure 27: Freightliner Cascadia Glider Delivery and Inspection

Source: Cummins Inc.

Step 2: Battery Chiller Installation

The battery chiller was installed between the frame rails, wired and plumbed (Figure 28).

Step 3: Fuel Cell Cradle Preparation

The fuel cell structural cradle was manufactured, and major components were installed, wired and plumbed (**Figure 28**).

Figure 28: Battery Chiller Installation (left) and Fuel Cell Cradle Preparation (right)

Source: Cummins Inc.

Step 4: Fuel Cell Subassembly Installation

The fuel cell subassembly was installed in the engine compartment ()

Figure **29**)

Figure 29: Hydrogenics Celerity Plus Subassembly Installation

Source: Cummins Inc.

Step 5: Hydrogen Tank System Installation

The hydrogen tank system was installed behind the cab (Figure 30).

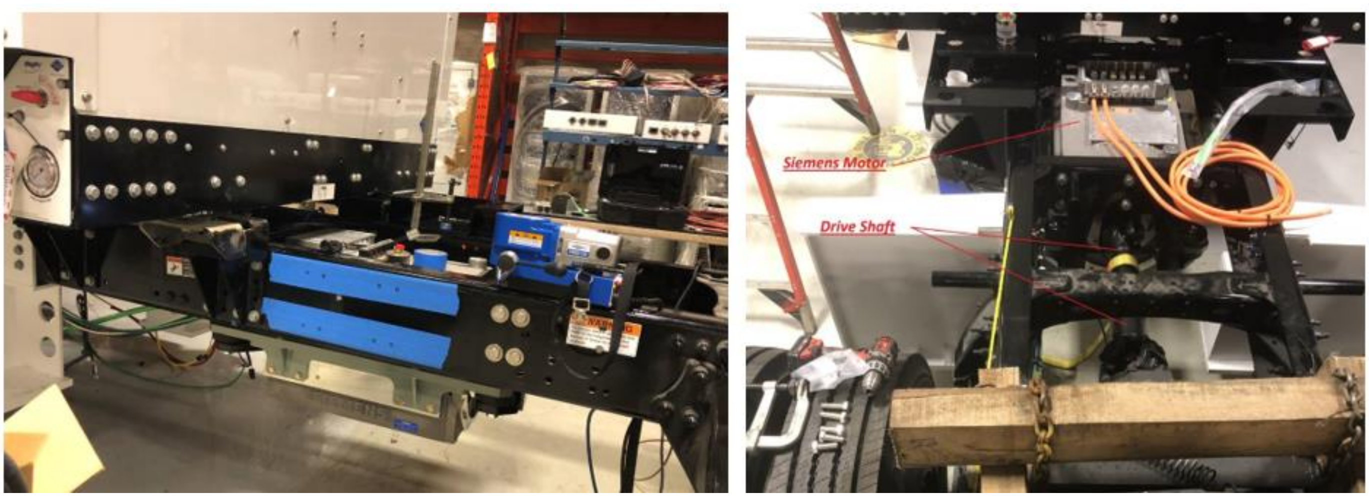
Figure 30: Hydrogen Tank System Installation

Source: Cummins Inc.

Step 6: Drive Motor Installation

The drive motor was installed between the frame rail and connected to the rear axles with a custom drive shaft (**Figure 31**).

Figure 31: Drive Motor and Drive Shaft Installation



Source: Cummins Inc.

Step 7: Battery Bracket Installation

The brackets to hold the two high voltage battery packs were mounted on both sides of the frame rails (**Figure 32**)

Figure 32: High Voltage Battery Bracket Installation

Source: Cummins Inc.

Step 8: Aerodynamic Fairings Installation

Additional aerodynamic fairings (roof fairing, cab and roof extenders and wheel covers) were installed (Figure 33).

Step 9: Air Compressor Installation

The brake air compressor was installed on the passenger side of the truck behind the passenger steps (**Figure 33**).

Figure 33: Aerodynamic Fairings (left) and Air Compressor Installation (right)

Source: Cummins Inc.

Step 10: Power Electronics Module Installation

The power electronics module was built, tested and installed behind the hydrogen tank system (**Figure 34**).

