DISCLAIMER

ZERO EMISSION CARGO TRANSPORT (ZECT) II DEMONSTRATION

South Coast Air Quality Management District

EERE Award Number DE-EE0006874

FINAL REPORT

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Project Duration:

Start Date: October 01, 2014 End Date: February 28, 2024

Project Cost:

Project Partners	Project Cost-share
DOE	$9,725,000
South Coast AQMD	$2,400,000
Others	$7,859,820
Total Project Cost	**$19,984,820**

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Executive Summary

The South Coast Air Quality Management District (South Coast AQMD), California Air Resources Board (CARB) and Southern California Association of Governments (SCAG) — the agencies responsible for preparing the State Implementation Plan required under the federal Clean Air Act — have agreed that attainment of federal air quality standards for the region will require a transition to the broad use of zero and near-zero emission energy sources in cars, trucks and other equipment. Accordingly, the 2012 South Coast AQMD Air Quality Management Plan, the SCAG 2012 Regional Transportation Plan, and the "Vision for Clean Air: A Framework for Air Quality and Climate Control Planning" all identify the need to immediately enact a phasing in of zero and near-zero emission technologies to meet air quality goals.

In 2014, South Coast AQMD was awarded grant funding under the US Department of Energy Zero Emission Cargo Transport (ZECT) II Demonstration program to develop and demonstrate zero-emission drayage trucks for goods movement operations between the Port of Los Angeles (POLA) and Port of Long Beach (POLB) near dock rail yards and warehouses: 1) development and demonstration of zero-emission fuel cell range extended electric drayage trucks and 2) development and demonstration of hybrid electric drayage trucks. The purpose of this project was to accelerate deployment of zero emission cargo transport technologies to reduce harmful diesel emissions, petroleum consumption and greenhouse gases in the surrounding communities along the goods movement corridors that are impacted by heavy diesel traffic and the associated air pollution.

Between 2014 – 2024, six ZECT II zero-emission fuel cell drayage truck platforms, including fuel cell range extended and CNG hybrid trucks, were successfully designed, developed, integrated, built, tested, and demonstrated with drayage fleet operators in transportation corridors within areas of the South Coast AQMD jurisdiction in Southern California such as in and around POLA and POLB. Portable hydrogen refueling was deployed to support the fuel cell vehicles. The project had real-time improvement with on-going debugging and optimizations while the vehicles were under demonstration. All platforms demonstrated sufficient or excess power, torque, and energy to support 82,000lbs Gross Vehicle Weight Rating and gradeability to perform their daily duty cycles. Collectively, the trucks drove over 23,000 miles during their respective demonstration phases.

The ZECT II project was the first of its kind to demonstrate the commercial viability that supported the additional technology breakthroughs for Class 8 zero emission trucks and validations as well as the regulatory basis for all the zero-emission regulation that we know today, such as the Innovative Clean Transit regulation, Advanced Clean Trucks and Clean Fleet regulations.

Background

The I-710 and CA-60 highways are key transportation corridors in the Southern California region that are heavily used on a daily basis by heavy-duty drayage trucks that transport the cargo from the ports to the inland transportation terminals. These terminals, which include warehouses and inland railways, are anywhere from 5 to 50 miles in distance from the Ports. The concentrated operation of these drayage vehicles in these corridors has had and will continue to have a significant impact on the air quality in this region thereby significantly impacting the quality of life in the communities surrounding these corridors. To reduce these negative impacts, it is critical that zero and near-zero emission technologies be developed and deployed in the region. A potential local market size of up to 46,000 trucks exists in the South Coast Air Basin, based on near-dock drayage trucks and trucks operating on the I-710 freeway. In areas with historically poor air quality like the South Coast Air Basin, zero emission transportation technologies are being considered and may become standard. The South Coast Air Quality Management District (South Coast AQMD), California Air Resources Board (CARB), and Southern California Association of Governments (SCAG) — the agencies responsible for preparing the State Implementation Plan required under the federal Clean Air Act — have stated that to attain federal air quality standards, the region will need to transition to broad use of zero and near-zero emission energy sources in cars, trucks, and other equipment. The SCAG 2012-2035 Regional Transportation Plan/Sustainable Communities Strategy (RTP/SCS): Towards a Sustainable Future[1] also lays out a long-term vision of a phased adoption of zero and near-zero emission technologies to meet air quality goals.

1 https://scag.ca.gov/post/2012-2035-regional-transportation-plansustainable-communities-strategy-executive-summary

Project Introduction

The South Coast AQMD, CARB, and SCAG, the agencies responsible for preparing the State Implementation Plan required under the federal Clean Air Act, agreed that achieving federal air quality standards in the region requires a transition to a widespread use of zero and near-zero emission energy sources in cars, trucks, and other equipment. One strategy for the Clean Fuels Program at South Coast AQMD is to achieve emission reductions within its jurisdiction through the commercialization of zero emission drayage truck technologies since a large volume with lower prices is key for wider deployment of zero emission technologies. The Zero Emission Cargo Transport (ZECT) II project aligns with the goals of that strategy.

The ZECT II project provided the development and demonstration of zero emission fuel cell range extended electric drayage trucks and the development and demonstration of hybrid electric drayage trucks for goods movement operations between the Port of Los Angeles (POLA) and Port of Long Beach (POLB) near dock rail yards and warehouses. This project aimed to accelerate the deployment of zero emission cargo transport technologies to reduce harmful diesel emissions, petroleum consumption, and greenhouse gases in the surrounding communities along the goods movement corridors impacted by heavy diesel traffic and the associated air pollution.

Five entities were selected to develop and demonstrate a total of seven Class 8 drayage trucks for this project. Those entities were:

- Center for Transportation and the Environment (CTE) for the development and demonstration of **one** Class 8 fuel cell range extended electric drayage truck;
- Gas Technology Institute (GTI) for the development and demonstration of **one** Class 8 CNG hybrid electric drayage truck;
- Transportation Power (TransPower) for the development and demonstration of **two** Class 8 fuel cell range extended electric drayage trucks;
- US Hybrid for the development and demonstration of **two** Class 8 fuel cell range extended electric drayage trucks; and
- International Rectifier (IR) for the development and demonstration of **one** diesel hybrid electric drayage truck.

Under CTE's project management, their subcontractor BAE Systems was to develop a battery-electric truck with a hydrogen fuel cell range extender in collaboration with Ballard Power Systems. The project was to test a hybrid electric fuel cell system, previously used in transit buses, for drayage applications. The electric drivetrain's power output was comparable to Class 8 truck engines with AC traction motors on each rear drive axle and a fully redundant powertrain. The vehicle operated primarily on battery power, engaging the fuel cell only when the battery reached a specific charge level. BAE Systems estimated the 30kg of hydrogen (25 kg usable) would provide about 112 miles of range per refuel.

Under GTI's project management, their subcontractor BAE Systems was to develop a battery-electric truck with a CNG range extender and optional catenary capability. The truck would operate in both zero emission all-electric mode and conventional hybrid mode using CNG. It would be powered by a BAE Systems propulsion system, which includes a 200kW Integrated Starter Generator (ISG), two dual 200kW propulsion control systems, and two AC traction motors. This setup was expected to provide a combined continuous power output of 320kW (430hp), similar to the power output of Class 8 truck engines at the time this project was awarded.

TransPower was to develop two battery-electric trucks with hydrogen fuel cell range extenders to increase range and maintain zero emission operation at the POLA and POLB. The fuel cell would boost onboard energy by 3.25 times, extending the range between recharge or refuels. The project was to use TransPower's ElecTruck™ drive system, integrating fuel cells provided by Hydrogenics USA, Inc. (Hydrogenics). Two demonstration trucks were to be built, one with a 30kW fuel cell and one with a 60kW fuel cell, to compare performance. To gain initial experience with the hardware and software requirements, a simple benchtop fuel cell system was set up using a single Hydrogenics HD30 fuel cell. The 60kW system would be designed for heavier loads and longer distances. The system would store 25-30kg of hydrogen onboard, offering an estimated fuel economy of 7.37mi/kg H2. The system was also to include a bi-directional J1772-compliant charger for recharging or power export.

US Hybrid was to develop two battery-electric trucks with onboard hydrogen fuel cell generators. With extensive experience in fuel cell technology for vehicles like cargo vans, buses, and military trucks. The trucks would feature an 80kW hydrogen fuel cell generator in charge-sustaining mode, eliminating the need for recharging. This design would reduce both the battery size and the requirement for charging infrastructure. The trucks were anticipated to have a range of 150 miles per refuel, each carrying approximately 20kg of hydrogen at 350bar, with quick refueling completed.

IR was to develop a diesel plug-in hybrid-electric vehicle (PHEV) truck and an ultra-fast charger (UFC) for use near POLA and POLB. The technology would feature a bolt-on conversion kit that can transform standard Class 8 drayage vehicles into PHEVs. The truck would operate in zero emission all-electric mode within a predetermined zero emission zone near the ports, switching to hybrid-electric mode outside of that boundary to improve fuel efficiency and reduce diesel consumption. The PHEV would also support ultra-fast charging (15 to 20 minutes), allowing for quick turnarounds and ensuring utilization rates comparable to conventional drayage vehicles.

Objectives

The objective of the ZECT II project at South Coast AQMD was to develop and demonstrate seven zero emission fuel cell and plug-in hybrid electric heavy-duty Class 8 drayage trucks for goods movement operations between POLA and POLB near dock rail yards and warehouses. This project aimed to accelerate deployment of zero emission cargo transport technologies to reduce harmful diesel emissions, petroleum consumption, and greenhouse gases in the surrounding communities along the goods movement corridors that are impacted by heavy diesel traffic and the associated air pollution.

Approach

South Coast AQMD, as the award recipient, administered and provided overall management in this project. South Coast AQMD's approach to implementing the proposed technology was to address some of the challenges of developing the fuel cell range extended and hybrid electric truck platforms with the cost and time constraints of this funding opportunity announcement. By bringing together small to medium sized vehicle integrator contractors along with global manufactures and developers, our strategy was to obtain the best partners with innovation and experience for this project. Vehicle integrators TransPower, Hydrogenics and US Hybrid, were extremely cost effective in demonstrating proof of concept and exploring design variants in a timely fashion; original equipment manufacturers (OEMs) BAE Systems, a global defense and security company, Kenworth Trucks, a major truck OEM, and Ballard Power Systems, an international fuel cell manufacturer, had engineering and manufacturing capabilities and experience; both BAE Systems and Ballard have experience in developing fuel cell transit buses. Together South Coast AQMD's project contractors offered the opportunity to explore design variations concurrently and address many of the challenges developing new technologies in a timely and cost-effective manner. Some of the metrics that were used to evaluate the design variants of the proposed fuel cell range extended and hybrid architectures were: operational capabilities, energy usage and efficiency, fueling/charging requirements and costs compared to diesel powered trucks.

Results

Center for Transportation and the Environment (CTE)

Figure 1: The CTE ZECT truck

Executive Summary – CTE

CTE's project successfully achieved its primary goal of advancing zero emission technologies for heavy-duty Class 8 trucks to improve air quality in Southern California transportation corridors. The vehicle design combined existing zero emission battery electric technology with a hydrogen fuel cell engine, which acted as a range extender, resulting in a fully zero emission drayage truck. Key project partners included the CTE, Kenworth, BAE Systems, Ballard Power Systems, and Total Transport Solutions Inc. (TTSI).

The project was divided into two phases. Phase I involved the design, build, testing, and delivery of a prototype fuel cell hybrid drayage truck, seen in **Figure 1**. The CTE team also procured hydrogen and established a fueling station. Phase II focused on the deployment, operation, and maintenance of the truck, with data on truck operations and fueling provided to the National Renewable Energy Laboratory (NREL) as required. The truck was delivered to TTSI in February 2019 and operated for two years until February 2021.

The vehicle was built on a Kenworth T680 Class 8 chassis, designed for drayage applications, with a Gross Combined Vehicle Weight (GCVW) capacity of up to 80,000 lbs. The custom chassis and modular platform facilitated the integration of hybrid-specific components, including traction motors, batteries, and power converters. It stores 25kg of usable hydrogen in a 350bar composite tank and is powered by a Ballard HD85 85kW proton exchange membrane fuel cell for load leveling and range extension. While the target range was 112 miles per hydrogen fill, the vehicle achieved 216 miles and completed 12,000 miles of testing at Kenworth's Research and Development Center in Renton, WA before being delivered to TTSI.

Vehicle performance data was collected and analyzed throughout the demonstration and key performance indicators were reported. The vehicle traveled 3,039 in-service miles and consumed 521kg of hydrogen, achieving a fuel economy of 6.5 miles per diesel-gallon-equivalent (mi/dge), surpassing the baseline drayage truck efficiency of 5.7 mi/dge.

The CTE project team maintained the vehicle throughout the demonstration, addressing typical issues common to such projects, with examples provided in the CTE report (*see Appendix A*). TTSI personnel received written documentation on vehicle operation and maintenance, along with on-site training. They operated the vehicle in regular revenue service, including fueling, and conducted periodic visual inspections of the vehicle systems.

The largest strides in technology readiness level (TRL) were gained by the overall vehicle design and architecture. Prior to this project, the hydrogen fuel cell drayage truck TRL was at Level 4, with proof-of-concept vehicles developed by earlier researchers. The manufacturing readiness level (MRL) was also at Level 4, focusing on manufacturing concepts and vehicle fabrication in research environments. With this demonstration project, the TRL of the hydrogen fuel cell drayage truck advanced to Level 7 (out of 10), indicating successful prototype demonstrations in real-world operating environments.

CTE Development and Demonstration of One Truck

CTE effectively managed the vehicle development phase to ensure the project stayed on schedule and within budget. Key actions included addressing the bankruptcy of World

CNG (original partner responsible for upfitting), establishing a two-tier project schedule, and holding kickoff meetings in April and May of 2016. CTE secured a Department of Energy's (DOE) US work requirement waiver for Kenworth's work and executed subcontract amendments to extend the project budget periods. During the vehicle demonstration phase, CTE ensured the project stayed on schedule and within budget and worked with NREL on data transmission and analysis. COVID-19 impacted TTSI's operations, leading to reduced freight volume and driver shifts. To cut costs, TTSI removed insurance from the zero emission vehicles and temporarily suspended the program. When World CNG filed for bankruptcy, the CTE team decided to shift integration work to Kenworth and BAE Systems instead of finding a new integrator.

Kenworth and BAE Systems collaborated to develop the preliminary vehicle design, including mechanical layout and installation drawings, based on defined operational requirements and duty cycle data from a diesel-equivalent vehicle. Ballard, BAE Systems, and CTE joined Kenworth in reviewing critical design and pre-production concepts to either approve the design or identify deficiencies that needed to be addressed.

The critical design review covering the truck layout seen in **Figure 2**, subsystem failure mode and effects analysis (FMEA), weight analysis, propulsion system, simulations, and integration plan, found most elements acceptable with a few minor issues, such as a missing backflow prevention device. These issues were corrected, and Ballard suggested a simplification to the fuel cell water system, reducing cost and complexity without compromising performance.

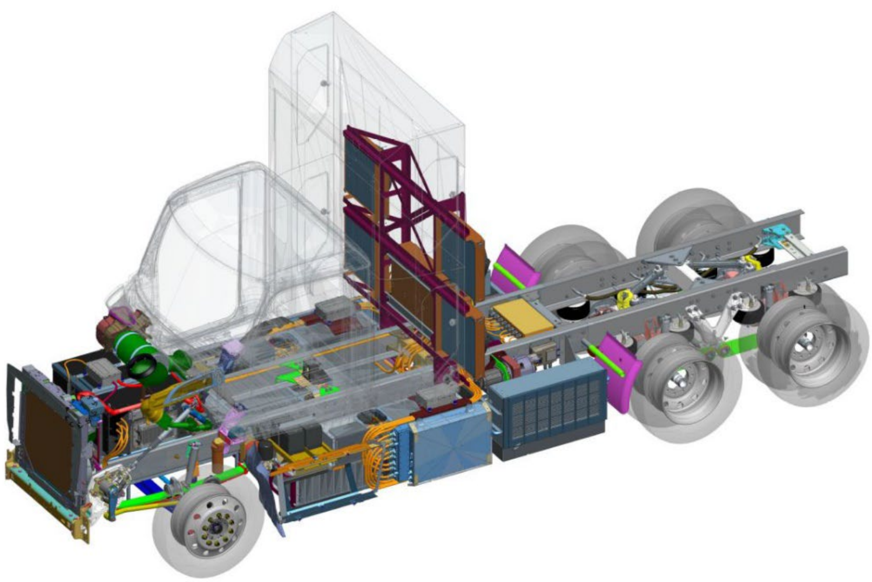

Figure 2: Overview of the CTE ZECT truck layout (hydrogen storage system not shown)

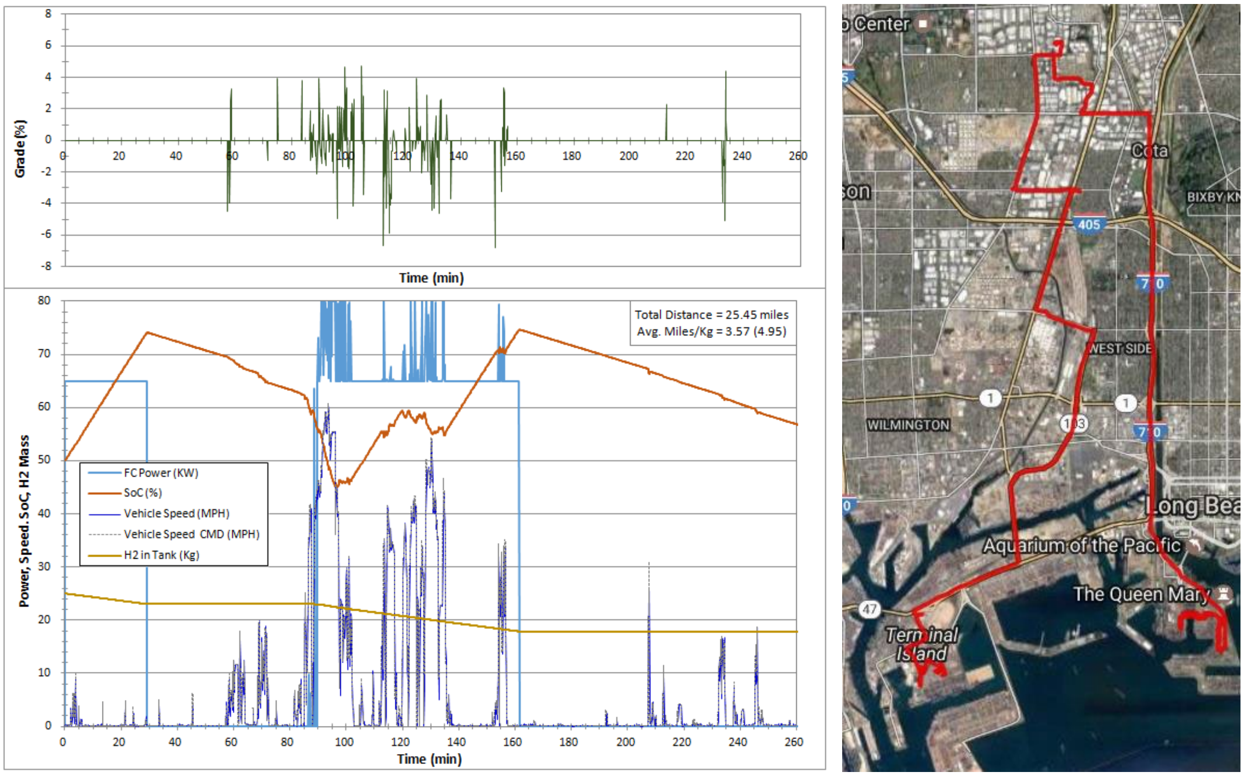

Figure 3: BAE Systems route simulation and results

CTE's subcontractor BAE Systems focused on developing the control laws, which are complex but critical for the performance of a fuel cell hybrid vehicle. For example, since the HD85 fuel cell's continuous power is less than what's required to climb grades at speed, the vehicle must rely on the battery pack for supplemental power. To optimize performance, the battery state of charge must be kept as high as possible. On the other hand, if the state of charge is too high and a downgrade is encountered, there is no place to store regenerated braking energy and the energy is lost to friction braking which ultimately reduces range. Additionally, another complication was that unlike a bus, the combined tractor and trailer weight of the ZECT truck can vary widely, and so variations in load also needed to be considered.

BAE Systems installed data logging equipment on in-service TTSI trucks to record speed and grade data from trucks performing similar tasks to the ZECT truck. This data was used to simulate truck performance, as seen in **Figure 3**, and update the vehicle control laws.

BAE Systems finalized requirements, control laws, and interface documents with Kenworth, while Kenworth addressed a safety concern with a motor design change. BAE Systems also updated the high-voltage and cooling routing, completed the energy storage system (ESS) design, and developed software for the truck's cooling systems. The CTE project team fabricated the fuel cell intake and exhaust plenums.

Kenworth received the diesel truck to be repowered with a fuel cell electric powertrain. AM Racing was selected to design and fabricate a custom traction motor housing for two Remy motors which provided a turnkey assembly that would generate power comparable to a diesel engine. Preliminary design estimates indicated competitive performance against Class 8 drayage diesel trucks. AM Racing also integrated an oil-to-water heat exchanger for external water cooling to reduce complexity. Eaton provided a 4-speed transmission, which was integrated with the dual motor system. Agility, a company selected by Kenworth, delivered a turnkey onboard hydrogen storage system.

In 2017, Air Products was selected as the hydrogen supplier at Kenworth's Renton and Mount Vernon facilities during commissioning and testing, using a diesel generator for the compressor due to limited power availability.

CTE and Kenworth coordinated with Air Products to complete site applications. The Renton site was the first fueling location, seen in **Figure 4**, requiring only a Tier 1 Temporary Use permit and a Renton Regional Fire Authority permit. As the hydrogen storage tank was under 10,000 gallons, no State Environmental Policy Act review was necessary. The CTE project team outlined hydrogen training and safety plans, covering H2, truck, station, fueling procedures, and technician/operator training, with details on locations, durations, participants, and responsible parties.

Figure 4: Refueling CTE ZECT truck trailer in Renton, WA

The system was tested in a lab environment at BAE Systems before integration into the Kenworth truck. BAE Systems' lab setup included a fuel cell shed, rotating dynamometer, and battery test facilities. Higher-level firmware, control laws, and the fuel cell hybrid system were tested in a fixed installation, with engineers directly monitoring tests and running repeatable test cases.

The rotating dynamometer was fitted with the dual Remy traction motors and transmission, which were part of the assembly fabricated by AM Racing. The dynamometer was used to test the power electronics' ability to drive the motor and transmission. BAE Systems fabricated a motor mount for the dynamometer and successfully tested the motors up to 440 kW, demonstrating full control across the voltage and speed range. This was a major step forward towards integration into the truck.

Kenworth acquired a diesel truck through its dealer system, which was displayed at the design review. The truck was then stripped of its engine, fuel tanks, and other components to be rebuilt from the frame up. Since the ZECT truck had no engine to drive accessories like power steering and air compressors, customized high-voltage electronic accessories were used, providing greater energy efficiency than traditional belt-driven components.

Ballard delivered the HD85 fuel cell to BAE Systems for testing. The fuel cell was mounted in the fuel cell shed and harnesses were fabricated to simulate operating conditions. BAE Systems conducted both low and high-voltage testing in collaboration with Ballard's engineering support and finalized fuel cell commissioning by implementing the software driver and validating its operation and performance.