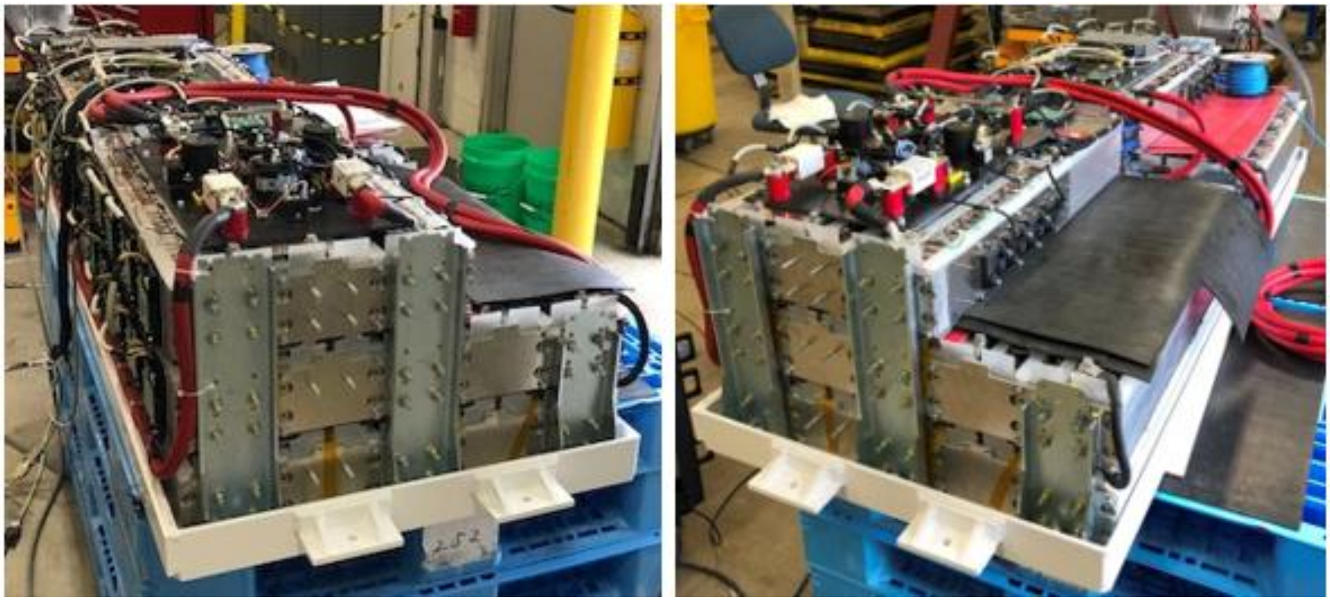
Figure 34: Power Electronics Module Build, Testing and Installation

Source: Cummins Inc.

Step 11: High Voltage Battery Packs Installation

The high voltage battery packs were installed in the brackets, wired and plumbed (Figure 35).

Figure 35: High Voltage Battery Packs Installation



Source: Cummins Inc.

Step 12: Truck Build Completion

The thermal management system plumbing as well as the low and high voltage wiring was finalized. The driver interface and controls were installed in the cabin. These last steps marked the completion of the truck build step (Figure 36).

Figure 36: Completed Hydrogenics Advanced Fuel Cell Vehicle

Source: Cummins Inc.

Step 13: Truck Commissioning

Upon completion of the truck build, the fuel cell system and major subsystems were commissioned, troubleshooting any issues and performing calibration tasks. Functional tests of all the subsystems as well as the advanced fuel cell propulsion system were done next before the first key-on test of the Hydrogenics Advanced Fuel Cell Vehicle was completed (Figure 37). Lastly, a first drive of the vehicle was completed at low speed (Figure 38).

Figure 37: Hydrogenics Advanced Fuel Cell Vehicle Commissioning

Source: Cummins Inc.

Figure 38: Hydrogenics Advanced Fuel Cell Vehicle First Drive

Source: Cummins Inc.

Performance Testing and Validation

Upon completion of the vehicle commissioning, the Hydrogenics Advanced Fuel Cell Vehicle underwent a series of test and validation activities to assess its performance and suitability for the fleet demonstration.

Vehicle Upgrades

After Hydrogenics was acquired by Cummins in September 2019, the administrative and technical responsibility of the project was transferred from Hydrogenics USA, Inc. to Cummins Electrified Power NA Inc. Cummins' engineers performed a detailed review of the design, build, integration and commissioning of the Hydrogenics Advanced Fuel Cell Vehicle and implemented a series of upgrades to bring the vehicle up to Cummins' standard of safety and performance as well as improve its reliability.

High Voltage Battery System Upgrade

The following upgrades and repairs on the high voltage battery packs had to be done by ACTIA: 1) the isolation measurement devices were fixed to provide accurate system isolation reading, 2) the emergency shut down circuit was rewired to pass the emergency shut down testing, 3) the Gore-Tex vent caps were replaced and the screws holding them upgraded to prevent further issues, 4) repaired loose captive nuts on battery pack mounting bracket, 5) replaced diagnostic serial ports that were not functioning, 6) relocated the diagnostic serial ports from inside to outside the battery box to prevent the service team from being exposed to high voltage during troubleshooting, 7) fixed battery management software bug preventing truck start, and 8) replaced wiring causing battery cooling issues.

High Voltage Battery Pack Crash Protection Bracket

The high voltage battery packs are mounted on both driver and passenger sides between the axles/wheels and outside the frame rails. The original design did not include any side impact protection for the packs. Considering the location of the packs and the potential risks of any side impact, a new crash protection bracket was designed and incorporated (Figure 39).

Figure 39: Original High Voltage Battery Pack Design (left) and with Crash Protection Bracket (middle and right)

Source: Cummins Inc.

Front Axle Upgrade

With the addition of the advanced fuel cell powertrain and the different weight repartition compared to a conventional diesel vehicle, the front axle exceeded the original rating of 12,000 lbs. maximum and therefore had to be upgraded to a higher rating. The Hydrogenics Advanced Fuel Cell Vehicle was upgraded with a 14,600 lbs. front axle and the wheels realigned. A new weight certificate for the altered vehicle was also applied by the company who performed the front axle upgrade (Table 4).

Table 4: Vehicle Weight Before/After Front Axle Upgrade

	Measured Weight	**Max. Rating Before Upgrade**	**Max. Rating After Upgrade**
Steering Axle Weight	12,860 lbs.	12,000 lbs.	14,600 lbs.
Drive Axles Weight	13,180 lbs.	20,000 lbs.	20,000 lbs.
Gross Vehicle Weight Rating	-	52,000 lbs.	54,600 lbs.
Curb Weight	26,040 lbs.	-	-

Source: Cummins Inc.

Power Steering System Upgrade

The original power steering hydraulic pump was not correctly sized, preventing the electric motor from delivering full power and ultimately leading to power steering stall issues during normal truck operation. A new power steering pump with a larger displacement was selected and installed on the truck. No further power steering stall issues were observed with this new pump.

Hydrogen Pressure Release Ports Relocation

Hydrogen pressure release device ports allow for hydrogen in the storage tanks to be safely released in the atmosphere in case of an emergency. The location of the hydrogen pressure release device ports on the Hydrogenics Advanced Fuel Cell Vehicle was deemed unsafe and needed to be modified. The original ports were located on the back of the storage enclosure and were blocked by the power electronics module (**Figure *40***).

Figure 40: Original Location of the Hydrogen Pressure Release Device Ports

Source: Cummins Inc.

The ports were rerouted straight up toward the top of the hydrogen storage enclosure, allowing safe venting in the atmosphere (Figure 41).

Figure 41: New Location of the Hydrogen Pressure Release Device Ports

Source: Cummins Inc.

Data Acquisition System Installation

A cloud-based data logger was installed to remotely monitor system performance during testing and validation as well as during the field demonstration period. The new data acquisition system also enables faster service and maintenance by providing remote diagnosis capabilities to the Cummins service team. A post data processing method was established as well to allow the system to automatically generate daily truck operation reports.

Hydrogen Storage Tanks Inspection

According to Federal Motor Vehicle Safety Standard No. 304, high pressure storage tanks should be inspected in a qualified service facility every three years (36 months) or every 36,000 miles, whichever comes first. The hydrogen tank system was manufactured in 2017 and passed inspection by a certified third-party inspection facility in January 2021.