BAE Systems completed the initial firmware for the fuel cell DC-DC converter, software updates for the truck's architecture, and successful testing of the battery pack with the propulsion system, addressing issues with the manufacturer, XALT. BAE Systems also built and installed the power interface module (PIM) in the lab for integration testing.

All major subsystems were integrated, including electric propulsion, fuel cell engine, energy storage, and cooling systems. The truck was stripped of its diesel components and the cab was removed to ease the integration process. Brackets were fabricated and mounted to the chassis to support the hydrogen storage system and other components.

The ZECT truck's cooling system featured four loops, each monitored for temperature and power demand. Fans control airflow and a coolant pump regulates heat removal to prevent battery drain. Tests were conducted to analyze and improve system efficiency.

The shift from a diesel engine to an electric transmission required alternative power for the 650V accessories. High-voltage, low current power was used for the custom air compressor, power steering pump, and A/C compressor. Kenworth developed software to manage the controllers for the electric motors and accessories.

Kenworth programmed the Vehicle Control Unit using low-voltage signals to simulate real-world conditions. To aid troubleshooting, they created a routing profile that separates high and low-voltage communication. Interface control documents were updated as the design evolved.

Kenworth designed steel brackets for the battery pack installation and developed the control systems. The battery pack assembly was installed and commissioned, with cooling loops and chillers controlled by the supervisory control system.

The installation of the Ballard fuel cell into the ZECT truck involved rerouting hoses, airlines, and coolant lines, as seen in **Figure 5**, to avoid interference with hybrid and standard components.

Figure 5: Routing and mechanical integration

During dynamometer testing, the chassis was run in full hybrid mode with the fuel cell at full power and charging the battery from 26% to 52% and from 19% to 62%, depleting the fuel tanks. The vehicle was then driven in battery-only mode to a weigh scale, measuring 22,800 lbs. It was then driven to the dynamometer in second gear, achieving 30+ mph, 290+ hp, and 3800+ lb-ft of torque. Road trials in Seattle took place in December 2017, as seen in **Figure 6**, with the truck operating in a fixed gear and without regenerative braking.

Figure 6: Functional road test and vehicle commissioning

The truck was also tested on a dynamometer at full power, running at 20-30 mph on a simulated 12% grade in a 100°F climate-controlled environment for 15 minutes, simulating the worst-case stress conditions.

The project encountered typical prototype integration issues, ranging from part replacements to software optimizations and subsystem faults. Some examples are:

- During a road test, unintended acceleration occurred due to a miscommunication between two Kenworth systems. The transmission splitter wasn't fully in neutral before the transmission system engaged, causing acceleration. Kenworth implemented a 3-level fix, including a tightened neutral zone, improved propulsion shifting, and a torque limit to prevent excessive acceleration.
- Water vapor from the fuel cell fogged the driver's windshield. Kenworth and BAE Systems developed a defrost solution using the fuel cell to heat defrosting liquid and software controls were added to meet Kenworth's standards for defrost performance.

To establish the demonstration fuel supply, TTSI secured approval to modify its master property lease with POLA for a hydrogen fueling station.

TTSI prepared the site to meet Air Products requirements and after securing necessary permits, Air Products installed mobile fuelers. The LAFD training, conducted by CTE's director with support from Air Products and the DOE, included both safety material and fuel demonstration. The session was well-received and LAFD provided approval for operation.

Kenworth and BAE Systems created a mock-up station to install the hybrid chassis harness and lay out wiring for the electrical integration. Kenworth installed shore power circuitry with four charging outlets: 220V for the main battery, two 110V for fuel cell and traction battery freeze protection, and 110V for low-voltage battery recharge. A design change was made to prevent overload. BAE Systems addressed fuel cell faults during electrical integration and both low- and high-voltage harnesses were delivered and installed.

Figure 7: The CTE ZECT truck climbing a 30% slope at 80,000 lbs. GCVW

In 2018, Kenworth began track testing, as seen in **Figure 7**, road trials, and system tuning, focusing on rapid mileage accumulation under various loads, speeds, and operational conditions. By the end of the validation period, the vehicle accumulated over 12,000 miles of testing. Testing activities included drivability, acceleration, steering, powertrain interaction with ABS, noise, electromagnetic radiation, gradeability, cooling tests, electric-only range, startability, and fuel economy. The vehicle met all performance requirements and exceeded the expected range, as seen in **Table 1**.

Performance Parameters	Expected Performance	Measured Performance
Hydrogen Storage	30 kg storage and 25 kg usable	30 kg storage and 25 kg usable
Range	112 miles	216 miles
Gradeability and Start-ability	6.5% grade at 35 mph 5.0% grade at 40 mph 15 second start-ability at 30% grade	6.5% grade at 36 mph 5.0% grade at 40 mph 15 second start-ability at 29% grade
Top Speed	70 mph	70 mph

Table 1: Vehicle performance

The CTE team planned post-testing and pre-delivery activities, including training for operators, maintenance teams, and first responders. Kenworth visited the demonstration site to update vehicle manuals for TTSI and developed an escalation plan in case the vehicle went out of service. Initial data packets were submitted to NREL for verification.

The vehicle faced several issues prior to shipment to TTSI, causing significant delays. For example, during validation testing, faults in power steering, the transmission, and the fuel cell engine led to significant downtime. The vehicle was sent to Kenworth's engineering center for repairs, with Ballard on-site for fuel cell diagnostics. Software upgrades were implemented to optimize performance before the vehicle was sent back for further testing. The goal was 40 fault-free hours before shipment to the demonstration site.

Kenworth completed track testing, road trials, and system tuning, then assigned the vehicle identification number (VIN). The vehicle was shipped to TTSI at POLA in February 2019.

TTSI and Kenworth received the vehicle and training was conducted for operators, maintenance staff, and first responders. Operator feedback was positive. The vehicle had minor issues, including oil and fluid leaks, refueling problems, and fuse failures. By June 2019, it had been driven 196 miles in service with TTSI.

The truck continued to operate without fault, completing 20-25 mile routes with varying freight loads (10,000-39,000 lbs.). In late 2019, the truck experienced a boot-up issue and intermittent power steering failure, traced to faulty internal motor wiring. After replacing the HV fuse and wiring, the vehicle returned to service. It ran without technical faults for the rest of the period but had downtime due to a miscommunication regarding hydrogen refueling. TTSI reported the truck completed 1,615.9 miles in 2019.

In 2020, the truck faced limited operation due to COVID-19. The truck operated without major issues, but TTSI's limited freight during the pandemic reduced mileage to only 334.2 miles completed during the first three calendar months. Regular operation resumed by mid-summer 2020, with freight volume exceeding pre-pandemic levels.

Subsequently, the truck experienced minor issues, including blowing a low-voltage fuse, affecting window and mirror controls, which was promptly fixed without downtime. TTSI notified the team that the truck would participate in an Amazon pilot program for one month, operating five days a week,150 miles per day. However, a power steering fault issue, led Amazon to ground the vehicle and return it to TTSI. TTSI's safety team grounded the vehicle until Kenworth resolved the issue.

The two-year demonstration period concluded in February 2021.

CTE's Final Report is included in Appendix A.

Gas Technology Institute (GTI)

Figure 8: Completed GTI HECT Truck

Executive Summary – GTI

GTI focused on the development of a heavy-duty EV truck featuring a near-zero emissions compressed natural gas (CNG) range extender. Designed to transport goods with lower emissions of harmful pollutants and greater energy efficiency than conventional diesel-powered trucks, the Hybrid Electric Cargo Transport (HECT) Truck, seen in **Figure 8**, utilized cutting-edge technologies designed by premier technological suppliers Kenworth Truck and BAE Systems. This collaboration resulted in a truck that is more fuel efficient, environmentally friendlier, and technologically more advanced than then-current commercially available trucks.

The HECT Truck integrates state-of-the-art hybrid technology, including the Motor Controller Propulsion Control System (PCS), Integrated Starter/Generator (ISG), PIM, and System Control Unit (SCU), all taking power in from the CNG engine and the ESS. These systems optimize power delivery to where it is required instantly. The truck also retains the reliability of air, suspension, and brake systems from the Kenworth Body Builder series. The truck was produced and successfully tested by TTSI at POLA.

GTI Development and Demonstration of One Truck

This project aimed to develop a near-zero emission, CNG-hybrid electric cargo-transport prototype truck to assess the commercial viability of Class 8 hybrid tractors, specifically targeting emission reductions in the South Coast Air Basin and surrounding goods movement corridors. GTI, Kenworth, BAE Systems, and CALSART worked together to create a battery-electric truck with a CNG-powered range extender engine. This technical concept combined all-electric and CNG-based operation to provide both zero emissions (all-electric) and conventional hybrid-electric modes. The drivetrain designed for this project offered a combined propulsion power of 320 kW, integrated into a Kenworth T680 tractor.

The HECT Truck is one of the six advanced hybrid vehicles funded by the ZECT II project, which aimed to design, build, and operate hybrid electric technologies from various providers. This system provided a balanced integration of both all-electric and CNG-engine operation to enable zero emissions driving and conventional hybrid-electric operation.

BAE Systems and Kenworth worked on designing the HECT Truck and propulsion system, procuring advanced components and subsystems. Some activities were handled separately while others were done collaboratively.

The HECT Truck features a Cummins-Westport L9N 9-liter natural gas engine producing 230 kW. The engine powers a generator that recharges the 100 kWh battery pack while the vehicle operates. The fuel is stored in an Agility type IV CNG high-pressure storage system, capable of holding 50 diesel-gallon-equivalent (DGE) of compressed natural gas at 3600 psi.

The HECT Truck utilizes two 160kW electric motors, driving a common shaft that connects to an Eaton 4-speed automated manual transmission. The propulsion system operates with power from three sources: the ESS, the Traction Motors, and the CNG engine. Power is collected and distributed as needed for propulsion, ESS charging, or accessories. Power distribution units (PDUs) route the power through fuses, relays, and breakers. Low-voltage power is directed to the Electric Vehicle Propulsion Control System (EVPCS), while high-voltage power is filtered, cleaned, and distributed to vehicle accessories such as the air conditioner, charger, power steering, and air compressor.

The mechanical layout of the propulsion system includes the ESS, PIM, and PCS, along with ancillary devices such as the HV air compressor, power steering pump, and coolant compressor. Components, especially the ESS, were positioned low to achieve a low center of gravity and minimize high-voltage cable length for better energy transfer efficiency. The PCS units were designed for easy access to facilitate inverter servicing.

Cummins-Westport provided and supported its L9N Near Zero Emissions CNG engine, which was paired with the BAE Systems Integrated Starter-Generator (ISG) as the primary range-extender for the truck. Major sub-assemblies were designed and fabricated in parallel, including the 650V high-voltage power steering pump, HV air compressor, AC compressor, AC traction motor (ACTM), Eaton 4-speed automated-manual transmission, Eaton high-voltage distribution unit, and the on-board CNG fuel storage system. The cooling system components were procured while the sub-assemblies were being fabricated.

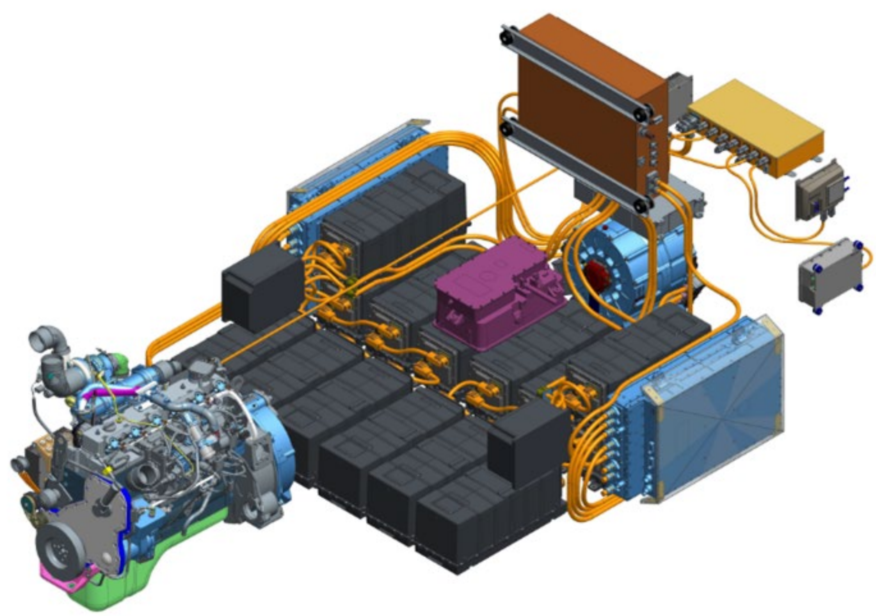

Figure 9: Main propulsion components and batteries; high-voltage hardware

Figure 9 and Figure 10 show the chassis layout (CAD models), depicting the arrangement of various components within the chassis. Space was allocated for the pantograph to allow vehicle design to proceed, though it was never installed. Provisions were made in the CNG on-board storage cabinet to attach pantograph arm supports.

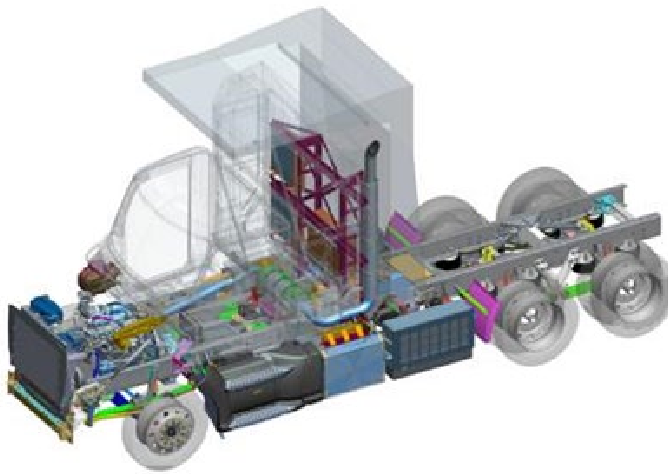

Figure 10: Model of GTI HECT chassis layout

BAE Systems conducted subsystem integration and testing. The power electronics system laboratory was set up to test key components of the propulsion system, such as the Remy (now BorgWarner) ACTMs, Eaton transmission, PIM, PCS, and XPAND battery packs for energy storage. The full propulsion system was installed and characterized in the BAE Systems laboratory to assess performance.

The test block diagrams were developed and executed according to the plan. In the setup, the PCS and PIM received power from the Integrated Starter Generator (ISG) and sent it to the DC Load Bank via a current sensor, while cooling loops were accurately characterized.

Four levels of testing were planned:

- Component testing: BAE Systems' testing of PCS, SCU, ACTM, and HVDP/Filter, as well as supplier testing for the ESS
- Subsystem testing: controller/communication integration, Hardware-in-the-Loop (HIL) integration, and propulsion subsystem integration
- System integration testing: complete propulsion system integration in a lab setting
- Vehicle-level integration: testing of the CNG engine and ISG.

The final phase of vehicle performance testing included tuning, optimization, and final performance validation on a test track.

The truck, equipped with a hybrid propulsion system, was fabricated at Kenworth and preliminary characterization of the CNG engine and generator was completed prior to on-road testing. The vehicle underwent closed-track testing at the Kenworth/PACCAR

Research and Development facility in Washington where both EV and hybrid operation modes, utilizing the CNG/genset range extender, were tested.

To meet the program's goals, the truck was required to meet specific performance parameters, including range, speed, and grade, while carrying a maximum payload of 80,000 lbs. A key aspect of the testing was the gradeability tests, which assessed the truck's ability to climb steep inclines, including the approach to bridges along its typical route at POLA.

The testing at the Kenworth/PACCAR facility included a mix of track testing and simulations based on component test data. These simulations which modeled typical routes, seen in **Figures Figure** 11 **and Figure** 12, were used to further analyze the truck's performance.

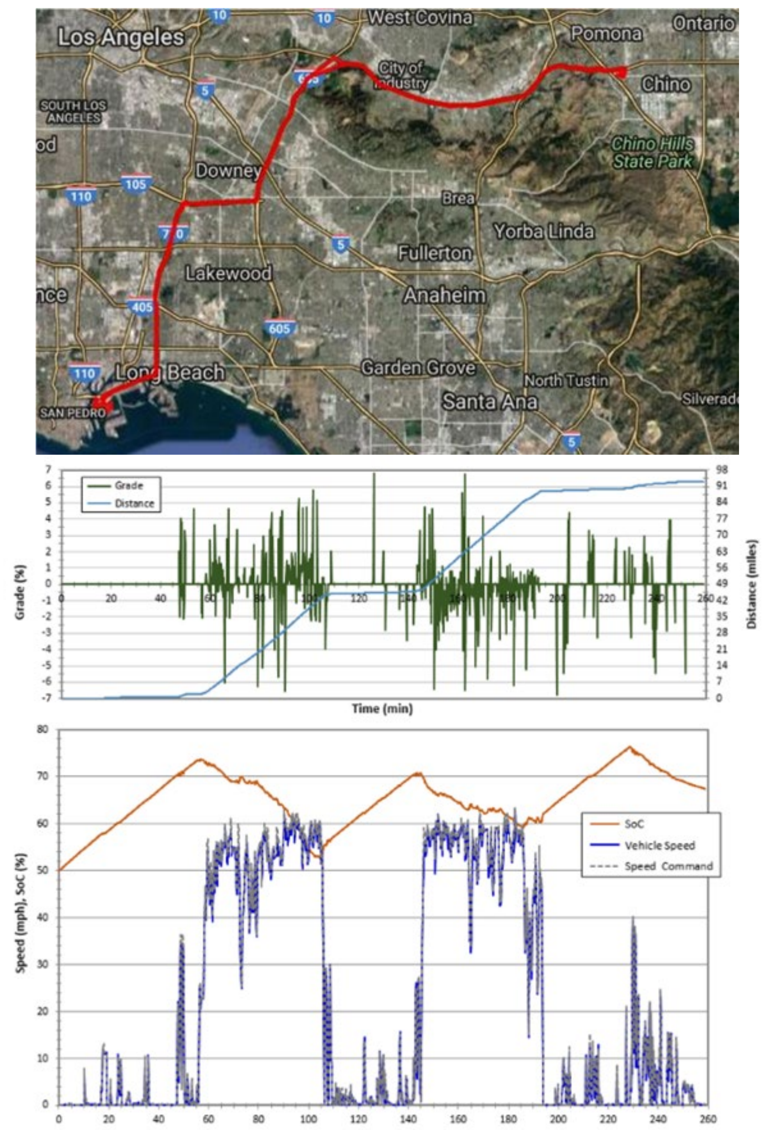

Figure 11: Simulation #1 route to Chino & results

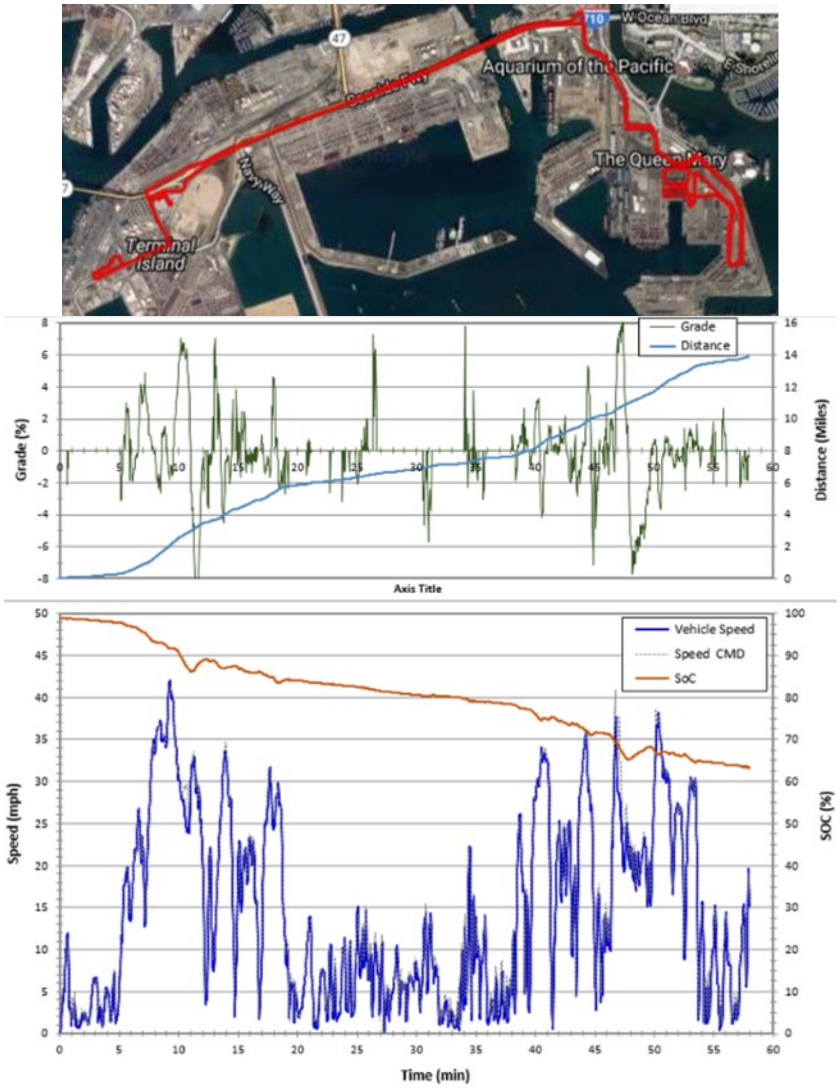

Figure 12: Simulation #2 EV mode in port area & results

Weighing the truck disclosed that the truck's front axle weight slightly exceeded its rating. To address this, a higher-rated axle was installed and tested before the truck was cleared for public road use. The added weight also required an upgrade to the power steering pump to ensure proper wheel turning when stationary.

Another issue identified was a pressurized air leak into the transmission, causing transmission oil to spill from the vent stack during gear shifts. This was traced to a pinhole in a transmission actuator, which was fixed, allowing proper shifting without fluid loss. Minor electrical issues, including faulty connector contacts and mis-wired harnesses, were also found and corrected during assembly. Advanced test harnesses could have reduced such issues, though they are more practical for fabrication of multiple copies of the same truck.

After preliminary testing at Renton R&D, the truck was sent to the PACCAR Test Center (PTC) for further testing, including load tests on the track and rapid mileage accumulation to verify performance and reliability.

Several tests were conducted to assess the truck's operational readiness and reliability. These tests included handling various road conditions such as grades, inclines, declines, start/stop intervals, and handling. In addition to track testing, the truck was tested on local routes to simulate real-world commercial driving challenges. Notable routes included those between the PACCAR Technical Center and the Kenworth R&D Center, which mimicked near-port applications. A hill route with a 9% grade and a stoplight tested the truck's ability to navigate bridges around POLA and POLB. Regional trips over Tiger Mountain and Snoqualmie Pass tested the truck's performance on long hauls, with sustained 5-6% grades and high-speed freeway driving mixed with high-traffic urban conditions.

The testing was designed to simulate a two-year test period rather than ten years of commercial use, while meeting all DOT and Federal Motor Vehicle Safety Standards (FMVSS) requirements for public road certification. Testing took approximately 15 months, completing 3,700 miles of track and road testing in Washington, with reliability targets being met under near capacity loads of 80,000 lbs.

Field testing revealed that the shore power connections and charging system required upgrades. In response, a "smart" shore power charging port was designed, built, tested, and installed on the HECT Truck. This system ensured power was directed only to areas that required it, preventing unused sections from drawing power, such as battery heating during warm nights. The upgraded system also allowed the truck's high-voltage batteries to be fully charged overnight, ensuring the truck started each workday with a full charge, thus extending its range per CNG fill.

Testing of the truck with upgraded transmission software revealed a condition where shifts were unsuccessful. Upon teardown, the electric motor supplier determined that the rotor assembly had not been properly torqued, causing movement under extreme loads. The motors were reassembled with high-strength fasteners, properly torqued, and returned to Kenworth for further testing.

During testing, another issue was discovered with the #2 ACTM''s resolver offset. Each ACTM consists of two motors with their own resolvers. Initial component testing did not identify the root cause of the issue, but software and firmware workarounds temporarily resolved the problem, allowing for further analysis. Eventually, the resolver offset was corrected, and transmission shifting was optimized, resuming track testing.

A challenge during extended testing at the PTC was the absence of a CNG fueling station within 75 miles of the test track. This required towing the truck to and from the fueling station for refueling during rapid mileage accumulation tests. Once the vehicle's reliability improved, it was able to travel under its own power to the fueling station, as seen in **Figure 13**.

Figure 13: GTI HECT Truck at refueling station

Another challenge was identified with the high-voltage distribution box. After several software modifications, the problem was traced to firmware that prevented reliable power switching at the digital power equipment (DPE). The issue required weeks of investigation, several test iterations, and the destruction of multiple DPEs before it was resolved. The firmware was updated and the unit was reassembled, reinstalled, and functionally tested. Performance tests were repeated to verify reliability.

Another challenge involved the power steering assembly, which continued to fault fuses despite software and firmware updates. Additional access ports were added to one unit, allowing engineers to install pressure sensors and measure operating pressures during specific vehicle maneuvers. Once the operating pressures were collected, it was discovered that the pump pressures were lower than expected, leading to operational faults and steering difficulties during dry-park maneuvers. The pump supplier designed and tested replacement pumps, which were delivered to Kenworth for testing.

Another challenge involved a loose high-voltage connection, which damaged the Battery Disconnect Unit (BDU). While replacing the BDU resolved the immediate issue, high-voltage grounding faults persisted. After a thorough investigation, it was determined that a fuse issue within one of the battery packs was the cause. All battery packs were removed, the fuses were inspected, and faulty fuses were replaced before the subsystems were reassembled and returned to service.

Kenworth conducted various tests typically associated with verifying and validating high-volume commercial vehicles, including assessments for aerodynamics and fuel economy. These tests examined airflow under the bonnet, under the fairing, and behind the cab. Fuel consumption was measured at constant speeds of 30, 45, and 60 mph, using routes designed to simulate TIAX, port deliveries, and heavy-duty city circuits (HDCC).

Kenworth conducted a variety of electrical and electronics tests on the vehicle, including EMI/EMR, vibration, environmental tests such as salt fog, water intrusion, freeze-thaw cycle, and checks for fluid compatibility and UV exposure. Additional tests evaluated low- and high-voltage systems, with specific tests on charge limits for shore power, regenerative braking, and generator power.

For noise, vibration, and ride quality, baselines were developed for drive-by noise, vehicle dynamics, and acceleration, braking, and steering responses. Ride and handling were assessed at multiple speeds and vehicle dynamics during lane changes were evaluated.

Powertrain validation included testing efficiency and performance across various grades, maximum starting grade, and the maximum range in all-electric mode.

Tests also included compatible material evaluation for deionized Water Ethylene Glycol (WEG), Finite Element Analysis (FEA) to prevent infant mortality (IM) risks, and scaled durability track testing to verify and validate IM mitigation.

Thermal management tests were conducted on the HECT Truck to assess cooling performance, system conditions under load, de-rate management under maximum load, and energy consumption. Cooling performance was tested by evaluating the capacity and limitations of each cooling loop as well as combined system-level limitations. System conditions under load were examined by collecting temperature data under various load and environmental conditions. De-rate management was tested during maximum load and regenerative braking, while energy consumption was measured during defrost, dehumidifying, cold starts, and high engine RPM during vehicle creep mode.

Key components of the HECT Truck were instrumented with thermocouples to guide thermal system model calibration. Temperatures were evaluated under stressed vehicle conditions, including a test with a GCVW of 80,000 lbs. at 35 mph on a high-speed track at the PTC. Testing was conducted several times, varying the use of cab air conditioning, and including a hot shutdown soak test in direct sunlight. A simulated power failure was performed by removing fuses to circulation pumps and fans, continuing to log thermal data during the key-off period. The results showed maximum temperatures at various locations under these conditions.

Vehicle operations testing included key-on and key-off sequences, E-Stop control, steering, braking (compressor performance and efficiency), acceleration, transmission shifting smoothness, and accuracy. Compliance was verified for SAE J2910, FMVSS 305, ISO 26262, and IEC 61580.

PTC testing identified areas for improvement, particularly in high-voltage fuse reliability for accessory loads, transmission shifting, and electrified accessories. These issues occasionally caused the vehicle to be untestable or resulted in test interruptions, with the need to replace high-voltage fuses due to in-rush current from accessories that were greater than expected.

In October 2019, after testing at PTC and accumulating 3,700 miles, the HECT Truck was delivered to TTSI for on-road testing. Training was conducted for TTSI and Inland Trucking and a fault escalation plan was created and reviewed by the stakeholders. By the end of 2020, the truck had logged 8,835 miles in commercial service.

During that period, two primary data collection tasks were performed. The first involved gathering performance data from the vehicle’s CAN networks, as required by NREL. The second task involved performing in-use emissions testing using a Portable Emissions Measurement System (PEMS) supplied by Sensors, Inc. CALSTART carried out the testing, analyzed and prepared a summary of the results, and prepared a commercialization roadmap and scenario analysis.

The HECT Truck successfully met or exceeded the performance expectations for a high-volume production vehicle. The tests conducted by the Kenworth team showed no significant issues, confirming the truck's compliance with design and performance requirements. However, areas for potential improvement were identified in HV fuse reliability, transmission shifting, and electrified accessories.

Throughout the project, the vehicle underwent extensive testing, with key findings including its performance in commercial service. The vehicle's duty cycles were measured and characterized by CALSTART, with driver feedback indicating the truck was favored for its performance and driver comfort. The fleet operators were confident in the vehicle's reliability, which was demonstrated by significant mileage accumulation, including long-distance trips up to 284 miles in a single day. While the truck faced occasional issues related to novel components (such as sensors, fuses, and the electric air compressor), these were not systemic.

Regarding emissions and fuel economy, the test results showed some improvements over conventional technologies, but were not as conclusive as expected, suggesting the need for further testing under controlled conditions. Additionally, the Cummins-Westport engine used in the vehicle is not optimized for hybrid applications, so with targeted optimization and support from Cummins, further improvements in emissions and fuel economy are anticipated.

Performance Parameter	Expected Performance	Observed Performance
Range	150 miles	284 miles
Top Speed	62 mph	65 mph
Gradeability	6.5% grade at 20 mph 5% grade at 30 mph	~8.5%+ at 20 mph* ~5.5%+ at 30 mph* *(simulation results)
All-Electric Range	20 miles or 1 hour	26 miles
Startability	30% (stretch goal)	20%

Table 2: Performance results

Overall vehicle performance achieved the targets presented, as seen in **Table 2**, with key characteristics like acceleration, range, and gradeability confirmed to be sufficient for the intended service and comparable to conventional diesel vehicles. Kenworth R&D's estimates closely matched the tested results. The HECT Truck's 230kW CNG engine was tested for its ability to maintain 60 mph on a high-speed test track with a flatbed, non-aerodynamic trailer with a GCVW of 80,000 lbs. Testing occurred on a test track with some elevation changes, but no regenerative braking was used.

Gradeability refers to a vehicle's ability to maintain speed while climbing a hill. Since PTC could not conduct off-site sustained hill climbs, it estimated gradeability using torque data and calculations. The analysis involved torque and power curves for continuous maximum load at varying motor speeds, which helped calculate the vehicle's maximum grade ascent at target speeds. The calculations assumed factors like air resistance, rolling resistance, drivetrain efficiency, and tractive force. The estimated gradeability by gear and speed showed acceptable performance.

Startability was tested on two large hills at PTC, one with a 20% grade and the other with a 30% grade. The vehicle was successfully launched on the 20% grade with the target load, though it was unable to start on the steeper 30% hill. Top speed tests were also conducted on the closed track and the vehicle easily reached its target. Additionally, battery temperatures were monitored during a max power test, which ran for 25 minutes at 35 mph, in 75°F conditions, using a dyno trailer to apply full load.

The Powertrain Systems Vehicle Acceleration Through Gears test assessed the acceleration of the loaded vehicle. It included standing-start acceleration to 30 mph, 60 mph, and time over a set distance to determine whether the vehicle could make it through an intersection before the light changes. The HECT Truck demonstrated strong acceleration, surpassing typical diesel trucks, especially in the 0-30 mph range. By 60 mph, the difference in speed between the HECT Truck and a comparable diesel truck had mostly leveled out. Acceleration performance was rated favorably and test results were compared to a Kenworth T680 with an MX-11 engine.

Slow-speed maneuverability is vital for Class 8 trucks, especially those operating in port facilities. A subjective driver-feedback survey evaluated tasks like docking a trailer, hooking up, and backing around corners. Drivers reported high confidence with the HECT Truck, feeling fully in control during all maneuvers. This ease of handling provides an advantage over conventional diesel engines, which rely on a clutch for vehicle motion.

The time needed for the air compressor to charge the air system was another important measure. While conventional trucks take between 120 and 180 seconds to reach full pressure, the HECT Truck required 148 seconds to go from 0 psi to 135 psi. Unlike conventional diesel trucks with fast-idle-control (FIC) to reduce this time, the HECT Truck lacks this feature, though this is not considered a major drawback.

Electrified powertrains offer numerous benefits but not without compromise, especially regarding the transition from diesel engine brakes to regenerative braking for hill descents. Maintaining control of steep grades is crucial for adoption in hilly terrains, but the trucks' large battery capacity offers considerable regenerative braking potential. At test weights of 80,000 lbs. and 65,000 lbs., regenerative braking performance was satisfactory on the high-speed track. However, off-site downgrade performance could not be verified. Additionally, airflow tests under the bonnet, fairing, and behind the cab showed no issues.

The vehicle's strong performance and positive fleet feedback indicate good potential for operator acceptance. Fuel economy and emissions testing generated inconclusive results, suggesting that more in-depth transient emissions testing or chassis dyno cycles were needed to better assess performance and identify optimization opportunities.

GTI's Final Report is included in Appendix B.

Transportation Power (TransPower)

Figure 14: In its first commercial haul, FC1 delivered steel from San Diego Harbor to Otay Mesa – November 01, 2017

Executive Summary – TransPower

TransPower successfully developed and demonstrated two Fuel Cell Range Extender (FCRE) Class 8 battery-electric trucks, which have been utilized in zero emission vehicle cargo movement in real-world demonstrations since 2017, as seen in **Figure 14**. The project has successfully integrated fuel cell and battery subsystems into the trucks, achieving a high level of system integration to ensure safe and reliable operations in drayage tasks. Additionally, the trucks served well for localized deliveries. Continuing development of batteries and drivetrain integrations is needed for powering such hybrid electric high-power vehicles.

Experience with these trucks has highlighted the need for ongoing improvements in components and the importance of matching trucks to their specific tasks. Further, it suggests the need for larger fuel cells for long-range delivery trucks and the need for active cooling of the batteries for trucks working more than single-shift days. ZE goods transport has become the new standard for ports and the beyond, with major truck manufacturers preparing commercial E-products and fuel cell technology gaining increasing market interest.

TransPower Development and Demonstration of Two Trucks

The TransPower electric trucks were built on a diesel chassis that was modified to accommodate electric components. These included a 300kW Motor-Drive System (MDS) with an Eaton truck transmission, which was automated to shift according to motor speed. The trucks also featured a Power Control and Accessory System (PCAS), managing high-amperage 400V power, vehicle control, and electric hydraulic and air supply. High-voltage batteries, capable of providing 300kW of drive power, were also integrated. Additionally, hydrogen fuel storage and a fuel cell Auxiliary Power Unit (APU) were included to maintain the battery charge throughout the day. These components were all controlled by microprocessors, including the System Control Module (SCM) for vehicle control, the Power Control Module (PCM) for transmission synchronization, and the Generator Control Module (GCM) for managing fuel cell operations, cooling, temperature, and power conversion.

TransPower management, while experienced with fuel cell power for transit buses, was new to gaseous fuels and fuel cells. To gain initial experience with the hardware and software requirements, a simple benchtop fuel cell system was set up using a single Hydrogenics HD30 fuel cell. This system included a DC-DC converter, similar to the one that would be used in the truck, to convert the fuel cell output (around 100 volts with hundreds of amperes) to charge a battery. Cooling systems for both the fuel cell and the DC-DC converter were mounted on the side of the bench.

TransPower's engineering team designed the fuel cell-based APU system to be installed in the trucks. The system linked two Hydrogenics HD30 fuel cells to a single large cooling system and a DC-DC conversion electronic system. The system was designed to boost the lower DC voltage from the two fuel cells in series to the nominal 400V required to charge the truck's batteries. Additionally, a second DC-DC converter operated from the high battery voltage to provide the nominal 24V needed to power the APU electronics and cooling systems.

Two distinct cooling systems were used: a high-power system with separate coolant pumps for each fuel cell and a large radiator to manage the 60kW fuel cell's heat rejection at low temperatures (typically 60°C), and a smaller system with an additional pump circulating coolant through the power converters and DC-DC inductors. Separate systems were necessary due to the fuel cell system requiring a low-conductivity coolant (distilled water) and incompatible materials in the DC-DC converters. For instance, copper, commonly used in cooling systems, could not be used in the fuel cell system as copper ions would poison the fuel cell catalysts.

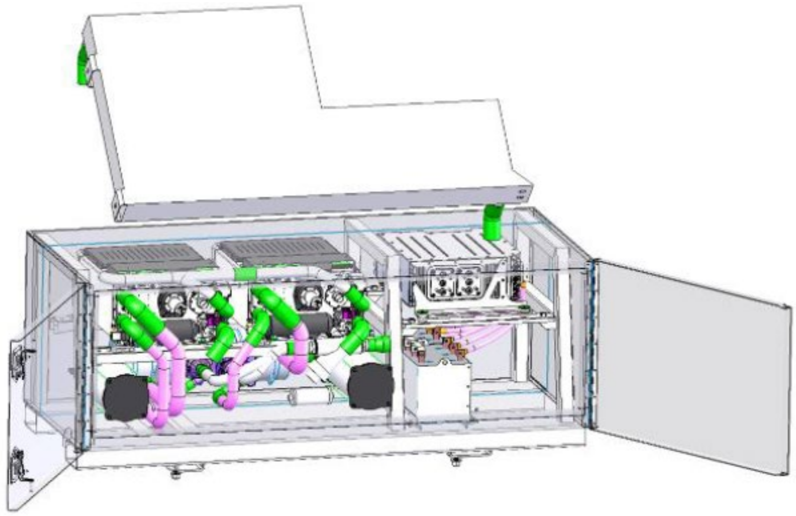

Figure 15: Fuel cell APU design with inverter and cooling package

The truck used four hydrogen storage cylinders, each with a nominal 16" diameter, stacked between the truck cab and the fuel cell APU, seen in **Figure 15**. A1 Alternative Fuel Systems, based in Fresno, CA, integrated the system, with SCI Worthington supplying Type 3 (aluminum liner) cylinders. The system stored 19kg of hydrogen at 350 bar (5,000 psi), providing about 6 hours of operation at 45kW or 9 hours at 30kW, with an expected range of over 120 miles, depending on load and driving conditions.

The truck, a Navistar Prostar conversion, had its wheelbase extended to accommodate the fuel and APU behind the cab. The Power Conversion and Accessory Subsystem (PCAS) was placed under the hood, while the batteries were located beneath the cab sides. The TransPower MDS converted power from the PCAS to driveshaft torque, up to 300kW. The Eaton transmission, driven by dual motors, provided multiple gears for torque and power across the speed range.

The prototype truck's battery design featured high-power-density Lithium Iron Phosphate KAM cells, coupled with a battery management system (BMS) designed by TransPower, which used charge shuffling balancing powered from the batteries.

The prototype truck "FC1" first operated as a battery electric vehicle in June 2017 and switched to hydrogen fuel in mid-July 2017, entering the commissioning phase, as seen in **Figure 16**. During its first month, both fuel cells were replaced. The development of the Generator Control Module (GCM) software, which manages the fuel cells, proved more challenging than expected, as the fuel cell controller would shut down at the slightest disturbance.

Figure 16: The prototype TransPower truck, FC1, about to enter commissioning (shown here without the port side cover for the hydrogen storage)

This process was a learning experience, starting with a single fuel cell bench-top system, followed by the development of the dual fuel cell system for the truck.

One of the notable early experiences was an extended trip with the prototype truck where it was driven on battery power to a shopping mall in Orange County, CA. The fuel cell was then used to recharge the batteries and the truck continued to Long Beach, CA for its first South Coast AQMD appearance, returning on its own power. After several months of fuel cell control coding development, the truck was operational for extended trips under full GCM control. Progress was rapid, but achieving near-full power for the fuel cell operation was only partly completed.

Early tests with a bobtail (the truck only without a trailer) revealed a range of over 200 miles without a trailer. However, the small fuel cell's range extender had limitations. While it worked well for stop-and-go operations like delivery and drayage, it was inadequate for long freeway trips, even without a trailer.

After delivery, the KAM cell battery pack performed well during commissioning but was used sporadically. The TTSI hydrogen fueling facility was not operational and the truck soon experienced failures due to the BMS and cell integration design.

The prototype truck's BMS, used only for the prototype, drew power during active balancing, which caused the battery to discharge. Without being plugged in every few days, the battery would discharge, damaging the cells. As a result, the battery had to be rebuilt, requiring replacement of both the BMS boards and the damaged cells.

Over 1,000 miles of commissioning were completed before the first commercial tow, which occurred in November 2017, delivering steel from the Port of San Diego to Otay Mesa.

Each tractor was equipped with telemetry to track selected parameters via CAN bus communication lines using Viriciti which tracks all trucks, providing real-time data on usage, operational parameters, and vehicle location.

Figure 17: FC2, shown here with trailer during commissioning, entered TTSI drayage service in 2019

Data was recorded during demanding excursions with FC2, shown in **Figure 17**, at 80,000 lbs. GCVW. Several key points emerged from the data: with 80,000 lbs. GCVW, the vehicle experienced severe slowing on the grades, a common issue with this series of trucks. Although the fuel cell genset was generating about 34kW, the battery SOC dropped below 40%, highlighting limitations in the fuel cell's power and difficulty achieving full power output. Additionally, discharge currents exceeded 800 Amps at times, causing the traction batteries to heat up, with temperatures reaching 46°C due to resistance and power dissipation in the BMS. The smaller KAM cell batteries on the prototype resulted in higher discharge rates, making heating a more significant issue compared to larger battery electric vehicles.

The idea of reducing high operating temperatures through a forced air cooling system for the KAM cell packs was considered, designed, but ultimately not implemented. This was mainly due to other challenges, particularly the repeated failure of the packs once the truck transitioned from daily use during commissioning to occasional use after being delivered to TTSI. Additionally, the forced air cooling system, which would have used cabin air to cool the batteries, presented complexity with the entry and exhaust paths to and from the battery boxes, which raised concerns about potential sealing issues in wet weather.

TTSI was TransPower's partner in demonstrating and using fuel cell range extender trucks for drayage service. Although FC1 was delivered in 2017, it did not enter commercial service with TTSI until early summer 2018 due to the need for various certifications and permits (i.e., Manufacturer's Certificate of Origin title, registration with license plate, experimental permit from the CARB for alternative-fueled vehicles, EPA testing exemption, lease agreement between TransPower and TTSI, automotive insurance ID card, VIN sticker, installation of TTSI recorders, RFID, and a safety card for first responders). Fuel availability was also a challenge, with Air Products installing a fueling station in early 2018. Initial reports on the fuel cell truck were favorable; however, reliability issues developed including failures with the battery BMS. If the truck was not used and charged regularly, the active BMS system would deplete the battery through constant balancing discharge, leading to massive battery failures. Additional issues arose with the fuel cell components, where a failure in either of the dual fuel cells would ground the truck. A hydrogen sensor also failed and hydrogen tank valves developed leaks, making necessary the replacement of all tank valves. Also, while TTSI used the truck on the night shift, a power failure occurred, stranding the driver. Despite efforts to replicate the failure, the cause remained unidentified and the truck usage became intermittent. This led to further fuel cell and battery failures, prompting FC1 to be returned to the factory for further testing and upgrades.

Figure 18: One of four battery enclosures mounted to truck FC2, later retrofitted to FC1 as well, shown in test with front cover off

The quality issues experienced with the cylindrical "YHKAM" batteries in the prototype truck, FC1, led to the decision to switch to nickel manganese cobalt (NMC) batteries manufactured by Nissan for the second truck, FC2. While the KAM battery performed well during initial deployment, the extended delays after delivery caused a lack of use, resulting in damage to the battery system. After several months of testing and consultations with Nissan, TransPower determined that the NMC batteries offered a significant improvement in battery quality, BMS, and energy capacity. The NMC batteries also provided better reliability and durability. The new battery enclosure, seen in **Figure 18**, was designed by TransPower and housed the Nissan batteries, which had a total storage capacity of 44 kWh per string. Four such enclosures were installed on FC2, increasing the total battery capacity from 140 kWh to 176 kWh. This upgrade was later retrofitted onto FC1, as seen in **Figure 19**, improving its performance and water ingress protection.

Figure 19: FC1, the prototype of the ZECT trucks, after being upgraded with NiMC storage batteries and the step structure shown below the cab

By early 2020, the upgrade was completed on FC1, making it identical in configuration to FC2. TransPower covered the cost of this battery upgrade for both trucks. The switch from KAM cell batteries to improved NMC batteries in FC2 had a downside: reduced performance at low SOC. The transition from lithium iron phosphate (LFP) chemistry to NMC batteries introduced a softer voltage curve. While the LFP batteries maintained a relatively stable voltage during discharge, the NMC batteries experienced a notable voltage drop, with higher voltages at the start of discharge but a more significant decline at low SOC. This shift in voltage behavior impacted the truck's performance at lower charge levels.

With NMC batteries, discharging from full charge to 30% results in a 14% drop in voltage, which makes vehicle performance more dependent on maintaining a higher SOC. Concerns from drivers were often linked to departing without first charging the batteries, which resulted in poor performance. It is critical for vehicles with NMC batteries to be plugged in to recharge before use unless the service is light enough for the APU to maintain the cell voltages.

During drayage operations, the truck typically operates at low speeds or is stationary, allowing the generator to recharge the battery as needed. The truck is often able to maintain an SOC above 75%, which is typical for this type of use. However, for freeway or long-distance service, maintaining the SOC becomes a more critical issue. The fuel cell's performance limitations, due to the challenges in controlling the Hydrogenics fuel cell engines, were particularly noticeable during longer trips.

Software improvements, along with the new batteries, led to better performance, as seen in the tests on the updated vehicle. Even though the APU power generation initially started low due to the high SOC, it steadily increased, reaching a practical limit of around 43 kW generation rate, which is near the rated 30 kW of the Hydrogenics fuel cell.

While the truck can handle high-speed, high-power use conditions, it is suited for short "sprints" with subsequent recharging either through the fuel cells or the vehicle's plug-in capability. The commissioning drives of FC2 in early 2019 involved several challenging full-load drives, including routes from Escondido to the Rainbow exit on the ridge in northern San Diego County.