Vehicle Performance Simulation

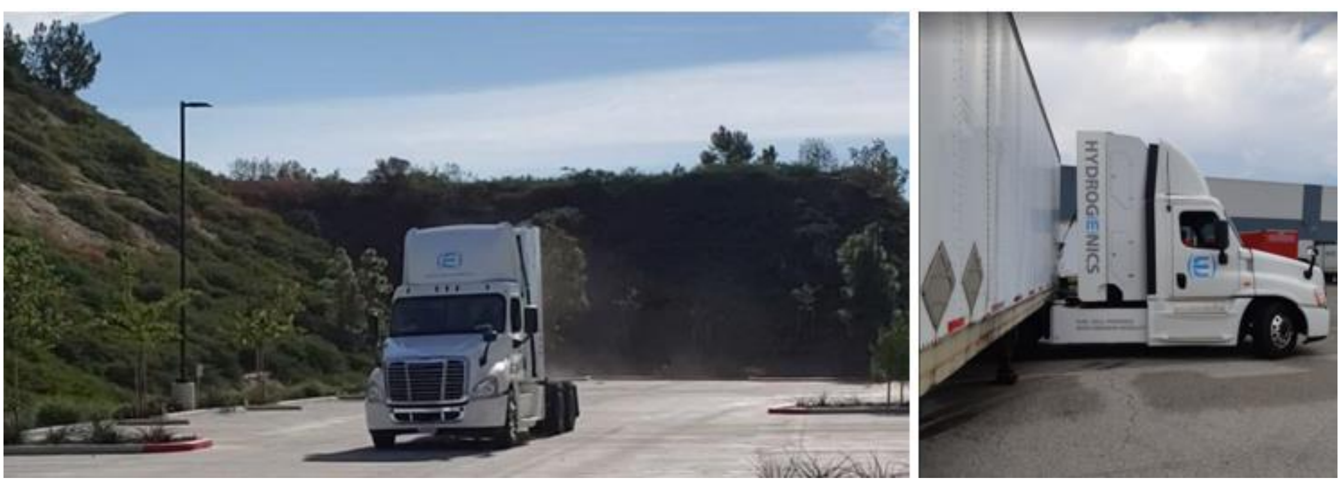
A detailed simulation model was created to perform a truck performance study and better calibrate the fuel cell power / high voltage battery allocation. The study revealed that the 60 kW Celerity Plus fuel cell module selected for this project is undersized to sustain the charge of the high voltage battery for drayage and regional delivery applications at or close to 82,000 lbs., requiring driving long highway operation or driving long steep slopes. Low power applications were identified where this issue would not negatively impact truck operation.

Vehicle Testing and Validation

The Hydrogenics Advanced Fuel Cell Vehicle underwent a series of validation and factory acceptance tests to evaluate the performance of the vehicle on the road and its suitability to serve in real-world drayage operation.

Parking lot testing (**Figure *42***) was performed to verify overall system functioning and ability to start and acceleration performance. Testing with a trailer was also done to assess trailer pulling and trailer swing capabilities and determine maximum fifth wheel kingpin location.

Figure 42: Parking Lot Testing



Source: Cummins Inc.

Bobtail road testing (no semi-trailer attached) was performed to verify performance under normal driving conditions (Figure 43).

Figure 43: Bobtail Road Testing

Source: Cummins Inc.

Road testing with a semi-trailer attached, unloaded, and fully loaded was performed to verify performance under normal driving conditions closely simulating real-world drayage operations (Figure 44).

Figure 44: Unloaded/Loaded Trailer Road Testing

Source: Cummins Inc.

The Hydrogenics Advanced Fuel Cell Vehicle was tested at the Del Mar hydrogen fueling station located at 3060 Carmel Valley Road, San Diego, CA 92130 (Figure 45) and at the SunLine Transit hydrogen fueling station located at 32505 Harry Oliver Trail, Thousand Palms, CA 92276 to verify that it can fuel at retail stations using standard fueling protocols and standard nozzles. The Hydrogenics Advanced Fuel Cell Vehicle was able to fully refuel at these stations without any issues.

Figure 45: Refueling Testing

Source: Cummins Inc.

Grade testing with a fully loaded semi-trailer attached was performed on the road to evaluate the performance of the Hydrogenics Advanced Fuel Cell Vehicle under a wider range of real-world drayage operating conditions (Figure 46).

Figure 46: Grade Testing

Source: Cummins Inc.

While the Hydrogenics Advanced Fuel Cell Vehicle performed well as a prototype vehicle, several critical issues were experienced during the course of the vehicle testing and validation that ultimately prevented the demonstration in real-world drayage operation. A short summary of the issues is provided below:

- Vehicle performance limitations described above in page 31.
- Battery State-Of-Charge is critical to the powertrain control system to manage fuel cell power demand. However, State-Of-Charge estimation on the high voltage battery is not reliable and varies unexpectedly. This causes poor system performance and drivability. State-Of-Charge estimation would need to be improved by ACTIA but since the battery used on the Hydrogenics Advanced Fuel Cell Vehicle is a prototype not planned to go into production, it may require significant additional resources.
- In late Q1 2021, the Hydrogenics Advanced Fuel Cell Vehicle experienced unexpected and sudden system shut down while driving. The issue requires troubleshooting and may need significant additional resources to fix.
- In late Q1 2021, the Hydrogenics Advanced Fuel Cell Vehicle experienced unexpected and sudden shutdowns of the Hydrogenics digital cluster display. The issue requires troubleshooting and may need significant additional resources to fix.
- Throughout the vehicle testing and validation, the truck experienced poor reliability of the Celerity Plus fuel cell module. Celerity Plus is a prototype fuel cell module that was designed in 2014 and it has not been pushed toward commercialization, Hydrogenics focusing instead on commercializing the HD45 fuel cell module. As a result, the Celerity Plus on the Hydrogenics Advanced Fuel Cell Vehicle is a prototype that hasn't been developed to meet the reliability and servicability requirements of real-world drayage operation.