By the end of 2020, the prototype truck, FC1, logged 3,790 miles while FC2 logged 7,215 miles. The trucks' availability improved over nearly four years of operation.

The two trucks met most drayage work needs. Drivers were proud to be in the program and accepted the limitations of restricted fuel cell power and range. Although the trucks can achieve over 200 miles of range without a load and 120-150 miles with a load, the power limitation restricts their use to shorter range, moderate-speed hauls.

The trucks have limitations that affect their performance. Firstly, while the trucks perform well at lower speeds (10-20 mph), their fuel cell output power limits their use for long freeway trips, where they can only operate for about an hour. This limits productivity, but the trucks are suited well for multi-shift use or city deliveries with breaks for fuel cell recharge. Despite these challenges, the trucks demonstrated the capability of ZEV cargo transport, towing legal loads, and daily usage with 100-200 miles of range.

TransPower's Final Report is included in Appendix C.

US Hybrid

Figure 20: The H_2Truck displayed at the ACT Expo

Executive Summary – US Hybrid

US Hybrid successfully developed two zero emission Class 8 fuel cell hybrid electric drayage trucks, seen in **Figure 20**, for real-world demonstration at POLA and POLB. Built on International ProStar vehicles with an 80,000 lbs GCVW, the trucks featured US Hybrid's EDU320 powertrain (320 kW) powered by a lithium-ion battery and 80 kW fuel cell generator for continuous operation. Each truck carries 20 kg of hydrogen, providing a range of 150-200 miles. The vehicles were controlled by US Hybrid's Vehicle Control Unit (VCU) using the J1939 CAN Bus protocol for drivetrain, battery, fuel cell, and overall performance management.

US Hybrid Development and Demonstration of Two Trucks

US Hybrid's project aimed to develop and build two Class 8 fuel cell hybrid electric drayage trucks for real-world demonstration with the goal of promoting and accelerating the adoption of fuel cell hybrid electric technologies in cargo transport. Upon completion, the vehicles were to be demonstrated in real-world drayage service for two years with a South Coast AQMD-approved fleet in the Basin.

In 2015, US Hybrid finalized the subsystem design and vehicle layout and ordered two 60-80 kW fuel cells from the US FuelCell facility in South Windsor, CT. The company designed the cooling system for the fuel cell engine, planning a custom, independent cooling system for the traction system, separate from the fuel cell's cooling, using the stock radiator. The electric powertrain for the fuel cell truck featured a gearless, direct-drive high-torque motor to reduce cost and maintenance. Preliminary designs for the battery housing and battery management system (BMS) were created and the company began packaging the vehicle's electric-driven auxiliary systems.

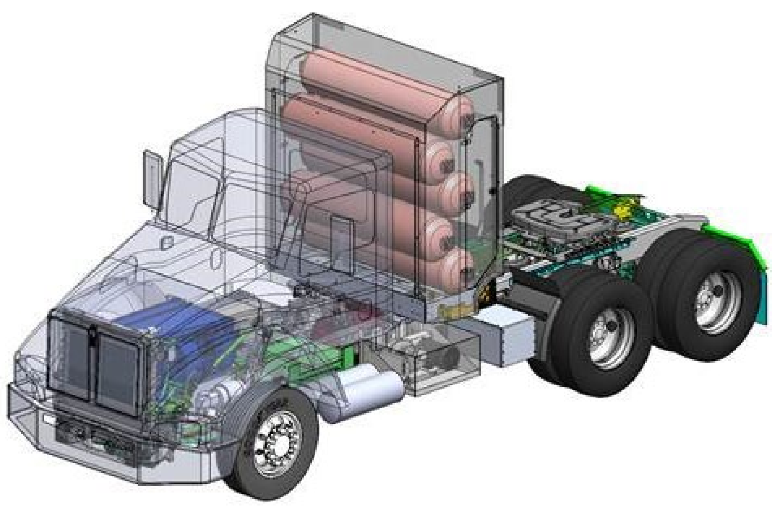

Figure 21: H_2Truck design with fuel cell storage tanks

The US Hybrid team in Torrance, CA and the US FuelCell team in South Windsor, CT continued design, seen in **Figure 21**, material procurement, and vehicle integration work. The vehicle-level design was confirmed and validated and engineers proceeded to subsystem fabrication and testing for H_2Truck #1.

In addition to integration work, testing of the DC-DC power converter was conducted at US Hybrid's Torrance facilities, while the US FuelCell team tested the fuel cell stack. Electric dual-motors were procured for both trucks. US Hybrid also procured hydrogen tanks and completed integration of the hydrogen storage and fill subsystem for H_2Truck #1, seen in **Figure 22**.

Figure 22: H_2 storage tank and fill compartment

In 2016, US Hybrid and US FuelCell designed and optimized the system, procured the materials, and fabricated the components. They received the fuel cell stack from US FuelCell and completed its installation within the stack enclosure on the H_2Truck #1, as seen in **Figure 23**. Many other key components, including water tanks and heat exchangers, were also procured.

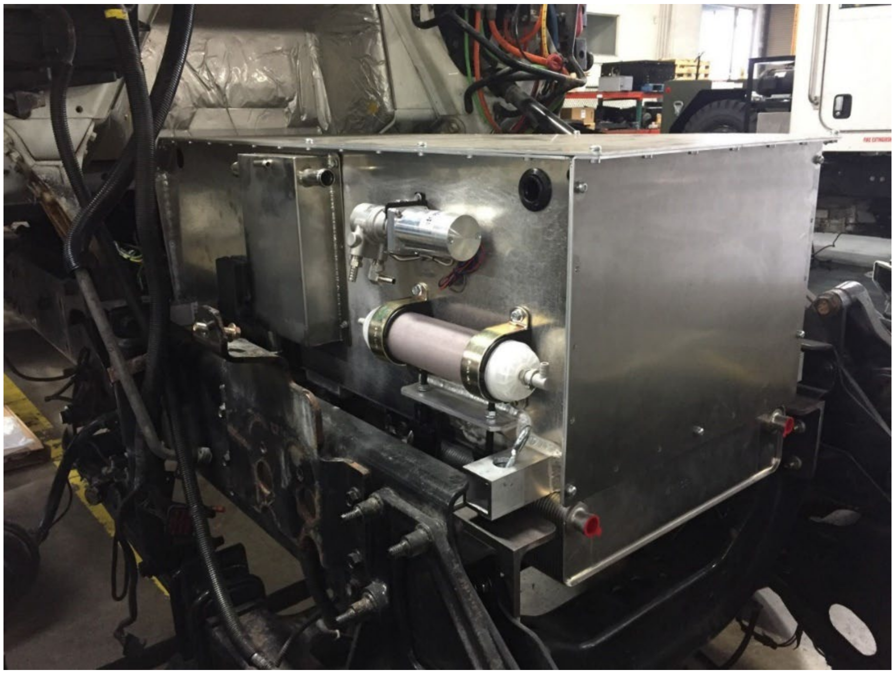

Figure 23: The updated fuel cell power plant in its enclosure

In 2017, the design of the fuel cell enclosure components, including the fuel processing system flow path mount blocks was completed. All components for the fuel cell power plant enclosure were then packaged and shipped to US FuelCell for reassembly and system testing.

The battery and auxiliary box designs were finalized and fabricated. The battery system, consisting of 7 modules and a BMS in series (total 36 kWh rating), was connected in preparation for final enclosure and chassis fit. The power converter components were assembled and prepared for installation into the auxiliary box. Additionally, US Hybrid also received and began software enhancement of the truck's dashboard.

Next, US Hybrid completed the validation of all auxiliary components and the fuel cell power plant cooling system. They also updated the vehicle and fuel cell control strategy following further modeling and optimization.

The FCe™80 fuel cell engine underwent performance and duty cycle testing, with integrated fuel cell engine performance. The data, seen in **Figure 24**, included hydrogen input, regulated DC voltage/current/power output, engine efficiency, and kWh/kg of hydrogen. At this performance level, 1 kg of hydrogen provided the equivalent energy of 180 kg (396 lbs.) of battery weight. The stack performance was expected to decrease by 15% at the end of its life.

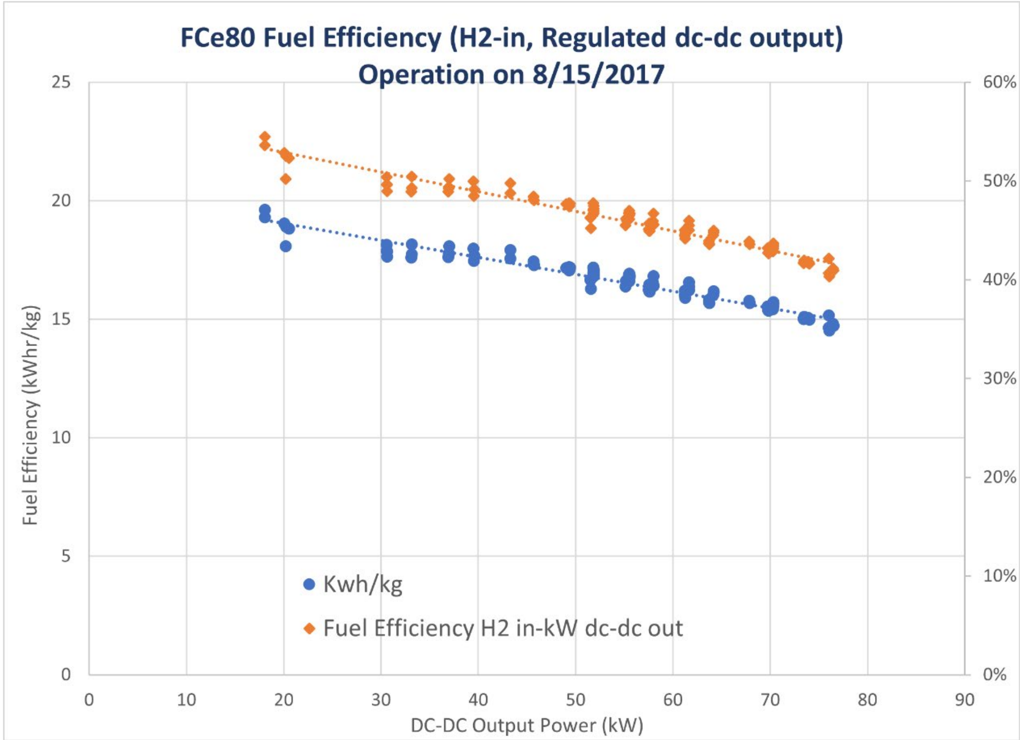

Figure 24: Data showing the FCe™80 fuel efficiency

Partial burn-in testing and validation was performed on the FCe™80, with output power remaining at 80 kW and the isolated DC-DC converter maintaining high efficiency. The FCe™80 underwent additional performance and duty cycle testing as well. The data indicated that the FCe™80, operating at ambient pressure with a high-efficiency isolated DC-DC converter, was the best in its class. Further optimization of the fuel cell engine was still expected.

In 2018, the FCe™80 underwent additional performance and duty cycle testing. The data further confirmed that the FCe™80, operating at ambient pressure with a high-efficiency isolated DC-DC converter, had the highest efficiency in its class globally for mobile applications, with further optimization expected.

The H_2Truck #1 was delivered to TTSI, as seen in **Figure 25**, for initial drive and testing and the fueling interface was validated by fueling from the TTSI station, as seen in **Figure 26**.

Figure 25: The H_2Truck #1 at the TTSI facility

Figure 26: The H_2Truck #1 fueling

H_2Truck #1 was deployed and operated at TTSI, with fuel consumption of 0.17 kg/mile loaded (80,000 lbs. GCVW) and 0.1 kg/mile unloaded (19,000 lbs. curb weight). **Figure 27 and Figure** 28 show performance data for H_2Truck #1 with and without the trailer. The truck was tested with 54,000 lbs. and 80,000 lbs. loads, confirming that it could sustain battery charge for operation at the port and maintain a constant speed of 55 mph using the 80 kW FCe™80 fuel cell engine. Energy efficiency and fuel consumption were quantified and work continued to refine range estimation and driver reporting. Critical operational temperatures and water balance were confirmed. Regarding H_2Truck #2, hydrogen tank assembly and fueling interface were integrated and tested, the electric powertrain was installed, and auxiliary systems, such as the compressor, eHydraulic, and DC-DC converter, were integrated and tested.

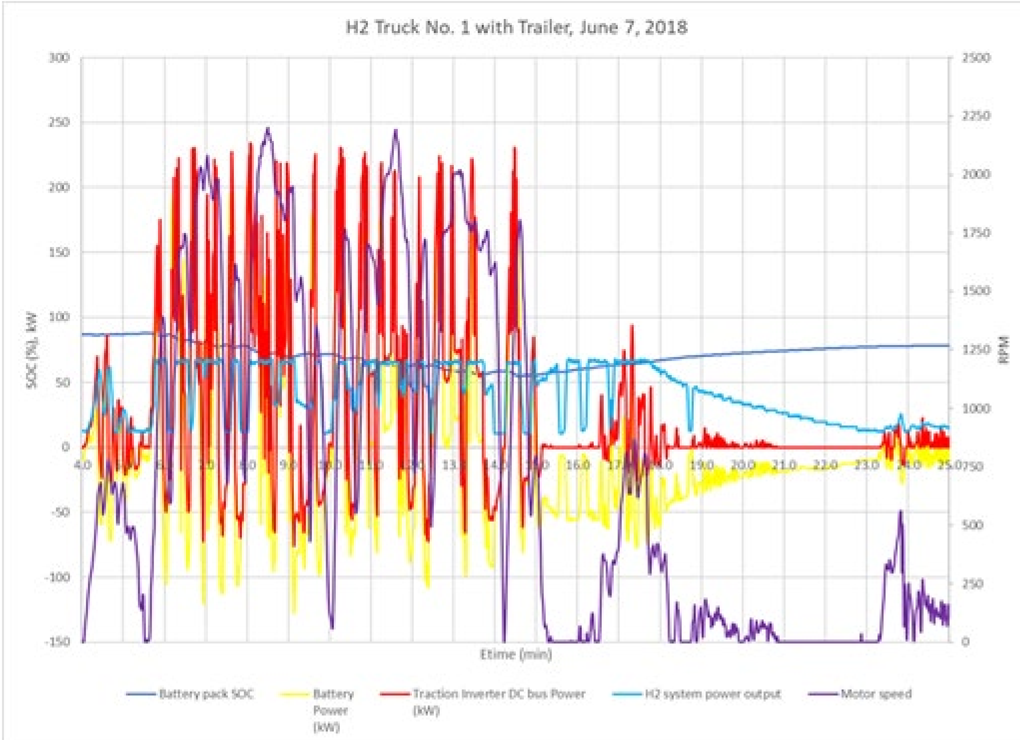

Figure 27: The H_2Truck operation data (battery SOC, power, fuel cell power, speed) with trailer weighing 80,000 lbs.

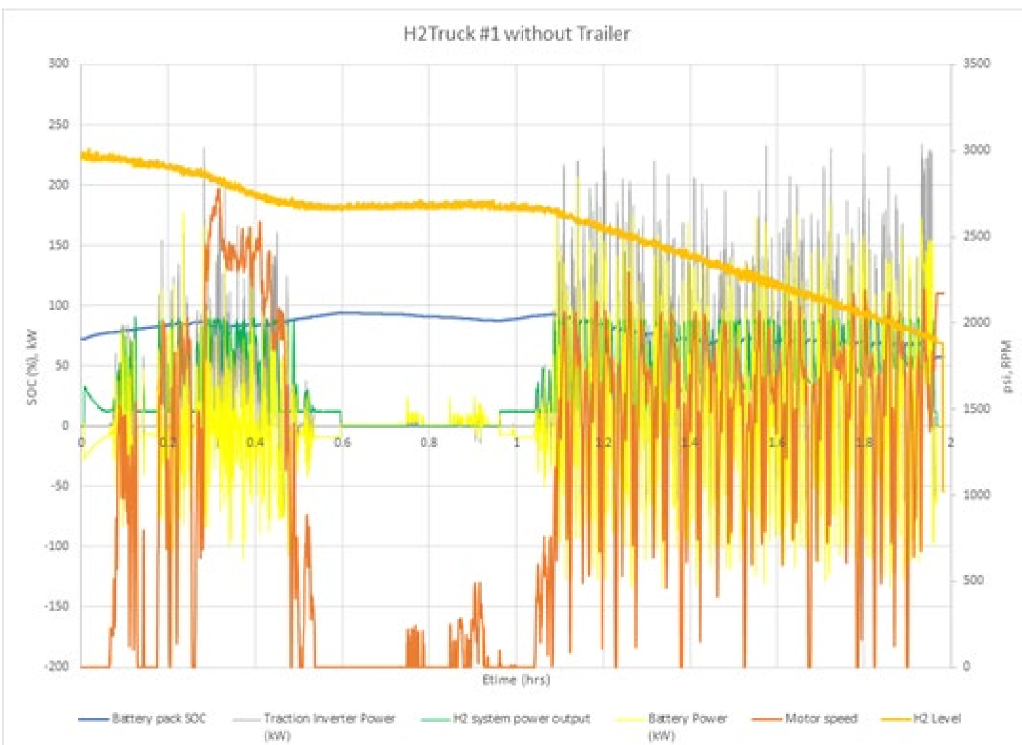

Figure 28: The H_2Truck operation data (battery SOC, power, fuel cell power, speed) without a trailer with a curb weight of 19,000 lbs.

US Hybrid deployed H_2Truck #1 for operation at TTSI, providing the vehicle's Operator's Manual and Service Maintenance Manual. Following deployment of the first vehicle, during in-house testing, corrosion was detected on the vehicle's manifolds, which affected coating integrity. To address the issue, the FCe™80 power plant was sent to US Hybrid's South Windsor, CT facility for manifold upgrades.

During the removal of the fuel cell engine, rust and debris were found in the cooling system, likely due to incomplete flushing or aging of the old radiator, as the system is a repower from a 2012 truck. The cooling lines were replaced and the system was re-flushed to ensure no debris or contamination remained in the cooling system.

US Hybrid completed the manifold upgrades of the FCe™80 powerplant and re-integrated it into H_2Truck #1, which was then returned to operation at TTSI in December 2018. The vehicle's daily report showed the following data:

- Operation hours: 3.3
- kW-hr: 116.0 (CSA) / 108.8 (Engine)
- Amp-hr: 590
- H_2 flow in: 6.31 kg
- H_2 consumed based on Amp-hr: 5.99 kg
- CSA kWhr/kg: 18.4
- FC Engine kWhr/kg: 17.2

With these results, fuel efficiency was calculated, showing that the fuel cell engine's efficiency of 17.2 kWh/kg.

US Hybrid also continued the manifold upgrades of the FCe™80 powerplant for H_2Truck #2. A new battery box for liquid cooling to rebuild the truck's cooling system, including flushing and changing the cooling lines was designed. Based on TTSI operator demand for higher highway speed at 80,000 GCVW, it was recommended to increase the fuel cell engine power to 100kW.

Based on test data from operation, TTSI liked to be able to maintain a speed of 60 mph on the H_2Truck. The 80 kW fuel cell engine was sized for the drayage truck drive cycle duty but, to meet the 60 mph continuous drive demand, battery storage was increased to 40 kWh and the fuel cell engine power was upgraded to 100 kW.

In 2019, US Hybrid completed several tasks, including procuring and fabricating the liquid cooling cold plate and new liquid-cooled battery boxes. The liquid cooling plates were installed on the battery boxes and the traction motor was integrated into H_2Truck #2. Power electronics (drive and auxiliaries) were also integrated into the truck.

US Hybrid then completed the integration of high-voltage and low-voltage wire harnesses, battery (A123, NMC modules with liquid cooling), and power electronics (drive and auxiliaries) in the truck. Once integration was finished, H_2Truck #2 was delivered to TTSI, as seen in **Figure 29**, prior to mid-2019 and operation support for both trucks continued.

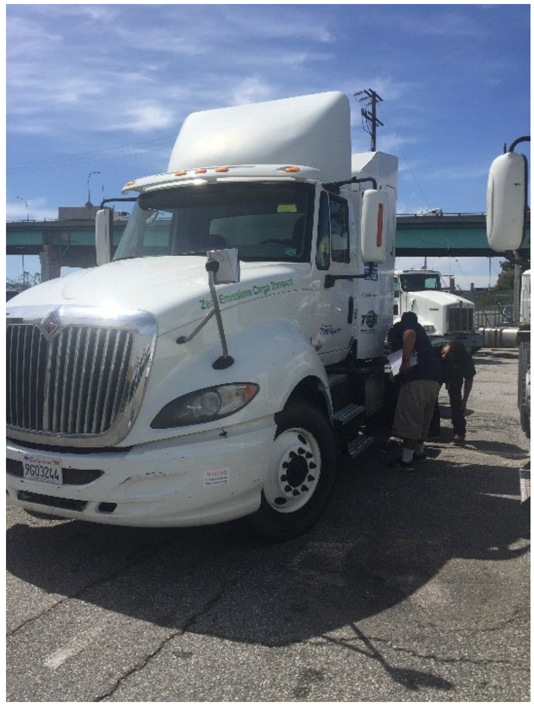

Figure 29: H_2Truck #2 was delivered to TTSI in May 2019

H_2Truck #1 remained deployed for demonstration at the TTSI facility through the end of 2019. The operation data for H_2Truck #1 is shown in **Figure 30** and **Table 3**.

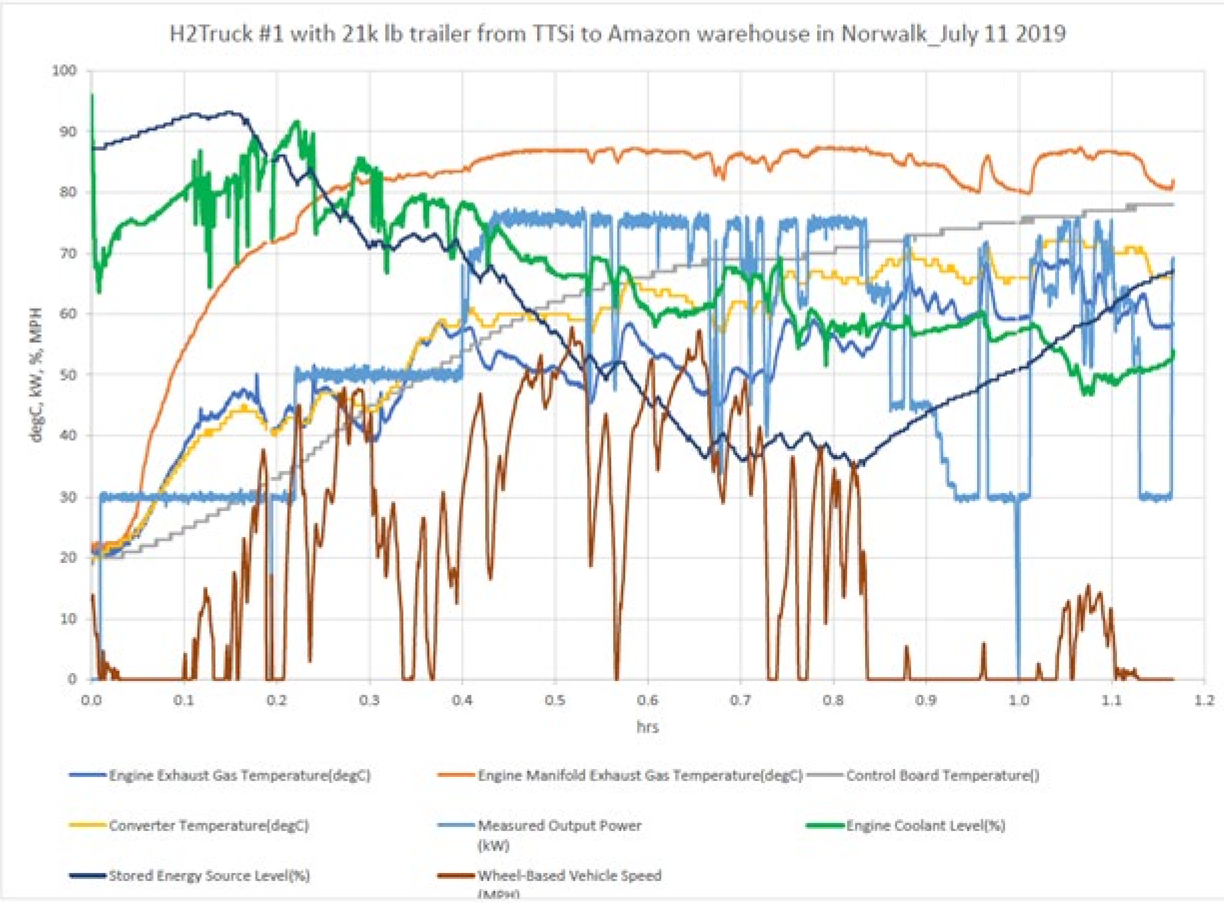

Figure 30: Sample operation data for H_2Truck #1 during demonstration at the TTSI facility (graph)

ZECT 2 H2Truck #1 Performance in Q3, 2019

H2Truck #1	Date	Operated Hours (hrs)	Average Power (kW)	Consumed Energy (kWHr)	Consumed H2 (kG)	Average SOC (%)	Average Speed (MPH)	Distance (miles)	kWHr/mi	kWHr/kg H2	H2 Fueling (kG) 23.5 kg Full
7/11/2019	Thu	2.9	36	107	6.8	77	12.5	37	2.9	15.7	9.1
8/13/2019	Tue	2.3	39	90	4.5	68	12	28	3.2	20.0	14.0
9/18/2019	Wed	5.2	21	109.2	7.9	80	8.6	44.72	2.4	13.8	10.1

Table 3: Sample operation data for H_2Truck #1 during demonstration at the TTSI facility (table)

After being deployed, H_2Truck #2 returned to the Torrance facility due to an issue with its hydrogen valves, which needed replacement as they failed to respond to the "Open" command. After the hydrogen valves were repaired, H_2Truck #2 was redeployed to TTSI in the beginning of 2020 but was not used due to a seasonal downturn. The COVID-19 pandemic led TTSI to suspend all non-essential equipment, including Alternative Fuel Vehicle (AFV) programs.

As operations gradually resumed, H_2Truck #2 was fully operational at TTSI in the closing months of 2020 and used for longer drayage deliveries with major customers.

Two fuel cell trucks were designed, developed, and deployed by US Hybrid for demonstration at POLA and POLB, with TTSI operating the vehicles. Drivers appreciated the smooth operation, especially at low speeds, noting the quiet performance similar to electric trucks. While the demonstration was successful overall, the two-year operation revealed areas for improvement:

1. Battery capacity needed to be increased from 42 kWh to 84 kWh to balance power between the battery and fuel cell.
2. Battery cooling to be implemented as high temperatures limited traction performance.
3. Hydrogen tank capacity to be increased from 30 kg to 60 kg to support the required driving range for two round trips to warehouses east of the ports.

US Hybrid's Final Report is included in Appendix D.

International Rectifier and Others – Efforts to Fulfill Development and Demonstration of One Truck

International Rectifier was to develop a plug-in diesel hybrid-electric Class 8 drayage truck, and ultra-fast chargers for use in or near POLA and POLB. The vehicle concept was to be capable of operating in a zero emissions (all-electric) mode in and around the two ports. Outside that predetermined Zero emissions Zone, the trucks would switch from all-electric to hybrid-electric mode where the vehicle would operate at higher efficiencies to reduce diesel fuel consumption. In late 2016, IR announced that it was being acquired by Infineon Technologies AG. After the acquisition, the new ownership declined to continue developing the truck.

Between 2017 and mid-2024, South Coast AQMD staff and the DOE explored together with numerous truck manufacturers/vendors/developers the fulfillment of the development and demonstration of one (the 7th) heavy-duty truck. Initially, DOE invited Hydrogenics USA, Inc. (Hydrogenics) to join the project and develop a fuel cell range-extended Class 8 drayage truck. Hydrogenics took over IR's commitment by proposing to develop a fuel cell range-extended drayage truck. In 2019, Cummins, Inc. acquired Hydrogenics and also created a wholly owned subsidiary of Cummins, Inc., called Cummins Electrified Power NA, Inc. The Fuel Cell Powertrain Integration Program at Accelera by Cummins made the decision to pivot from the program due to changes in their core fuel cell strategy from low pressure to high pressure products in FCEVs. The availability of the latest high-pressure product essentially did not align with the timing/delivery obligations of the grant at the time. Between March 2023 and July 2024, South Coast AQMD staff and the DOE explored the development and demonstration of the 7th truck with Nikola Motor Company (Nikola), American Honda Motor Co., Inc. (Honda), and AB Volvo (Volvo). Nikola had already initiated FCEV truck production prior to DOE/South Coast AQMD approving them as a replacement vendor, Honda expressed concerns about the data logging process and overall timeline, while Volvo did not qualify under the Build America - Buy America Act requirements set forth by the DOE.

South Coast AQMD PI and co-PI worked closely with the DOE Program Manager on this matter. During their virtual meetings, the DOE PM mentioned that South Coast AQMD has been very successful in this project, completing six of the planned seven truck developments and demonstrations and urged South Coast AQMD staff to proceed with the closeout of this project.

Conclusions and Lessons Learned

The ZECT II project was built upon the success of prior truck demonstration projects, such as the ZECT I project. ZECT I enabled vendors, like US Hybrid, to progress in electric powertrain technology. Demonstration projects like ZECT I and ZECT II provide many lessons that future projects can learn from, including but not limited to vehicle performance or maintenance. Although most challenges were expected, vendors such as TransPower and US Hybrid were able to address issues related to collecting data and new technology improvement issues.

The project experienced typical technical issues such as blown fuses, damaged sensors, data upload technical difficulties but also new technology specific improvement & issues such as software updates, battery disconnect failures, blown internal battery fuses, inconsistent traction motor resolver, transmission shift position sensor issues, fuel cell coolant contamination, cooling system control for fuel cell stack as well as leakage of hydrogen tank valves to name a few. Despite these challenges overall, the project had the following takeaways at the time the ZECT II platforms were completed:

- Drivers provided positive feedback for drivability and performance, but reliability is an issue,
- Supply base is not ready and suppliers do not have broad knowledge in applications,
- Too many connections (high- and low-voltage power systems, CAN network, cooling) and proper routing design are integral to chassis layout,
- Cooling (particularly for fuel cell stacks) is challenging and critical,
- Battery technology and management systems for heavy-duty vehicles are still evolving and maturing,
- Power electronics firmware needs to become more automated, and
- Design validation is required for single larger fuel cell stack and modular multi-stack.

Overall, the ZECT II was deemed a successful project due to the fact that six of the planned seven ZECT II platforms, including fuel cell range extended and CNG hybrid trucks, were successfully designed, built, tested, and demonstrated with drayage fleet operators in transportation corridors within areas of the South Coast AQMD jurisdiction in Southern California such as the in and around the Ports of Los Angeles and Long Beach. Some of these platforms further led to commercial products that are on the market today. Portable hydrogen refueling was deployed to support the fuel cell vehicles. The project had real-time improvement with on-going debugging and optimizations while the vehicles were under demonstration. All platforms demonstrated sufficient or excess power, torque, and gradeability to transport most payloads.

CTE successfully developed one battery electric Class 8 truck with a hydrogen fuel cell engine, which was a success due to its ability to exceed the target range of 112 miles per hydrogen fill by achieving 216 miles and completing 12,000 miles of testing prior to being delivered to the intended operator. The vehicle was also able to achieve a fuel economy of 6.5 mi/dge, which surpassed the baseline drayage truck efficiency of 5.7 mi/dge. With this demonstration project, CTE believed the TRL of the hydrogen fuel cell drayage truck had exceeded their projected TRL and advanced to Level 7 and thus indicated successful prototype demonstrations in real-world operating environments. Overall, the CTE truck drove a total of 3,039 miles during this demonstration.

GTI successfully developed a near-zero emission, CNG-hybrid cargo-transport prototype that received feedback from drivers that the truck was favored for its performance and driver comfort, where drivers were confident in the vehicle's reliability. As part of this project, GTI designed a "smart" shore power charging port that ensured efficient use of power and prevented power being directed to unnecessary sections. The upgraded system also allowed the vehicle's batteries to be fully charged overnight, thus extending its range per CNG fill. The vehicle was able to outperform expected goals for long-distance trips by achieving up to 284 miles in a single day. This project also demonstrated that the truck met other specific performance parameters, including speed and grade, while carrying a maximum payload of 80,000 lbs. Overall, the GTI truck drove a total of 8,835 miles during this demonstration.

TransPower successfully integrated fuel cell and battery subsystems into two trucks, achieving a high level of system integration to ensure safe and reliable operations in drayage tasks. Drivers provided feedback that the vehicles had smooth and quiet operation and power responsiveness. The two trucks met most drayage work needs and demonstrated the capability of zero-emission cargo transport by towing legal loads with a daily usage of 100-200 miles of range with no emissions other than water. The two trucks, FC1 and FC2, drove a total of 3,790 and 7,215 miles, respectively, during this demonstration.

US Hybrid's development of two fuel cell trucks was a success since both trucks were deployed for demonstration at the ports and achieved target values for various operating parameters. Each truck had approximately 20 kg of hydrogen storage on board to provide the targeted operating range of 150 miles, even surpassing that goal for an estimated range between 150 to 200 miles in drayage operations. The trucks were also able to achieve the goals of reaching a maximum speed of 55 miles per hour on level ground, energy efficiency of less than 3 kWh per mile, and a refuel time ranging between 10-15 minutes for hydrogen.

Since the ZECT II project first started, there has been a significant evolution in zero and near-zero Class 8 truck technologies. The ZECT II project pushed the envelope on zero emission technology and demonstrated the first fleet of fuel cell electric and plug in hybrid electric vehicles in drayage and Class 8 service in California. It was also the first of its kind to demonstrate the commercial viability that supported the additional technology breakthroughs for Class 8 zero emission trucks and validations as well as regulatory basis for all the zero emission regulation that we know today, such as the Innovative Clean Transit regulation, Advanced Clean Trucks and Clean Fleet regulations as well as California Governor Newsom's Executive Order N-79-20 for 100% ZEV sales by 2035 that included Class 8 zero emission drayage trucks. The ZECT II demonstration project was an important step that has inspired and led to subsequent demonstration projects such as the Volvo Low Impact Green Heavy Transport Solutions (LIGHTS) project that has resulted in the full commercialization of the Class 8 Volvo VNR electric; the Daimler Innovation Fleet and Daimler Customer Experience Projects that has resulted in the commercial launch of the Daimler Class 8 eCascadia. Zero-emission demonstration projects have evolved into pilot deployment projects such as the Joint Electric Truck Scaling Initiative that supports the scaled deployment of 100 Class 8 battery-electric trucks at two sites with supporting infrastructure in Southern California overburdened communities. For With regard to fuel cell technology, the NorCAL Zero-Emission Regional and Drayage Operations with Fuel Cell Electric Trucks project is currently underway in the Port of Oakland, that performs a similar scaled deployment with 30 Class 8 fuel cell trucks manufactured by Hyundai. At this time, South Coast AQMD administers a series of smaller scale fuel cell deployment projects with Hyundai. None of these subsequent landmark projects could have happened without the successes of the ZECT II demonstration project.

Today, over 162 medium and heavy-duty ZEV models are available on CARB's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) list with many more new OEMs seeking to release new truck models.

Appendices

A FINAL REPORT – Center for Transportation and the Environment

FINAL REPORT - Center for Transportation and the Environment.pdf

B FINAL REPORT – Gas Technology Institute

FINAL REPORT - Gas Technology Institute.pdf

C FINAL REPORT – Transportation Power

FINAL REPORT - Transportation Power.pdf

D FINAL REPORT – US Hybrid

FINAL REPORT - US Hybrid.pdf

ZECT Drayage Truck Project

Final Report

Contractor: Center for Transportation and the Environment (CTE)

SCAQMD Contract Number: 15635

Project: Zero Emission Electric Drayage Truck with Fuel Cell Range Extender

Date Report Submitted: April 30, 2021
Reporting Period: April 27, 2016 - April 15, 2021

Company Technical Point of Contact:
Name: Jason Hanlin
Title: Director of Technology Development
Email: jason@cte.tv
Phone: 404-808-6489

Subcontractor(s):
PACCAR Inc. (Kenworth) – Vehicle OEM and Integrator
BAE Systems plc (BAE) – Propulsion System Supplier and Integrator
Ballard Power Systems – Fuel Cell Supplier
Total Transportation Services Incorporated (TTSI) – Vehicle Operator
Air Products Inc. – Hydrogen Fuel Supplier

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Acronyms and Abbreviations

ACTM	AC Traction Motor
AHJ	Authority Having Jurisdiction
APS	Auxiliary Power System
BMS	Battery Management System
CEC	California Energy Commission
CLAW	Control Laws
CTE	Center for Transportation and the Environment
DAQ	Data Acquisition
DOE	Department of Energy
EERE	Energy Efficiency and Renewable Energy
EET	Electric Transportation Technologies
EISA	Energy Independence and Security Act
ESS	Energy Storage System
EV	Electric Vehicle
EVPCS	Electric Vehicle Propulsion Control System
FC(E)	Fuel Cell (Engine)
FCTO	Fuel Cell Technologies Office
GVW	Gross Vehicle Weight
HSS	Hydrogen Storage System
HV	High Voltage
kg	Kilogram
kW	Kilowatt
LV	Low Voltage
OEM	Original Equipment Manufacturer
PDU	Power Distribution Unit
PEM	Proton Exchange Membrane
PIM	Power Interface Module
PMP	Project Management Plan
SCAQMD	South Coast Air Quality Management District
SCU	System Controller Unit
SOC	State of Charge
TRL	Technology Readiness Level
VMEC	Vehicle Master Events Controller
ZECT	Zero Emission Cargo Transport

Executive Summary

The following report describes the design, build, and demonstration work associated with the ZECT II Fuel Cell Drayage Truck project sponsored by South Coast Air Quality Management District (SCAQMD). The team achieved the primary goal of the project, which was to make significant strides developing zero-emission technologies for heavy-duty Class 8 trucks that would accelerate the improvement of air quality in southern California transportation corridors. This vehicle's architecture blended existing zero-emission battery electric technology with a zero-emission hydrogen fuel cell engine acting as a range extender to create a zero-emission drayage truck. Project team members included the Center for Transportation and the Environment (CTE), Kenworth, BAE Systems, Ballard Power Systems, and Total Transport Solutions Inc. (TTSI).

The project scope was split into two phases. During Phase I, the project team completed the design, build, test, and delivery of the prototype fuel cell hybrid electric drayage truck. The team also procured hydrogen and established a hydrogen fueling station for the use of all three SCAQMD drayage truck teams. Phase II focused on the deployment, operation, and maintenance of the drayage truck. The team also provided truck operation and fueling station data to National Renewable Energy Laboratory (NREL) in accordance with their requirements. The truck was delivered to TTSI on February 4, 2019 and operated from February 15, 2019 through February 15, 2021 at TTSI.

The vehicle platform is a Kenworth T680 model heavy duty class 8 chassis that can be used in drayage applications and is capable of moving the drayage loads up to the full GVW of 80,000 lb. The custom chassis and modular platform provided simple packaging and layout of hybrid specific components such as traction motors, batteries and power converters. The vehicle stores 25 kg of usable hydrogen in a 350 bar composite tank and is powered by Ballard's HD85 85 kW (net) proton exchange membrane (PEM) fuel cell for load levelling and range extension. The target vehicle range was 112 miles on a single fill of hydrogen gas, and the vehicle achieved a range of 216 miles and completed 12,000 road and track miles at Kenworth's Research and Development Center in Renton, WA prior to delivery to TTSI.

The team collected vehicle performance data throughout the demonstration and compiled, analyzed, and reported on key performance indicators. The vehicle traveled a total of 3,039 in-service miles and consumed 521 kg of hydrogen over the course of the demonstration, indicating an overall fuel economy of 6.5 miles per diesel-gallon-equivalent (mi/dge) compared to the baseline drayage truck efficiency of 5.7 mi/dge.

The vehicles were maintained by the project team throughout the demonstration. The vehicle experienced typical issues for a demonstration project, and several examples are discussed in this report. The project team provided TTSI personnel with written documentation on vehicle operation and maintenance, as well as on-site training. TTSI personnel operated vehicles in typical revenue

operations including fueling the vehicles. TTSI also performed periodic visual inspections of the vehicle systems.

The largest strides in Technology Readiness Level (TRL) were gained by the overall vehicle design and architecture. The hydrogen fuel cell drayage truck TRL prior to this project was at a strong Level 4 with several proof-of-concept vehicles constructed by previous researchers. Similarly, MRL of these vehicles was at Level 4- with identification of manufacturing concepts and fabrication of vehicles in laboratory or research environments. With this demonstration project, the research Team believes it has advanced the TRL of the hydrogen fuel cell drayage truck to a Level 7 (out of 10) with prototype demonstrations in operating environments.

Project Introduction

Background

The Fuel Cell Technologies Office (FCTO) is a key component of the Department of Energy's (DOE) Energy Efficiency and Renewable Energy (EERE) portfolio. The FCTO aims to provide clean, safe, secure, affordable, and reliable energy from diverse domestic resources, providing the benefits of increased energy security and reduced criteria pollutants and greenhouse gas emissions.

On April 29, 2014, DOE released *DE-FOA-0001106: Zero Emission Cargo Transport (ZECT) Demonstration*. This funding opportunity sought "to focus on accelerating the introduction and penetration of Zero Emission Carbon Transportation (ZECT) technologies." The FOA defined ZECT technologies as, "those that produce zero emissions from the transport vehicle (or other equipment) which propels cargo for all or large portions of their duty cycle."

South Coast Air Quality Management District (SCAQMD) wrote a proposal combining the DOE funding with funding from the California Energy Commission and the Ports Technology Advancement Program. SCAQMD proposed to build and demonstrate trucks from three different teams as well as provide a single fueling infrastructure for all three teams. The Center for Transportation and the Environment (CTE) partnered with BAE Systems (BAE); Kenworth, a division of PACCAR (Kenworth); Total Transportation Services (TTSI); Ballard Power Systems (Ballard); and World CNG to form one team for this project. The other two teams are led by Transpower and US Hybrid.

On February 15, 2016, SCAQMD executed a contract with CTE to lead the team developing the Kenworth/BAE truck as well as the fueling infrastructure for all three teams. Before the project was underway, World CNG, the integrator for the project, filed for Chapter 7 bankruptcy. Rather than bring in a new integrator, CTE and the project team elected to move the integration work to Kenworth and BAE.

Project Partners, Roles, and Bios

CTE, Kenworth, BAE Systems, Ballard Power Systems, and Total Transportation Solutions Inc. (TTSI) formed a team to respond to the DOE FOA.

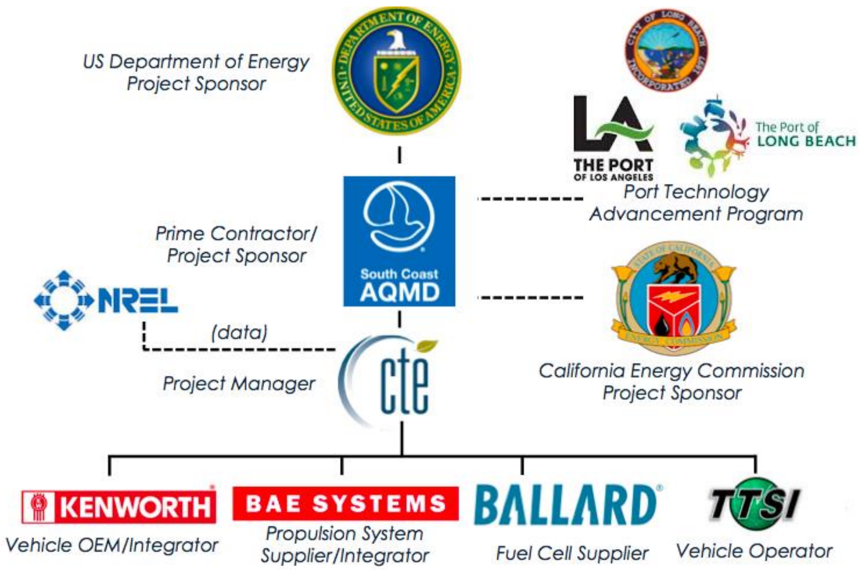


Figure 1. Project Organization Chart

Center for Transportation and the Environment (CTE) – 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. CTE collaborates with federal, state, and local governments, fleets, and vehicle technology manufacturers to advance clean, sustainable, innovative transportation and energy technologies. CTE has demonstrated experience in all aspects of developing and deploying medium- and heavy-duty fuel cell vehicles, equipment, and the hydrogen fueling infrastructure to serve them. CTE also has offices in Berkeley, California, Los Angeles, California, and St. Paul, Minnesota.

Kenworth Truck Company (PACCAR) – Kenworth Truck Company, a U.S. company, is a global manufacturer of custom medium- and heavy-duty trucks for the North American market. In business since 1923, Kenworth has established a reputation as a leader in developing aerodynamic and alternative fuel vehicles with a goal of improving fuel efficiency and reducing both criteria and greenhouse gas emissions in the trucking and freight industries. Kenworth's green-fleet product line includes aerodynamic trucks, compressed and liquefied natural gas trucks, and medium and heavy duty commercial electric vehicles.

BAE Systems plc – BAE Systems is a global defense and security company with approximately 100,000 employees worldwide. The company delivers a full range of products and services for air, land, and naval forces, as well as advanced electronics, security, information technology solutions and customer support and services.

Ballard Power Systems – Ballard Power Systems is headquartered in Burnaby, British Columbia, Canada, where the company operates a high-volume proton exchange membrane (PEM) fuel cell manufacturing facility, as well as a fully equipped R&D engineering and test facility. Ballard also has sales, R&D, and manufacturing facilities in Denmark, the United States, and Mexico. Ballard designs and manufactures market-leading clean energy proton exchange membrane (PEM) fuel cell stacks, power modules as well as complete systems for both stationary and motive power applications. To date, Ballard has designed and shipped close to 150 MW of hydrogen fuel cell products.

Total Transportation Services Incorporated (TTSI) – TTSI is a large freight transport company based in southern California, with a fleet of 168 heavy-duty drayage trucks serving the Ports of Los Angeles and Long Beach. TTSI is recognized as a leader in using clean propulsion technologies in its operations. Its port fleet consists of 57 LNG Kenworth trucks and 111 trucks that burn low-sulfur diesel fuel. It was the first drayage operator to place into service LNG tractors at the Ports of Los Angeles and Long Beach. In 2013, it began testing an early prototype zero-emission fuel cell-electric Class 8 heavy-duty truck. The company is dedicated to working with technology companies and the trucking industry to achieve a commercially viable zero-emission truck capable of handling a GVWR of 80,000 lbs. in its daily operation.