Noise Testing

Noise testing was conducted on the Hydrogenics Advanced Fuel Cell Vehicle to assess its noise profile. Testing was performed using a smartphone app that has an accuracy of +/- two decibel measuring the following:

- Closed hood measurement:
    - Front/Left/Right of the Vehicle: Microphone must be six feet away at a height of five feet from the truck,
    - Inside cab: Microphone must be one foot away from the driver's right ear and at the same height of the driver's ear pointing towards the windshield.
- Open hood measurement:
    - Front of the truck: Microphone must be one foot away and at a height of five feet from the ground pointing towards the truck,
    - Left/Right of the Truck: Microphone must be six feet away at a height of five feet from the truck,
    - Inside cab: Microphone must be one foot away from the driver's right ear and at the same height of the driver's ear pointing towards the windshield.

Three 30-second measurements were recorded for each setup/orientation. The testing results are detailed in Table 5 below.

Table 5: Noise Testing Results

	Description	Front	Left	Right	Inside Cab Open	Inside Cab Closed
Hood Closed	Ambient Level	56	56	58	50	40
	Key On	56	56	58	50	40
	Cranked	58	57	58	50	42
	Cranked + Air Conditioning On	62	61	63	59	58
	Cranked + Air Conditioning On + Compressor	63	63	65	64	60
Hood Open	Ambient Level	55	55	56	52	35
	Key On	55	56	53	52	35
	Cranked	52	54	58	52	40
	Cranked + Air Conditioning On	57	55	60	60	58
	Cranked + Air Conditioning On + Compressor	63	63	65	64	59

Source: Cummins Inc.

Noise testing verified that the interior noise level does not exceed 75 decimal and outside noise level at idle does not exceed 65 decimal, well below the noise of a standard diesel engine which produces approximately 100 decimal.

Fuel Economy Evaluation

Fuel economy evaluation and testing was not performed due to the issues described above in pages 33 and 34.

CHAPTER 4: Conclusion

Project Success

Despite facing challenges, the project successfully demonstrated the technical and commercial viability of hydrogen fuel cell propulsion technology purposely designed and developed for Class 8 drayage trucks. It demonstrated a simplified integration and development process of an advanced fuel cell propulsion system into a Class 8 drayage truck (Figure 47). Funding from the CEC was a critical enabler to the overall success of Hydrogenics. By selecting Hydrogenics, the CEC grant review process provided a valuable third-party evaluation of its business model for Cummins' due diligence prior to its acquisition of the company in 2019.

Figure 47: The Hydrogenics Advanced Fuel Cell Vehicle

Source: Cummins Inc.

As one of the first fully functioning heavy-duty fuel cell trucks ever built in California, the Hydrogenics Advanced Fuel Cell Vehicle represents a meaningful step in the hydrogen fuel cell industry. For Cummins, it is an important building block in becoming a leader in fuel cell powertrains for heavy-duty mobility applications.

Lessons Learned

Throughout the duration of this project, Hydrogenics and Cummins learned valuable lessons that they believe can be helpful for the CEC or companies supporting the hydrogen and fuel cell market.

1) *Current system design is not optimized for most truck duty cycles.*

The current fuel cell powertrain architecture and design, with its direct drive architecture, 60 kW fuel cell module and 100 kWh battery, is not optimized for drayage and regional delivery applications at or close to 82,000 lbs., requiring driving long highway operation or driving long steep slopes. In particular, it cannot provide sufficient power, torque and energy to support an 82,000 lbs. GVWR drayage truck throughout its daily duty cycle and prolong the life of the battery by operating in a charge sustaining mode.

2) *Current system design is not well-suited for commercialization.*

The current powertrain architecture and design is a prototype that will not be commercialized and cannot be easily supported in the field. It uses many prototype components that cannot be easily repaired or replaced due to prototype parts availability and product obsolescence. In addition, the current powertrain control system is a prototype that is not using industry standards and cannot be supported by Cummins' service team using standard diagnostic tools.