Air Products, Inc. – Air Products is one of the world's leading hydrogen suppliers. As a company operating in over 40 countries for over 70 years, Air Products has built leading positions in key growth markets. With annual revenues of up to $10 billion and operations in over 40 countries, the company's employees build lasting relationships with their customers and communities based on understanding, integrity and passion. Corporate headquarters are located in eastern Pennsylvania's Lehigh Valley, near Allentown.

Project Objectives

The goal of this project is to build a robust zero-emission, heavy-duty Class 8 drayage fuel cell truck that can effectively demonstrate reliable service transporting up to 80,000 lbs. on multiple service routes with differing duty cycles. The intent is to leverage the success of tier one technology companies experienced at building fuel cell, hybrid-electric propulsion systems for heavy-duty transit buses. Working in partnership with Kenworth, a division of PACCAR and a leading heavy-duty truck OEM, the project engineered and built a prototype vehicle that was then demonstrated and evaluated over a 24-month deployment on regularly scheduled routes serving outlying communities off the I-710 freeway in Los Angeles. Performance and operations data collected during the demonstration phase will help identify the pathways and barriers to commercialization.

Project Relevance and Outcomes

The project's vehicle architecture provides the following benefits:

- A system that is easily packaged into current fleet and custom over the road vehicles.
- Technology and components that are currently in operation and have been fully integrated into and demonstrated in the heavy-duty hybrid transit bus market.
- An integration team that has been working together for over two decades and has world class experience, expertise, and excellence in integration of the technology.
- A system and architecture that can be easily scaled and sized for a variety of bus and truck (Class 5 – 8) platforms.
- The system architecture provides a redundant and fault-tolerant system from the power source to the electric drivetrain.

The proposed architecture for the zero-emission drayage trucks helps the ports implement zero-emission technology that meets the performance and operational needs of drayage vehicles. The project also supports the goals of state regulatory bodies that seek to reduce or eliminate emissions from the most used vehicle in the ports and in the I-710/CA-60 and I-10 corridor.

Project Approach

General Approach

The purpose of this project is to accelerate deployment of zero-emission cargo transport technologies that reduce harmful diesel emissions, petroleum consumption, and greenhouse gases in surrounding communities along goods movement corridors. To achieve this purpose, the project team developed a zero-emission battery electric Class 8 drayage truck with a hydrogen fuel cell range extender. This prototype truck then demonstrated its use in goods movement operations between the Ports of Los Angeles and Long Beach and the near-dock rail yards and warehouses.

To develop the initial truck prototype, the project team adapted a hybrid electric fuel cell propulsion system that is currently used for transit buses so that it was suitable for a Class 8 truck used in a drayage application. The power output of the electric drive train is two electric motors with 270 kW combined power output, comparable to a current Class 8 truck engine's power output. One AC traction motor was mounted on each rear drive axle, and the electric drive train was designed to be fully redundant. The vehicle operates using 100 kWh Li-ion batteries, engaging the 85 kW (net) fuel cell system only when the batteries reach a specified state-of-charge (SOC). The hydrogen storage capacity is 30 kg (25 kg usable), which will provide approximately 112 miles of range between refueling.

The project team demonstrated the vehicle with a drayage operator, TTSI, for two years between the Ports of Los Angeles and Long Beach, warehouses, and near-dock rail yards. Performance and operations data were collected, analyzed, and reported during the demonstration period. Air Products provided the hydrogen fuel for the demonstration period via on-site tube trailers that were periodically refilled.

CTE was responsible for project management including overall project oversight and day-to-day project management activities. Project management activities included but were not limited to developing and executing a project management plan; providing independent third-party analysis and evaluation of data collected and reported during project duration; and verifying and validating the status of costs, budget, milestones, decision points, and schedules. BAE and Kenworth co-led the vehicle design and build during the development phase. They also provided technical assistance and advisory support for data collection and project support throughout both phases. Ballard provided the fuel cell system and also supported BAE and Kenworth during integration.

Technical Approach

Task 1: Project Management for Phase 1 (Vehicle Development)

Tasks Summary: CTE managed the first phase of the project: building the prototype vehicle, successfully testing vehicle performance, and preparing the vehicle for delivery to the drayage operator.

Task Details:

- CTE managed and coordinated all subcontractor activities.
- CTE maintained project schedule.
- CTE managed cash flow requirements.
- CTE managed risk associated with the project.

Task 2: Project Management for Phase 2 (Demonstration and Data Collection)

Tasks Summary: CTE managed the second phase of the project to demonstrate the daily service of vehicle while working with the drayage operator and subcontractor to ensure continued operation and data collection throughout a two-year demonstration.

Task Details:

- CTE executed the transfer of prototype vehicle to drayage operator.
- CTE executed operations plan with drayage operator.
- CTE implemented data collection plan and procedures to collect data.
- CTE oversaw ongoing operations and data collection.
- CTE resolved problems to maximize in-service operation during the two-year demonstration period—maximize vehicle miles traveled.

Task 3: Establish Contracts

Tasks Summary: CTE notified all teammates of grant award, negotiated and contracted with each teammate for their scope of supply, and issued notices to proceed.

Task Details: The teammates on this project proposal were sent notice of award letters and were asked to confirm their quotes and schedules for the scope of this project. Each quote was negotiated and finalized and a contract was put in place for the various scope of supply with the respective teams. In addition, the grant for this project required 50% cost share, and several organizations pledged cost share as funding or as in-kind effort. Those pledges were confirmed by requesting written confirmation of their cost share obligation. The contracts were established utilizing top level project plan.

Task 4: Define Project Plan

Tasks Summary: Once all contracts were in place, CTE converted the proposal project plan into a detailed, integrated Project Management Plan.

Task Details: CTE detailed the high-level project plan provided in the schedule to show key milestones, hand-offs, reviews, long lead procurement items, key integration, and vehicle drive test tasks and clearly represented cost share tied to respective milestones. CTE then compiled these details into a master schedule and submitted as a project plan to SCAQMD.

Task 5: Vehicle/System Design

Tasks Summary: In this task, Kenworth, BAE Systems, and TTSI focused primarily on the design effort related to developing the truck with the proposed zero-emission system technology.

Task Details:

- Kenworth/BAE Systems collaborated to develop vehicle mechanical layout and installation drawings.
- BAE Systems and TTSI verified and updated the duty cycle and system usage.
- Kenworth/BAE Systems performed required analysis to verify performance based on duty cycles developed.
- Kenworth/BAE Systems performed system and vehicle weight analysis and verify conformance to established highway and TTSI standards.
- BAE Systems defined the cooling system requirements.
- BAE Systems developed and verified controls through simulation in lab environment.
- Kenworth identified a cooling system based on requirements provided by BAE Systems.
- BAE Systems defined energy storage capacity, fuel storage capacity, and vehicle range.

Task 6: Long Lead Items Procurement

Task Summary: Once the design was accepted and agreed upon, the respective members of the team commenced long lead items procurement to start mechanical integration.

Task Details:

- Kenworth started procuring vehicle mounts and brackets required for all vehicle components.
- BAE Systems started procuring propulsion system components and energy storage system.
- Kenworth procured cooling system.
- Kenworth supplied truck to be modified.
- Kenworth supplied electric accessories.
- Kenworth/CTE procured fuel cell engine and hydrogen fuel storage system.
- CTE led pre-production meeting to ensure specifications are reviewed, production plan is well-coordinated among team members, and team is ready to start production.

Task 7: Secure H2 Fuel Supply for Testing

Task Summary: In parallel with the onset of long lead item procurement, a final determination was made concerning the source of fuel and the ideal location to support the testing program in Mt. Vernon, Washington. A fueling plan was executed.

Task Details:

- CTE to identify fueling options and sources of fuel.
- CTE/Kenworth to decide on the best option for fueling, location, and fueling logistics to support testing program.
- CTE to procure fuel supplier.
- CTE to submit permitting application to AHJ.
- Fuel supplier to set up hydrogen fueling station.
- CTE to establish fueling protocol to govern fueling operation.

- CTE and fuel supplier to conduct training for Kenworth and BAE personnel and first responders.
- CTE to ensure commissioning of hydrogen fueling station.

Task 8: Lab Integration of Sub-System Components

Task Summary: All major subsystems were integrated in a lab environment to verify operation, define and validate controls, mode and fault logics, communication and full hardware-in-loop system of system integration.

Task Details:

- BAE to set up lab to integrate the electric propulsion system with the fuel cell engine and cooling system.
- BAE to develop and integrate controls and mode/fault logic in lab.
- BAE to develop system level test plan for lab test.
- BAE to demonstrate system operation in lab environment to validate controls and mode logic.
- BAE to verify all communications and fault logic.

Task 9: Vehicle Mechanical Integration

Tasks Summary: Kenworth received key components and installed the components in alignment with the approved vehicle 3D CAD model.

Task Details: All major subsystems including but not limited to electric propulsion, fuel cell engine, energy storage, cooling system, fuel storage system and electric accessories were delivered to Kenworth. Kenworth completed mechanical integration of all components, mounts, brackets, plumbing, and wiring in the truck with support from BAE Systems.

Task 10: Secure H2 Fuel Supply for Demonstration Program

Task Summary: Develop and execute fueling plan to support vehicle during the two-year demonstration period.

Task Details:

- CTE to identify fueling options and sources of fuel.
- CTE/TTSI to decide on the best option for fueling, location, and fueling logistics to support daily operation of truck for two-year period.
- CTE to procure fuel supplier.
- CTE to submit permitting application to AHJ (Port of Los Angeles).
- Fuel supplier to set up fueling station on Port property.
- CTE to establish fueling protocol to govern fueling operation.
- CTE and fuel supplier to conduct training for TTSI personnel and first responders.

Task 11: Vehicle Electrical Integration

Tasks Summary: Deliver key electrical interconnect components to Kenworth. They electrically connect the key components in alignment with the approved vehicle 3D CAD model. Fuel cell is operated for the first time.

Task Details:

- BAE Systems to deliver high voltage harnessing to Kenworth.
- Kenworth to design and install the low voltage harnessing.
- Kenworth will connect the hydrogen storage system to the fuel cell along with completing all harness installation on the vehicle and perform low voltage check out.
- BAE Systems and Ballard Power Systems will work with Kenworth to operate the fuel cell engine with the vehicle stationary and operate all accessories and demonstrate battery charge and discharge.

Task 12: Vehicle Testing/Validation

Tasks Summary: Perform road trials and system tuning prior to assigning VIN and delivering vehicle to drayage operator.

Task Details:

- Kenworth, with support from BAE Systems, will perform a series of road trials simulating the desired duty cycle.
- The Team will tune the system during the road trials to align as closely as possible to the vehicle design system performance analysis.
- Kenworth will perform final vehicle acceptance by the team, assign VIN and deliver truck to drayage operator. In addition to meeting internal vehicle test and validation requirements, the performance parameters listed in the table below will be verified and a report on the actual performance of each parameter as tested will be provided.

Performance Parameters	Expected Performance*
Fuel Economy	4.5 to 6.0 mi/kg
Hydrogen Storage	30 kg storage and 25 kg usable
Range	112 miles
Gradeability and Start-ability	6.5% grade at 35 mph 5.0% grade at 40 mph 15 second start-ability at 30% grade
Top Speed	70 mph
Operating Temperature	-4 F (-20 C) to 115 F (46 C)

* Note: All performance parameters tested with a vehicle GVW of 65,0000 lbs.

Task 13: Vehicle In-Service Operation and Data Collection

Tasks Summary: Operate vehicle in drayage service for 24 months. CTE will train drayage operator to operate vehicle in drayage service. All subcontractors will support vehicle operation to ensure reasonable up time and limited down time for repair. CTE will install data loggers on the demonstration vehicle to collect data for the National Renewable Energy Laboratory (NREL) analysis and dissemination (see Attachment 2 for data requirements). CTE will work project team and NREL for formatting and transfer of vehicle and infrastructure data.

Task Details: End-user operates vehicle in service and other teammates support vehicle operation to ensure reasonable up time and limited down time for repair.

Project Results

Technical Results

Table 1. Project Task Status

Task Description		Percent Complete
1	Project Management for Phase 1	(100%)
2	Project Management for Phase 2	(100%)
3	Establish Contracts	(100%)
4	Define Master Project Plan for Subcontractors	(100%)
5	Vehicle/System Design	(100%)
6	Long Lead Items Procurement	(100%)
7	Secure Hydrogen Fuel Supply for Testing	(100%)
8	Lab Integration of the Sub-System Components	(100%)
9	Vehicle Mechanical Integration	(100%)
10	Secure Hydrogen Fuel Supply for Demonstration	(100%)
11	Vehicle Electrical Integration	(100%)
12	Vehicle Testing and Validation	(100%)
13	Vehicle In-Service Operation and Data Collection	(100%)

Task 1: Project Management for Phase 1 (Vehicle Development)

Percent Complete: 100%

Work Accomplished

During the vehicle development tasks, CTE conducted all project management activities to ensure the project was progressing while adhering to the project schedule and budget. These activities included but were not limited to:

- Addressed issue with World CNG (original partner responsible for upfitting) filing for bankruptcy.
- Established and maintained a high-level (two-tier) project schedule.
- Held internal team project kickoff meeting on April 19, 2016.

- Prepared for and administered the Project Kickoff Meeting on May 10, 2016. Posted meeting minutes and action items for the project.
- Administered weekly team meetings and posted meeting minutes.
- Administered action items for the project.
- Developed reporting and invoicing templates for subcontractors.
- Developed consolidated list of design requirements based on the prime contract, CTE proposal, and requirements of project team members.
- Held preliminary design review meeting on September 20, 2016 at Kenworth's facility in Renton, WA. This meeting confirmed the selection of most of the major components in the system.
- Applied for and obtained a waiver of DOE US work requirement for a portion of Kenworth's development work.
- Executed subcontract amendments with members of the project team to open additional project budget periods.

Project management activities conducted during the vehicle demonstration phase were recorded under Task 2.

Task 2: Project Management for Phase 2 (Demonstration and Data Collection)

Percent Complete: 100%

Work Accomplished

During the vehicle demonstration, CTE conducted all project management activities to ensure the project was progressing while adhering to the project schedule and budget. These activities included but were not limited to:

- Maintained an integrated project schedule and continued working with BAE and Kenworth to ensure their own schedules are compatible with each other and the overall project schedule
- Administered weekly team meetings and posted meeting minutes
- Administered action items for the project
- Compiled monthly progress reports with input from team members
- Conducted a budget re-baselining activity to ensure the remaining project budget was adequate relative to the remaining work
- Observed vehicle training on site at TTSI
- Administered biweekly meetings to discuss and monitor the hydrogen refueling systems
- Visited TTSI to review project progress and discuss steps to ensure program success
- Developed and distributed subcontract amendments to the project team to extend the project schedule in order to align with the end date of the SCAQMD agreement
- Worked with NREL to determine status of data transmission and analysis

Issues and Risks Identified:

COVID-19 heavily impacted the volume of freight TTSI moves on a weekly basis. Drivers were operating in limited shifts as TTSI continued to assess impacts to its business. To reduce costs, TTSI removed insurance from the zero-emission vehicles and suspended the program for several months.

Task 3: Establish Contracts

Percent Complete: 100%

Work Accomplished

Before contract execution, CTE ensured validity of the original proposed project tasks, budget, and schedule. CTE also reviewed and addressed prime contract terms and conditions, including the unique requirements imposed by the CEC agreement. Further, CTE established and negotiated all flow down terms and conditions and ensured that vendors and subcontractors could meet requirements.

The project contracts were executed as follows:

- Prime contract between SCAQMD and CTE was fully executed on April 27, 2016.
- Kenworth subcontract was fully executed on May 20, 2016.
- BAE Systems subcontract was fully executed on May 24, 2016.
- Ballard Power Systems subcontract was fully executed on October 13, 2016.
- Air Products subcontract was fully executed on November 14, 2017.
- TTSI subcontract was fully executed on February 20, 2018.

Issues and Risks Identified

Before the project was underway, World CNG, the integrator for the project, filed for Chapter 7 bankruptcy. Rather than bring in a new integrator, CTE and the project team elected to move the integration work to Kenworth and BAE.

Task 4: Define Master Project Plan for Subcontractors

Percent Complete: 100%

Work Accomplished

The purpose of the Project Management Plan is to provide a formal document used to guide both project execution and project control. The primary uses of the project plan are to document planning assumptions and decisions; facilitate communication among stakeholders; and document approved scope, cost, and schedule baselines.

The Project Management Plan was completed and delivered on March 23, 2017. The Project Management Plan can be provided by CTE upon request.

Task 5: Vehicle/System Design

Percent Complete: 100%

Work Accomplished:

Kenworth and BAE Systems collaborated to develop the preliminary vehicle design including mechanical layout and installation drawings. The preliminary design was based on the defined operational requirements as well as duty cycle information from a diesel-equivalent vehicle. To finalize vehicle design, a combined critical design review and pre-production meeting was held at Kenworth Research and Development Center in Renton, WA on March 9, 2017. Ballard, BAE, and CTE joined Kenworth in the review, the purpose of which was to either approve the design of the truck or address deficiencies found so the design could be approved. The pre-production meeting was rolled into the same meeting for logistical purposes. The goal of the pre-production meeting was to verify the plan to integrate the truck and identify any obstacles that might prevent the build.

During the critical design review, the truck layout (Figure 2), subsystem FMEA, truck weight analysis, propulsion system architecture, simulation results (Figure 3), and truck integration plan were all reviewed and found acceptable with only a few exceptions. The exceptions were minor problems and easily fixable. An example exception is a missing backflow prevention device in one of the cooling loops (Figure 4). These exceptions were noted and were corrected in the design. In one case, Ballard suggested a simplification to the fuel cell water system that reduced cost and complexity without sacrificing performance. Based on the design review, Ballard, BAE, Kenworth, and CTE all agreed that the design was acceptable.

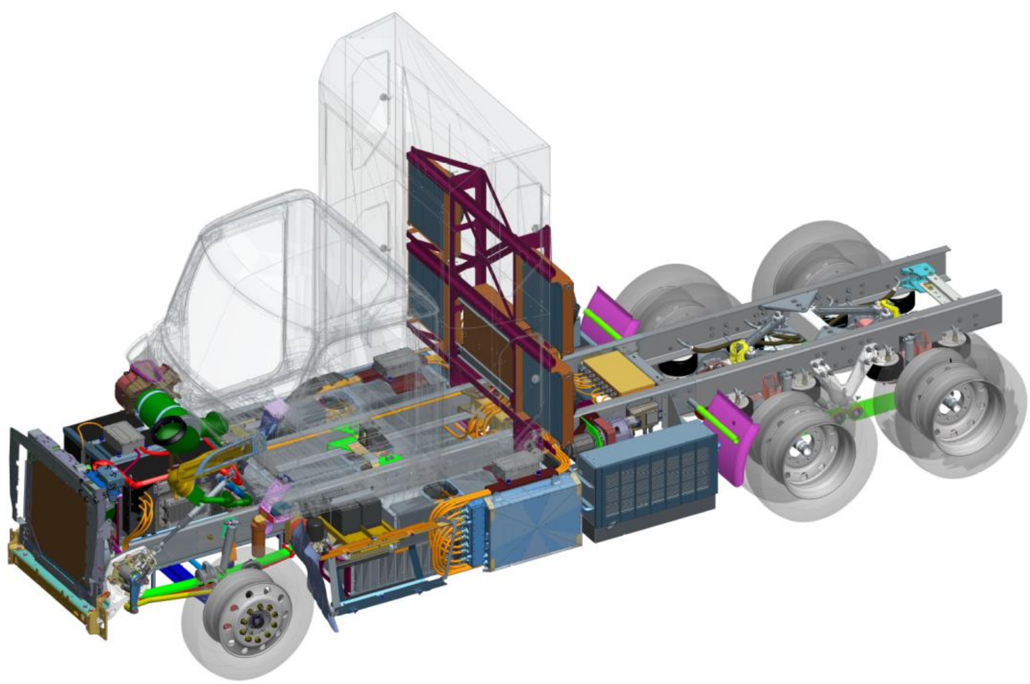


Figure 2. Overview of truck layout (Hydrogen storage system not shown)

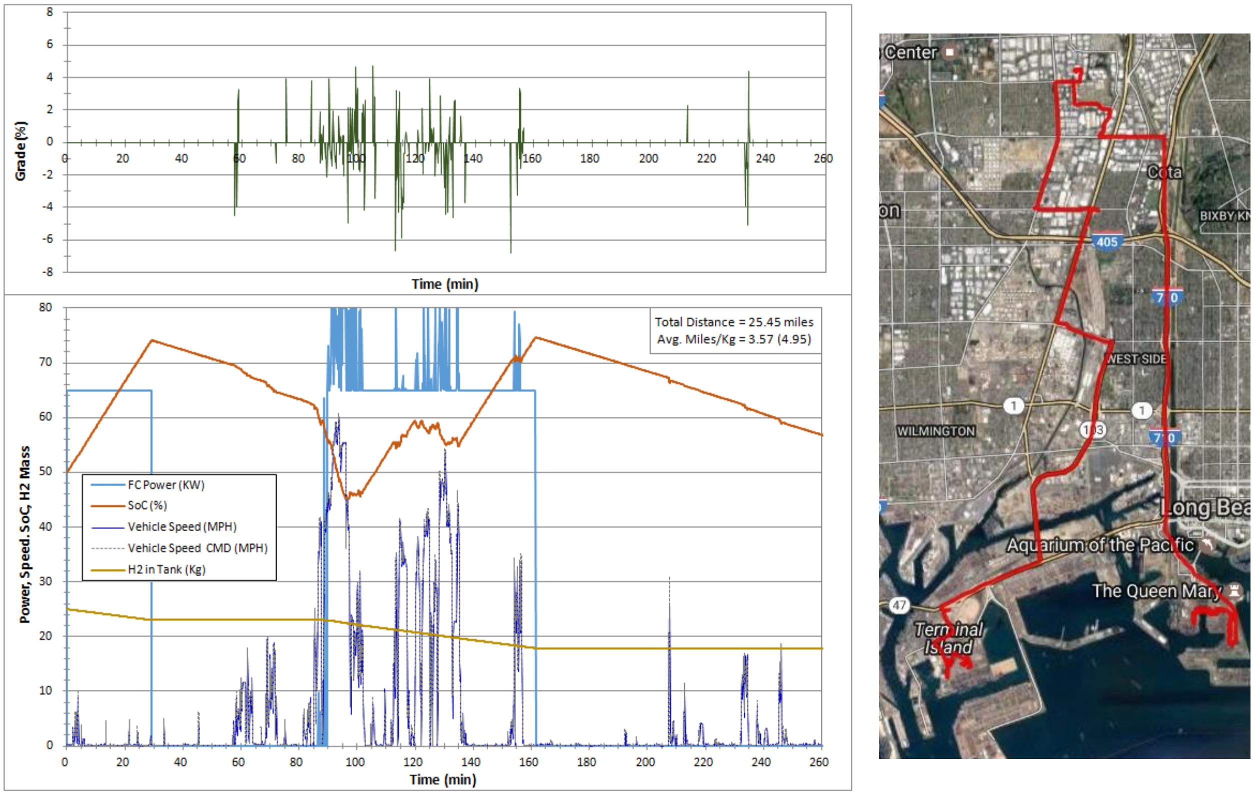


Figure 3. BAE route simulation results

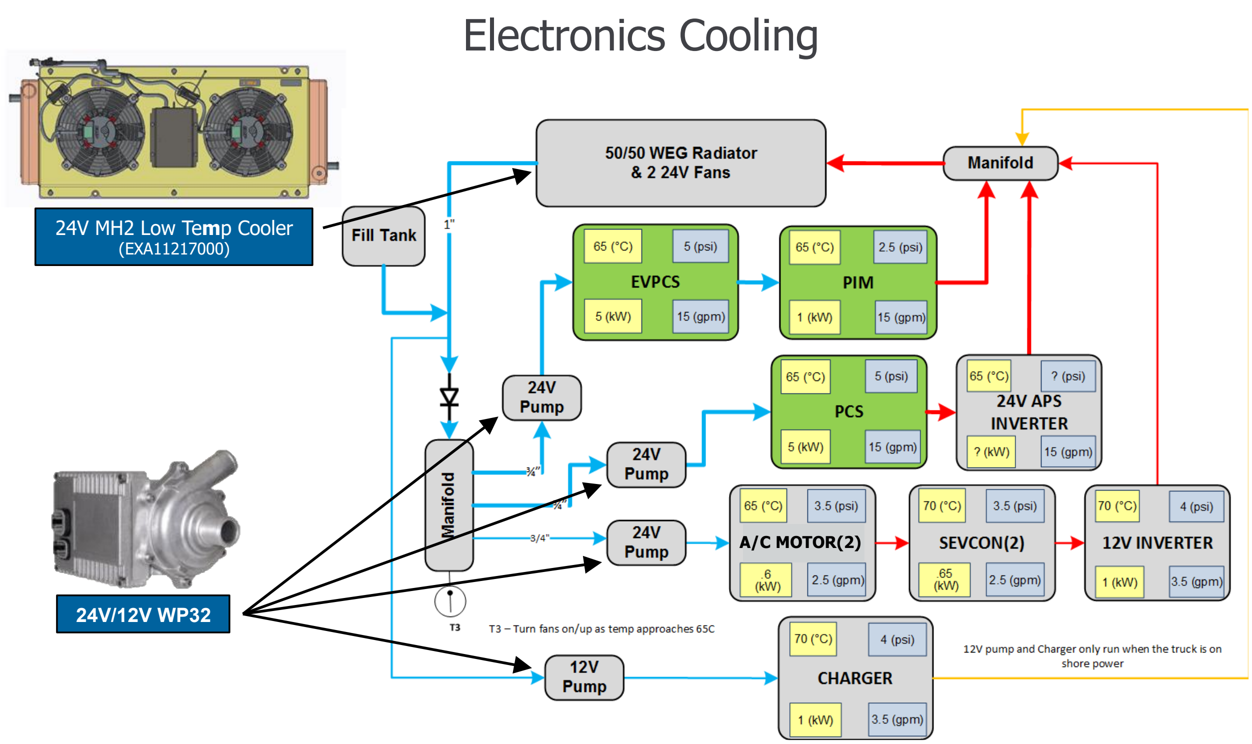


Figure 4. Power electronics cooling system

The pre-production meeting did not identify any design or integration obstacles so production was approved. The Project Team issued notice to proceed to Kenworth, BAE, and Ballard based on successful critical design review and pre-production meeting.

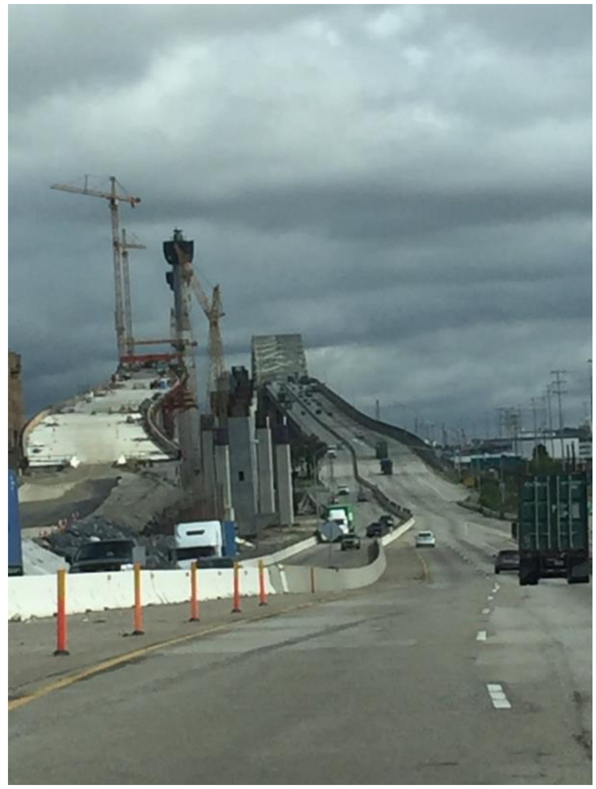


Figure 5. Photo of Gerald Desmond Bridge approach

BAE's work focused on continued development of the control laws, which are complex in a fuel cell hybrid vehicle but critical to its acceptable performance. For example, because the available continuous power of the HD85 fuel cell is less than the power required to climb grades at speed (Figure 5), the vehicle must use the battery pack to provide supplemental power at times, so the battery state of charge should be kept as high as possible. On the other hand, if the state of charge is too high and a downgrade is encountered, there is no place to store regenerated braking energy and the energy is lost to friction braking which ultimately reduces range. Clearly, the control laws required careful design to balance performance and range. Another complication is that unlike a bus, the combined tractor and trailer weight of the ZECT truck can vary widely, and so variations in load also need to be considered.

For this reason, BAE installed data logging equipment on in-service TTSI trucks to obtain real world speed and grade data from trucks doing the same job the ZECT truck will do. This route data was used to simulate the truck and predict performance. The vehicle control laws were updated based on the results of the simulations.

The interface between BAE and Kenworth equipment was also a major focus of the design effort. The interface control documents previously developed were further refined as the design changed and new information became available. These documents specify both power and signals that pass between the BAE and Kenworth systems, and the physical interfaces through which they pass. The documents include details such as length of cables, size of wires within the cable, connector and termination part numbers, and CANbus network definitions. The interfaces between the HD85 and the BAE/Kenworth are already well defined in the Ballard integration manual and were not the focus of the effort.

To close out this task:

- BAE finalized their requirements documents, control laws, and interface documents with Kenworth.

- Kenworth successfully implemented a change in motor design addressing the high voltage interlock which resolved a safety concern.
- BAE successfully updated the design of the high voltage routing and the cooling routing.
- BAE completed design for all parts of the energy storage system (ESS).
- The Project Team fabricated the fuel cell air intake and exhaust plenums for incorporation into the truck.
- BAE developed software for the four independent cooling systems on the truck.

Issues and Risks Identified

The project team needed to order certain major components and start sub-system bench testing earlier than planned in order to complete lab setup and begin subsystem testing and stay on schedule.

Task 6: Long Lead Items Procurement

Percent Complete: 100%

Kenworth Procurement

- Kenworth received the diesel truck to be repowered with the fuel cell electric powertrain (Figure 6).
- AM Racing was selected to design and fabricate a custom traction motor housing for two Remy motors. It will provide a turnkey assembly that will allow the dual Remy electric motors to generate a power output similar to a comparable diesel engine. Preliminary design estimates suggested the truck would perform competitively against current Class 8 drayage diesel trucks. AM Racing also integrated an oil-to-water heat exchanger within the motor housing to allow water cooling to be used external to the enclosure to reduce complexity. Eaton provided a 4-speed transmission for the truck. The transmission mated with the dual motor system fabricated by AM Racing.

Figure 6. Diesel truck before conversion

- Agility, a company selected by Kenworth for this task, delivered a turnkey onboard hydrogen storage system.

BAE Systems Procurement

- Although BAE's hardware largely consisted of existing products, the control cards in some of the power electronic modules have been updated and were considered long lead parts.
- High-voltage filters were built for this project. These filters use magnetic components that are typically custom built and have long lead times. BAE procured all of the components for the high-voltage (HV) filter and shipped the completed filter to Kenworth.

- BAE received items for the power interface module (PIM) and motor drives to assist in completion of the propulsion system.
- BAE procured materials to complete the electric vehicle propulsion control system (EVPCS) build and testing.
- Procured additional dual power controller circuit card assembly (DPC CCA) and several components required to modify the CCA to fit the application.
- BAE cut all of the HV cables to proper lengths for the truck. It procured all interface plates, Sealcons, and mounting hardware to install the HV cables on the various LRUs. Prior to shipping the HV cables and associated hardware to Kenworth, BAE installed all of the PowerLok connectors in-plant.

Task 7: Secure Hydrogen Fuel Supply for Testing

Percent Complete: 100%

Work Accomplished

During 1Q2017, the request for proposals to procure the hydrogen fuel supply was finalized and distributed. The proposal process included a mandatory on-site meeting at TTSI where fueling equipment would be installed. Multiple proposals from qualified vendors were received and scored. South Coast Air Quality Management District participated in this process, although they did not evaluate proposals.

Air Products was selected as the vendor for the hydrogen fuel supply, and CTE completed contract negotiation. Air Products provided hydrogen at Kenworth's Renton and Mount Vernon facilities during commissioning and testing. A diesel generator was necessary to operate the compressor because only 110 VAC single-phase power was available on site.

CTE and Kenworth coordinated with Air Products to complete the site applications. The first location that was used for fuel is the Renton site, and it was determined that a Tier 1 Temporary Use permit and a permit for Renton Regional Fire Authority would suffice for the City of Renton. Since the capacity of the hydrogen storage tank is less than 10,000 gallons, a State Environmental Policy Act review was not necessary for the Tier 1 Temporary Use Permit. CTE and Kenworth fulfilled the required in-person intake appointment.

Internally, the project team met to establish the outline for hydrogen training and safety. Training encompassed H2 training, truck training, station training, fueling procedures, and technician and operator training. The training plan also defined the location, length, and participants for each type of training as well as the parties responsible for conducting training.

Permitting, Install, and Commission – Renton, WA

CTE staff visited the site on August 23 and met with representatives from Air Products, Kenworth, the City of Renton, and the Renton Regional Fire Authority. An operating permit application was formally submitted in late August and a permit was issued by the City of Renton on September 12. The station was installed and commissioned the week of October 23 (Figure 7).

Figure 7. Refueling trailer in Renton, WA

Permitting, Install, and Commission – Mt Vernon, WA

CTE staff visited the site on August 23 and met with representatives from Air Products, PACCAR, Skagit County, and the Skagit County Fire Marshal. An operating permit application was formally submitted in September and a permit was issued in early October. The station was installed and commissioned during the week of November 13 (Figure 8).

Figure 8. Refueling trailers at PACCAR Test Center in Mt Vernon, WA

Task 8: Lab Integration of the Sub-System Components

Percent Complete: 100%

Work Accomplished

The system was tested in a lab environment at BAE before integration into the Kenworth truck. Before lab integration could occur, the lab itself was setup at BAE's facility. BAE's lab consists of a fuel cell shed, rotating dynamometer, and battery test facilities. The higher-level firmware, control laws, and fuel cell hybrid system were all tested in a fixed installation where engineers directly monitored the tests and ran repeatable test cases.

The rotating dynamometer was fitted with the dual Remy traction motors and transmission, which constituted the main part of the assembly that AM Racing fabricated for the truck. The dynamometer in Figure 9 was used to test the power electronics' ability to drive the Remy motors and transmission combination. BAE fabricated an ACTM motor mount for dynamometer installation and successfully ran traction motors up to 440 kW. The team demonstrated full control of the motor across its voltage and speed range. This was a major step forward towards integration into the truck.

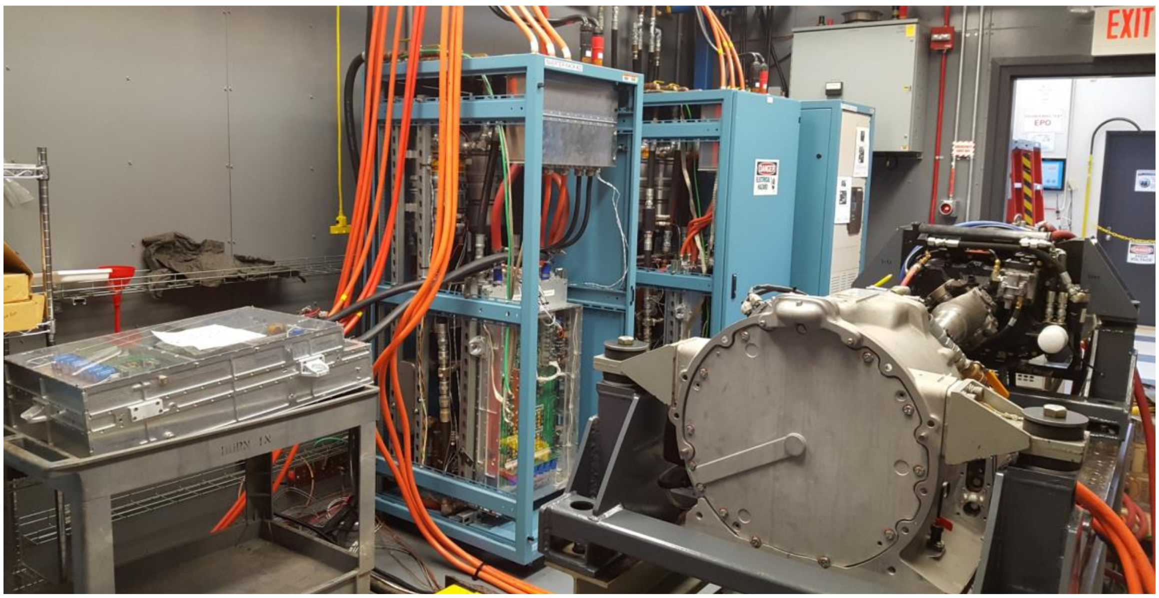


Figure 9. BAE dynamometer lab for testing the motor, drives, and transmission for the ZECT truck

As mentioned in Task 6, Kenworth purchased the actual truck that became the ZECT truck, and it was on display at the design review. Although Kenworth manufactures the trucks, the easiest and cheapest way for Kenworth to obtain one for this program was to buy a truck through its dealer system. The diesel truck it purchased was subsequently stripped of its engine, fuel tanks, cab, and other components in preparation for being rebuilt from the frame up. Accessories such as power steering, brake air compressors, and air conditioning compressors are belt driven in conventional trucks. The ZECT truck has no engine to belt these accessories off of, so customized high-voltage accessories were required. These high-voltage electronic accessories were more energy efficient than the belt driven components that they replaced.

In 2Q2017, Ballard delivered the project HD85 fuel cell to BAE Systems for testing. The fuel cell was mounted into the fuel cell shed, and fuel cell harnesses were fabricated to better simulate operating conditions. BAE has conducted low voltage and high voltage testing in close collaboration with Ballard's engineering support. To close out fuel cell commissioning, BAE implemented the fuel cell software driver and performed tests to validate the operation and expected performance.

Other notable accomplishments for Task 8 include:

- BAE completed the initial version of the fuel cell DC-DC converter firmware, drivers for the DC-DC converter and fuel cell, and software and control law updates for the truck architecture.
- BAE completed comprehensive testing of the battery pack with the BAE propulsion system and working through issues with its manufacturer, XALT.
- BAE completed build of PIM and installed in lab for integration testing.

Task 9: Vehicle Mechanical Integration

Percent Complete: 100%

Work Accomplished

This task focuses on the integration of all major subsystems including but not limited to electric propulsion, fuel cell engine, energy storage, cooling system, fuel storage system, and electric accessories. To begin the integration process, the truck was stripped of its diesel components and the cab removed to make it easier to work on, as shown in Figure 10. Brackets were fabricated and mounted to the chassis in preparation to attach the hydrogen storage system and other components.

Figure 10. Vehicle Chassis Pre-Assembly

Subsystem Installation

Cooling System

The cooling system in the ZECT truck is composed of four different loops, as seen in Figure 11. Cooling operation must match the needs of the cooling loops to prevent excess battery drainage. The fans control the amount of airflow into the system, and the coolant control pump determined the amount of heat that can be removed from the cooling system. Each of the four loops ran in harmony, but monitored individually for temperature and electrical power demand. The project team conducted cooling system tests (Figure 12) and analyzed the results for efficiency improvements to the loops.

Figure 11. Four Loop Cooling System

Figure 12. Cooling System Testing

High Voltage Accessories

The transition from a diesel engine to an electric transmission system required alternative means of power for the 650 V accessories. The determined method to accomplish this was high voltage, low current electrical power for the customized air compressor, power steering pump, and A/C compressor. Kenworth developed the software to manage the controllers that power the electric motors and the high voltage accessories. The system was developed and tested, as shown in Figure 13.

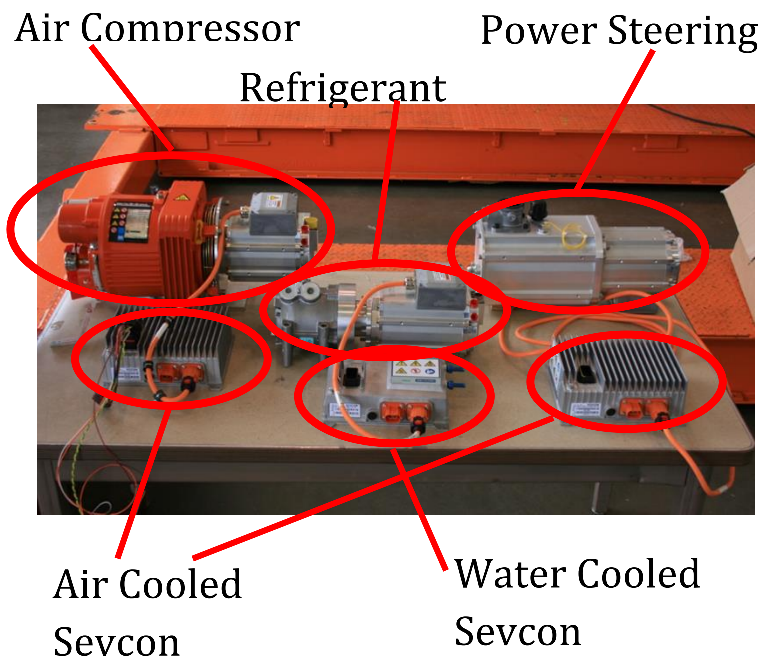


Figure 13. High Voltage Accessories

Vehicle Control Unit (VECU)

Kenworth programmed the vehicle control unit (VECU) based on low voltage electrical signals designed to simulate a real-world operation environment. In order to improve the ability of the project team to troubleshoot or diagnose issues encountered in the field, Kenworth established a routing profile for the chassis that separates high voltage and low voltage communication. The interface control documents were updated as design changes occurred.

XPAND Battery Pack

Kenworth designed and fabricated the steel brackets for installation of the battery pack into the vehicle chassis. Kenworth also developed the control systems for the battery pack. Figure 14 shows the completed battery pack assembly before it was installed in the vehicle and commissioned. Battery cooling loops with chillers were also installed and actuated by supervisory control system.

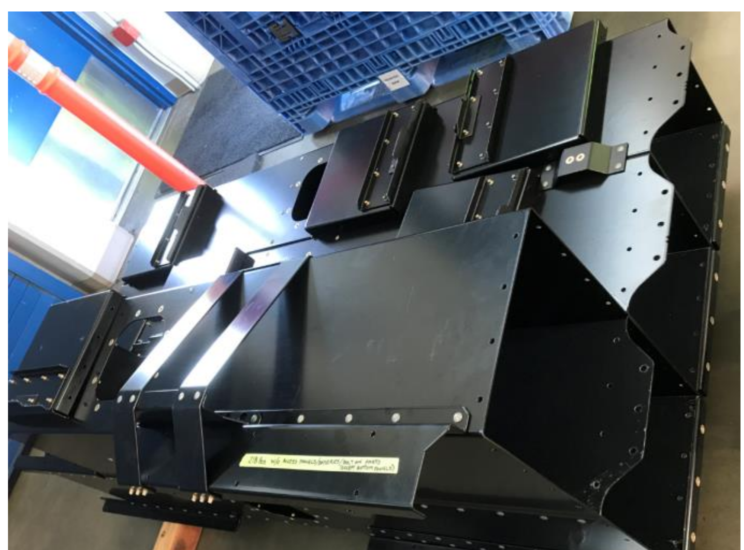


Figure 14. ESS Assembly

Fuel Cell

Another important aspect of system installation was the fitting of the Ballard fuel cell into the ZECT truck. Hoses, airlines, and coolant lines were rerouted to avoid hybrid and standard components per the chassis layout.

Figure 15. Fuel Cell Installation

Figure 16. Routings and Mechanical Integration

Initial System Testing:

In the dynamometer test, the chassis was run in full hybrid mode with the fuel cell at full power and used to charge the battery from 26% to 52% and from 19% to 62% state of charge, completely emptying the fuel tanks (Figure 17).

Figure 17. Initial Dynamometer Test

The vehicle was driven in battery-only mode (i.e. not operating the fuel cell) to the weigh scale, which measured 22,800 lbs. The vehicle was then driven to the dynamometer in second gear, run for 30 minutes, hit 30+ mph, 290+ hp and achieved 3800+ lb.-ft. of torque. The team performed road trials in Seattle for as part of the commissioning process in mid-December 2017. The vehicle was driven with the transmission in a fixed gear and without regenerative braking. Figure 18 shows the truck driving past the port of Seattle.

Figure 18. Functional Road Test & Vehicle Commissioning

The truck (Figure 19) was operated on a dynamometer at full horse power at full load at 20-30 mph on a simulated 12% grade and in a climate-controlled area at 100°F for 15 minutes. These conditions are representative of the worst-case stress test.

Figure 19. The Truck in its Final Stages of Integration and Preparation for Testing

Issues and Risks Identified

Overall, the project team encountered issues that are typical for prototype projects during the mechanical integration of the components and subassemblies. These issues range from simple replacement parts to software optimization to entire subsystem faults. The following are three specific issues encountered during integration:

Example 1:

During an early road test, the vehicle accelerated unintentionally due to a miscommunication between two Kenworth systems. The transmission splitter, a pneumatic piston on the arm that shifts between three different states, was not set fully in neutral position before the transmission system thought it was, resulting in acceleration. Kenworth implemented a 3-level fix that includes a tightened neutral zone, a tightened propulsion when the vehicle is shifting between gears, and a torque limit was set in speed control mode where the torque cannot exceed 5% without the propulsion being suspended.

Example 2:

Water vapor from the fuel cell was dispensing directly onto the driver windshield, causing the window to fog and disrupt the driver's view as shown in Figure 20. Kenworth and BAE developed a means of window defrost by running the fuel cell to heat the defrosting liquid. Software controls were implemented to achieve satisfactory window defrost performance in compliance with Kenworth internal standards.

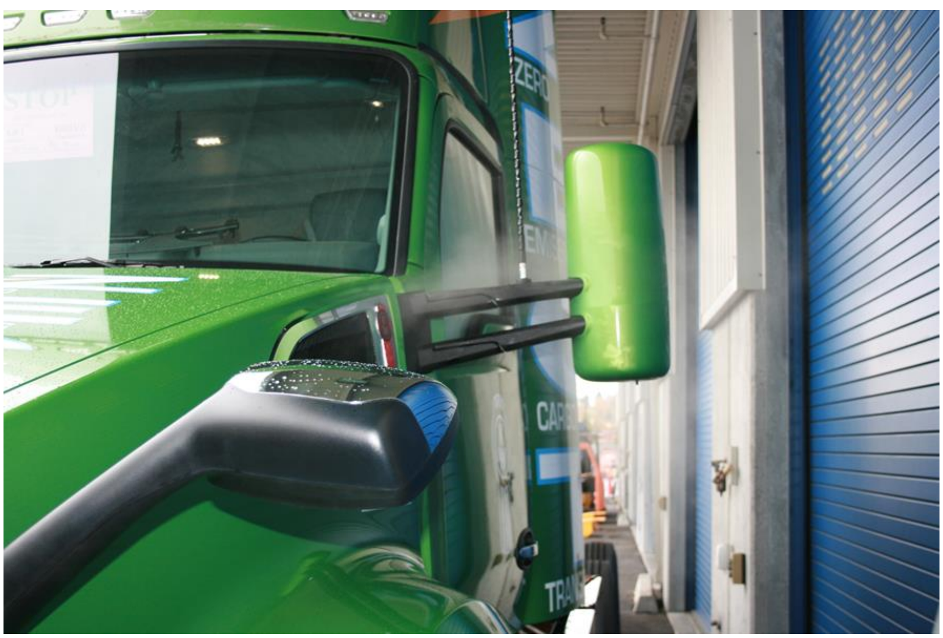


Figure 20. The water vapor from the fuel cell amassing on the driver windshield

Example 3:

The truck returned from the CES exhibition in Las Vegas (Figure 21), but the team was unable to power up the truck when it arrived. A week's worth of effort was needed to investigate the power drain and restore the vehicle to working order. Systems were run through several wake-up and run tests and driven to confirm the chassis was not damaged or defective.