3) *Current system design is not well-suited for mass market penetration.*

The current powertrain architecture and design is a prototype that is not suited to accelerate the mass market penetration of advanced zero emission fuel cell drive system technology in a drayage truck. In particular, it uses many prototype components that are not commercial off-the-shelf. For instance, the Celerity Plus 60 kW fuel cell module is a prototype whose production has been discontinued. The ACTIA 43 kWh battery system is a prototype battery pack, custom-designed for the Model Year 2018 Freightliner Cascadia 125DC platform.

4) *State is lacking hydrogen fueling infrastructure.*

Hydrogen fueling infrastructure, and especially infrastructure for medium and heavy-duty vehicles, remains wholly inadequate in California to support the commercialization of hydrogen fuel cell propulsion technologies. In addition, the availability of hydrogen at the existing hydrogen fueling stations is unreliable and remains a major concern for companies looking at converting their truck fleets to zero-emissions vehicles.

Next Steps

Going forward, Cummins is involved in several projects pursuing its most up-to-date heavy-duty fuel cell powertrain architecture and design which incorporates the key learnings from this project and leapfrogs incremental design improvements on a powertrain architecture and design originally developed in 2015. Cummins' latest generation architecture and design bring forward a state of the art fuel cell powertrain that 1) is customized, tested, and optimized for regional haul and port applications, 2) can demonstrate the market viability of advanced zero emission fuel cell drive system technology in a heavy-duty truck, and 3) accelerates the mass market penetration of heavy-duty hydrogen fuel cell trucks.

GLOSSARY

CALIFORNIA ENERGY COMMISSION (CEC)—The state agency established by the Warren-Alquist State Energy Resources Conservation and Development Act in 1974 (Public Resources Code, Sections 25000 et seq.) responsible for energy policy. The Energy Commission's five major areas of responsibilities are:

1. Forecasting future statewide energy needs
2. Licensing power plants sufficient to meet those needs
3. Promoting energy conservation and efficiency measures
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
5. Planning for and directing state response to energy emergencies.

CUMMINS—Cummins Inc. designs, manufactures, distributes, and services diesel and natural gas engines. The Company also manufactures electric power generation systems and engine-related component products, including filtration and exhaust aftertreatment, fuel systems, controls, and air handling systems.[1]

DIRECT CURRENT (DC)— A charge of electricity that flows in one direction and is the type of power that comes from a battery.

FUEL CELL—A device or an electrochemical engine with no moving parts that converts the chemical energy of a fuel, such as hydrogen, and an oxidant, such as oxygen, directly into electricity. The principal components of a fuel cell are catalytically activated electrodes for the fuel (anode) and the oxidant (cathode) and an electrolyte to conduct ions between the two electrodes, thus producing electricity.

HYDROGENICS CORPORATION (Hydrogenics)—A company that designs and manufactures hydrogen generation, energy storage, and fuel cell products.[2]

HYDROGENICS USA, Inc. (Hydrogenics USA)—Hydrogenics USA was the U.S. business entity of Hydrogenics Corporation.

KILOWATT (kW)—One thousand (1,000) watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon, a typical home, with central air conditioning and other equipment in use, might have a demand of four kW each hour.

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1 Cummins, Inc. https://www.bloomberg.com/profile/company/CMI:US

2Hydrogenics Company Profile https://www.dnb.com/business-directory/company-profiles.hydrogenics_corporation.b6fa9a4c9c6ffa4de0846f6e2ae09e27.html

KILOWATT-HOUR (kWh) —The most commonly used unit of measure telling the amount of electricity consumed over time. It means one kilowatt of electricity supplied for one hour. In 1989, a typical California household consumes 534 kWh in an average month.

POUND (LBS)— A pound or pound-mass (abbreviations: lb, lbm, lbm or ℔) is a unit of mass used mainly in the imperial and United States customary. The most common definition today is the international avoirdupois pound which defined as exactly 0.45359237 kilograms, and which is divided into 16 avoirdupois ounces. So, 1 pound = 16 ounces. The symbol comes from the Roman word libra (hence the abbreviation "lb") while the name pound is a Germanic adaptation of the Latin phrase libra pondo, "a pound by weight". Note that the pound is a unit of mass, not a weight unit. The unit of weight is the pound-force.

VOLT (V)—A unit of electromotive force. It is the amount of force required to drive a steady current of one ampere through a resistance of one ohm. Electrical systems of most homes and offices have 120 volts.