Figure 21. HECT and ZECT Vehicles on Static Display at CES Las Vegas

Task 10: Secure Hydrogen Fuel Supply for SCAQMD Program Demonstration

Percent Complete: 100%

Work Accomplished

To establish the demonstration fuel supply, TTSI obtained formal approval to modify the master property lease between Harbor Performance Enhancement Center (HPEC), which is TTSI's parent company, and Port of LA (POLA) to allow a hydrogen fueling station on the property leased by HPEC. The POLA Board approved the modified lease on October 19. TTSI also held meetings with the LAFD Fire Marshall to review the application and to address any concerns they had.

A teleconference was held on November 17 to discuss the permitting process with the City of Los Angeles. The permitting process was completed as follows:

1. Prepared wet-stamped drawings that were certified by a California Professional Engineer (PE);
2. Obtained a permit from the LA Department of Buildings and Safety in San Pedro;
3. Presented the LA permit to Port of Los Angeles for its review and obtained a permit from POLA; and
4. Obtained the final approval from the LA Fire Marshal.

The planning permit application for the site was submitted and approved on January 22, 2018. The permit was taken to POLA so that it could issue a Harbor Engineering and Planning (HEP) Permit. Additionally, the team completed a Consolidated Emergency Response Contingency Plan (CUPA) to set up the inspection post-equipment, which is the last step in getting approval from the City of Los Angeles.

TTSI graded and prepared the site to satisfy the requirements stipulated by Air Products. Additionally, an older fence was removed, and 120V electrical power was installed. TTSI installed a truck gate so that both fueling trailers and mobile fuelers could enter the site. Contractors also installed standard CalTrans K-Rail barriers and cut out northern accesses fences for the mobile fueling panels but elected not to install lighting fixtures for these areas.

After the appropriate permits were obtained, Air Products installed the mobile fuelers. Due to the late arrival of imported flow-meters and additional permitting concerns, Air Products engineers traveled to the site and installed the required meters on February 19. The final inspection was conducted in the presence of the POLA inspector, TTSI, and Air Products to confirm that the site was built to specification (Figure 22).

Figure 22. Commissioned San Pedro Hydrogen Fueling Station

Due to concerns about permitting approval, the San Pedro team did not conduct the LA Fire Department training session until Wednesday, February 21, after CUPA certified the site. This training was conducted in TTSI's offices by Jaimie Levin, CTE's director of West Coast operations, and included safety material support from Air Products and the Department of Energy. The on-site component involved a demonstration of fueling another on-site hydrogen truck, whose representatives also gave a brief presentation. Overall, the training was well-received by the participants, and the LA Fire Department submitted its approval.

Task 11: Vehicle Electrical Integration

Percent Complete: 100%

Work Accomplished

In order to complete the electrical integration, Kenworth and BAE erected a chassis mock-up station to hold the hybrid chassis harness during the wire layout. The first step was to build a single wire system and lay it into the chassis at points of the intended route. The single wire harness was pulled from the chassis, and the multi-wire was then built around this skeleton. Verification and documentation steps were completed to ensure as-built conditions were documented and managed (Figure 23).

Figure 23. Harness Build and Electrical Integration

Kenworth installed all shore power circuitry including all four battery charging outlets: 220V to recharge the battery via charging station, two 110V for fuel cell and traction battery freeze protection, and 110V to recharge low voltage batteries. To prevent overload, this work required a change in design, which was implemented. BAE resolved all fuel cell faults associated with the electrical integration, and both low- and high-voltage harnesses were delivered and installed.

Task 11 was complete once the vehicle was capable of hybrid propulsion. All further electrical tuning fell under Task 12.

Task 12: Vehicle Testing and Validation

Percent Complete: 100%

Work Accomplished

Kenworth began conducting track testing, road trials, and system tuning in 2Q2018. The emphasis of track testing was rapid mileage accumulation testing: essentially accumulating as many miles as possible and under multiple loads, full range of vehicle speeds, and varying operational characteristics that replicate real world applications. By the end of the validation period, the vehicle accumulated more than 12,000 miles of track testing and some operations on the open road.

Other vehicle validation testing activities included:

- Drivability, shift smoothness (loaded and bobtail)
- Acceleration 0-60 mph, loaded
- Steering effort and feel
- Powertrain interaction with ABS
- Drive-by noise; in-cab noise
- Electro-magnetic radiation
- Gradeability (Figure 24)
- Cooling cell tests at 100F
- Electric-only range
- Startability
- Fuel Economy

Figure 24. ZECT Climbing 30% Slope at 80,000 GVW

Table 2 shows the outcomes of validation testing against the expected performance stated in the project proposal. Fuel economy was not provided during this phase, and it will be discussed under the **Data Summary** section of this report. The vehicle was able to meet all of the performance requirements and greatly exceeded the expected range.

Table 2. Vehicle Performance - Measured against Expected

Performance Parameters	Expected Performance*	Measured Performance*
Fuel Economy	4.5 to 6.0 mi/kg	*Not Measured in Task 12*
Hydrogen Storage	30 kg storage and 25 kg usable	30 kg storage and 25 kg usable
Range	112 miles	216 miles
Gradeability and Start-ability	6.5% grade at 35 mph 5.0% grade at 40 mph 15 second start-ability at 30% grade	6.5% grade at 36 mph 5.0% grade at 40 mph 15 second start-ability at 29% grade
Top Speed	70 mph	70 mph
Operating Temperature	-4 F (-20 C) to 115 F (46 C)	*Not Measured in Task 12*

* Note: All performance parameters tested with a vehicle GVW of 65,0000 lbs.

The team also began planning for post-testing, pre-delivery activities such as training for vehicle operators, maintenance teams, and local first responders. Kenworth visited the demonstration site to review and update vehicle manuals to best serve the end user, TTSI. The project team developed an escalation plan that details the order of events should the vehicle go out of service during the demonstration period. Initial vehicle data packets were submitted to NREL to verify the data submission procedure.

Kenworth completed track testing, road trials, and system tuning during the reporting period and assigned the VIN. The vehicle was shipped on February 1, 2019 and delivered to the operator, TTSI, at the Port of LA on February 4, 2019 (Figure 25). Kenworth submitted vehicle performance parameters that were measured during the test and validation phase to close out Task 12.

Figure 25: The vehicle was loaded up and shipped on Friday, February 1st, 2019

Issues and Risks Identified

The vehicle experienced several issues that resulted in significant testing delays. The risks associated with technical issues would require more time and resources to resolve at the demonstration site, at the expense of impacting the overall project schedule. An example is described below.

Example 1:
During validation testing, the vehicle experienced faults related to power steering (Figure 26), the transmission, and the fuel cell engine (Figure 27) that caused significant downtime. The vehicle was shipped to Kenworth's engineering center for diagnosis and repair, and Ballard was on-site for all fuel cell diagnostic and repair activity. Several software upgrades were implemented into the vehicle to continue optimizing performance. The vehicle was then repackaged and sent back to PACCAR Technical Center with the goal of achieving 40 fault-free hours of continuous operation before being shipped to the demonstration site.

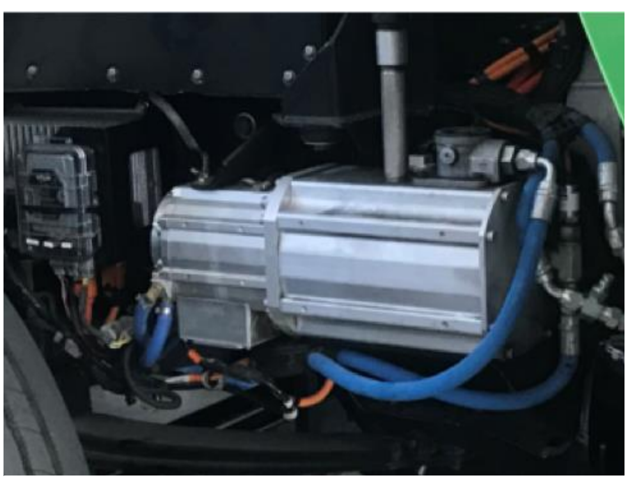


Figure 26. Power Steering

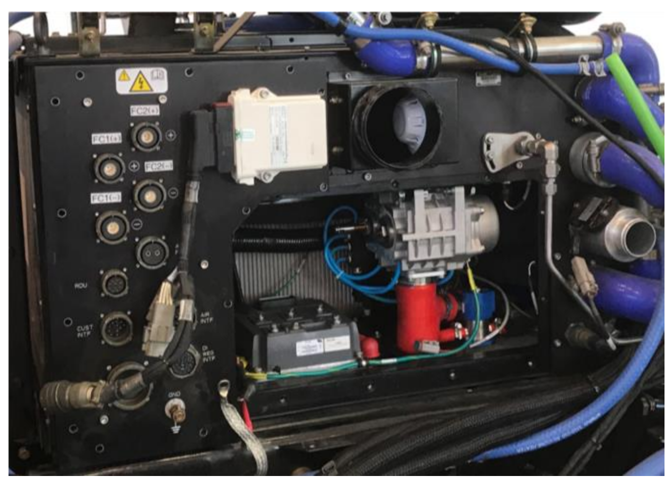


Figure 27. Fuel cell with repaired coolant pump

Task 13: Vehicle In-Service Operation and Data Collection

Percent Complete: 100%

Work Accomplished

First and Second Quarter, 2019

TTSI and Kenworth staff received the vehicle on February 4, 2019. Kenworth conducted training for TTSI operators and maintenance staff as well as local first responders. Operator training was hands-on, and the operators' initial impressions of the vehicle were positive. Internal maintenance and safety training were also conducted at the Kenworth dealership in Carson, CA.

The vehicle made several commercial runs for TTSI but experienced minor issues: oil leaks, fluid leaks, an inability to refuel with hydrogen, and HV and LV fuse failures. By the end of June 2019, the vehicle had been driven 196 miles in service with TTSI.

Third and Fourth Quarter, 2019

The truck ran without fault for the month of October 2019, completing approximately 20-25 mile routes up to four times a day with freight varying between 10,000 and39,000 lbs.

At the end of November, an operator experienced a boot-up issue and intermittent power steering failure on bumpy roads. The Kenworth team came on site to investigate and determined the root cause of the issue was the internal motor wiring. The technicians replaced a HV fuse and the faulty wiring, and the vehicle returned to service shortly after the repair.

The vehicle operated without technical fault for the rest of the reporting period but experienced downtime due to a miscommunication related to the hydrogen reorder process. This miscommunication between TTSI and Air Products that was addressed in the 2020 Hydrogen Fueling Kickoff Meeting held by CTE. TTSI reported the truck completed1,615.9 miles in 2019.

First and Second Quarter, 2020

The truck operated in limited duration early in the reporting period as it was pulled from its regular service operation to showcase at the SCAQMD Forum. Additionally, one of the H2 trailers experienced a control board failure, which was replaced in less than one week. Once the truck re-entered operation with TTSI, it ran without fault for a week before indicating low fluid on the fuel cell system. The root cause of the leak was originally thought to be the deterioration of the sight glass used to measure the current fluid level. The fuel cell fluid was topped off, the sight glass was replaced, and the truck re-entered operation with TTSI for the rest of January.

The truck operated without issue for most of February; however, TTSI's limited freight due to COVID-19 resulted in the truck to accumulating less mileage: 224 miles in the month of February. The truck also saw limited operation in March due to COVID-19 impacting freight volume, and TTSI elected to suspend the alternative fuel vehicle program due to a significant drop in freight volume.

Impacts due to COVID-19 initially brought TTSI's average of 1,600-2,000 containers down to approximately 500 containers, and TTSI's operations staff was downsized, accordingly. TTSI reported the truck completing 334.2 miles in 1Q2020.

In June, TTSI's freight volume began to pick back up to an average of around1100 containers a week, or about 35% below their average before COVID-19, which led TTSI to begin hiring and training drivers again. Soon after, TTSI elected to resume the alternative fuel vehicle program, and the demo trucks were all re-insured in mid-June. However, the vehicles did not return to service during 2Q2020 due to ongoing driver training and delays renewing the vehicle tags with the DMV.

TTSI immediately resumed regular operation of the truck in drayage service. Depending on the day's delivery schedule, the truck was run only in the morning or the afternoon because it was limited to the shorter, local delivery routes. The truck continued to run almost every day, dependent on availability of local delivery routes, for the rest of 2Q2020 without any major issues. By the end of June 2020, TTSI freight volume was higher than pre-pandemic levels (around2200 crates per week).

Third and Fourth Quarter, 2020

Early in the reporting period, the truck blew an LV fuse causing failures of the window and mirror controls. The fuse was quickly replaced and did not result in any downtime. Additionally, TTSI had to tow the truck once after a driver reported it was overheating; however, upon review, TTSI discovered the driver had neglected to fuel the truck before taking it out. Due to increases in freight volume, TTSI began training additional drivers so that the truck could be operated every day of the week with the potential for two shifts per day. Towards the end of October, the truck took part in a procession of 44 zero-emission trucks across the new Port of Long Beach bridge, as shown in Figure 28**Error! Reference source not found.**.

Figure 28. Kenworth ZECT in Port of Long Beach Bridge Procession

The truck operated consistently throughout October 2020, and the project team evaluated the potential to deploy the truck on longer routes such as Fontana (50 miles one way). The truck's performance capabilities, potential refueling issues, and potential risks were evaluated. To support this evaluation, NREL provided a preliminary analysis of the data collected up to this point to help determine the limitations of the truck and establish where the highest potential for failure is during a longer route. Additionally, Air Products expressed concern with using another provider's H2 station near Fontana. Troubleshooting a failure could result in difficulties identifying which H2 station caused the failure as a result of different molecule sourcing and fueling procedures. Kenworth drew attention to the risk of damaging prototype parts under strenuous load that cannot be replaced before the end of the demonstration. The project team worked to minimize these risks and developed a plan to test the truck on a longer, more strenuous route.

In early December 2020, TTSI notified the team that the truck would be participating in an Amazon pilot program for one month. During the program, the truck was domiciled in Fontana and was placed in service for five days a week completing around150 miles per day. This daily mileage consisted of two 45-mile roundtrips and the approximately 26 miles between Fontana and the designated fueling site. Plug Power was responsible for the refueling of the truck for the duration of the pilot. The truck entered service for Amazon on December 10; however, it experienced an issue with the power steering on December 14. The driver attempted to fix the issue by restarting the truck, but powered on the truck too quickly resulting in a malfunction because the truck requires a minimum of three to five minutes in standby after being powered down. Kenworth technicians were able to resolve the issue on December 16 allowing the truck to return to service on December 17. On December 18, the truck experienced another power steering fault while in operation leading Amazon to ground the vehicle and return it to TTSI.

Ultimately, the Amazon pilot ended roughly a week and a half early due to the two power steering faults. Kenworth engineering team provided a separate diagnosis for the two faults. After ending the pilot, the truck was returned to San Pedro operations and experienced another similar fault related to the power steering system. TTSI's safety team grounded the vehicle until Kenworth could provide a guarantee that the issue was fully resolved. Kenworth sent a technician to attempt to further diagnose the issue, but the intermittent nature of the failure meant there were no abnormalities in the data thereby making the root cause difficult to pinpoint. Additionally, Kenworth could not guarantee any fault resolution for a demonstration project as power steering issues can occur on commercial trucks.

The two-year demonstration period concluded on February 15, 2021. Figure 29 shows the daily total distance that the truck operated over the course of the full demonstration period. The truck is planned to return to Kenworth's test center in Renton, WA.

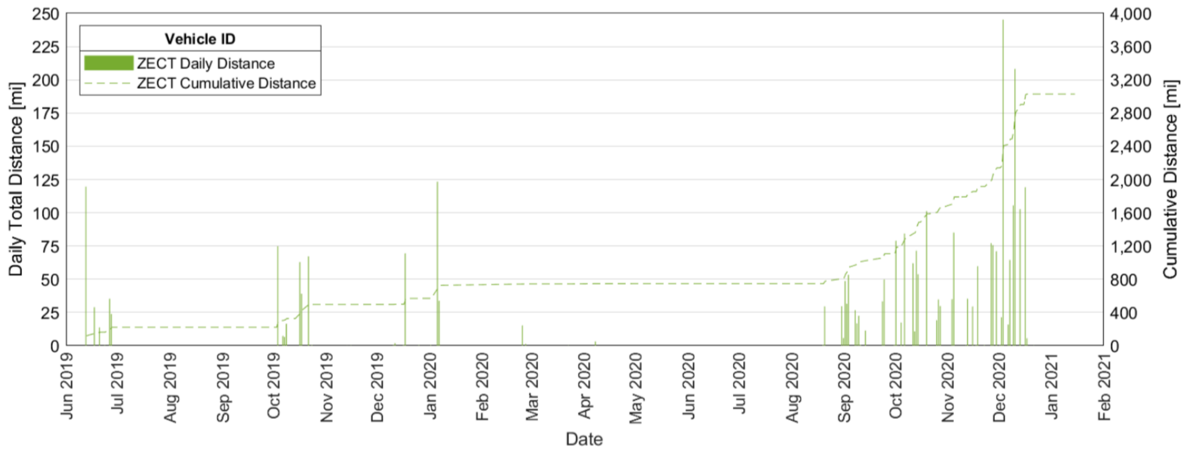


Figure 29. Daily Total Distance vs. Date

Issues and Risks Identified

Issue #1:
During routine inspection, a TTSI maintenance staff member mistakenly put diesel coolant into the fuel cell coolant reservoir. Ballard was on-site to flush the coolant lines and fill them with appropriate coolant. The project team revisited the service manual and project goals to reiterate maintenance and safety procedures. TTSI will provide additional labeling on the coolant reservoir as a means of preventing this issue from repeating.

Issue #2:
At the end of Task 12, Ballard discovered that the fuel cell power output was de-rated from 85kW to 55-70kW. Ballard technicians completed diagnostics at the Kenworth dealership in Carson, CA in February 2019. Ballard performed a dry out and leak test of the fuel cell and then conducted stationary testing with no issues. The vehicle needed to operate at higher power to validate that the fuel cell was fully functional.

While reviewing vehicle performance data, BAE and Ballard discovered that BAE's current draw was higher than what was allowable by the fuel cell. This issue caused the fuel cell to shut down outside of demonstration service. The project team collaboratively investigated root cause, developed and tested a solution, and implemented the solution into the vehicle propulsion system software.

Issue #3:
During the demonstration period, the truck experienced failures in the transmission system resulting in missed shifts and faulty operation. Kenworth returned the vehicle to its facility in Renton, WA for further investigation, and root cause was determined to be a broken set screw for the position sensor in the transmission. The original set screw was inappropriate for this application, and a more robust set screw was procured and tapered as a preventative measure. Additionally, excessive gear wear associated with longstanding transmission gear shift inconsistencies caused an increased build-up of metal shavings in the transmission fluid. These metal shavings are attracted to the magnetic position sensor and have caused scoring on the

gear assembly. The metal shavings were removed to the best of the team's abilities, and the damage to the gear assembly is not significant enough to require replacement. The transmission was rebuilt with the original gear assembly and integrated back into the vehicle.

While the vehicle was available in Renton, the motor was replaced (Figure 30) with an upgraded motor that ensures stability against issues observed in the HECT truck, which has experienced failures related to the connection of the motor shaft and rotor. This motor upgrade was a proactive step to ensure better vehicle reliability during the remaining demonstration period. The new motor leaked oil into the high voltage housing due to missing sealant on the pipe-threaded plugs. The chamber was cleaned and new plugs with sealant were installed. Kenworth R&D tested it in coordination with BAE and found no further issues with the motor.

Figure 30: ZECT wheels in the air to prepare for motor characterization work

Issue #4:
During the demonstration period, the truck faced several issues simultaneously: limited fuel cell power, dead LV batteries, and a blown power steering HV fuse. The team determined that the fuel cell was not given an appropriate amount of time to warm up once the truck was started which resulted in limited fuel cell power; however, the vehicle experienced a new fuel cell fault occurring when the main hydrogen low-pressure valve drops out and cuts off the fuel cell's hydrogen supply. A Ballard technician traced this fault to a defective relay board. Ballard replaced the old relay board with a new board that features Ballard's most up-to-date software, which resolves the start-up and low-pressure valve faults. Ballard technicians then completed a fuel cell dry-out as a preventative measure to mitigate any issues that could arise from longer

periods of inactivity. Kenworth replaced the failed LV battery and power steering HV fuse, validated vehicle functionality, and returned the truck to TTSI to resume service operation. Ballard provided Kenworth technicians fuel cell preventative maintenance training to ensure the Kenworth team can maintain the fuel cell moving forward.

Issue #5:
After TTSI restarted their alternative fuel program, it intended to immediately return the truck to service. However, the truck had issues with the 24V battery when TTSI tried to start it. Kenworth engineers determined the truck was inoperable due to a high voltage interlock loop (HVIL) failure which prevented the fuel cell from powering up. Kenworth and TTSI worked closely to troubleshoot the ZECT's 24V system, and Kenworth sent TTSI tools to conduct voltage tests on the truck fuses and report back to their engineering team. Resolution required several weeks of testing on different sections of the harness, testing of multiple component connectors, and an in-depth review of the data files collected immediately prior to the HVIL fault. During troubleshooting, TTSI realized that an operator had tripped the e-stop, which prevented the truck from starting up and was the root cause of all issues related to the HVIL failure.

Data Summary

Overview of ZECT II Baseline Data and NREL Data Collection

NREL managed the data collection process for all ZECT II projects. NREL began by collecting robust baseline data from thirty unique Class 8 drayage trucks over 557 days of operation. Each vehicle was fitted with an ISAAC DRU908 data logger and captured 1 Hz J1939 CAN and GPS data as outlined in Appendix A: Data Collection Parameters. The baseline fleet accumulated 71,243 miles, which NREL processed into representative drive cycles for comparison against all future zero-emission drayage trucks, including those deployed under ZECT II.

In the scope of this project, the baseline data played an additional role during the development and design of the Kenworth prototype truck. Numerous components in this system were being integrated together for the first time and required the development of complex control laws to meet vehicle performance requirements. NREL's representative drive cycles played a significant role in tuning these controls to balance the efficiency of the vehicle with the performance characteristics needed to handle the route types typical of drayage service.

During the demonstration of the Kenworth truck, NREL oversaw the entirety of the data collection process. Kenworth pulled the raw data from the vehicle and transmitted the data to NREL via a secure FTP server. Each raw data stream was processed and harmonized to align with other ZECT II truck data streams, which included unit conversions, consistent parameter naming conventions, sampling frequency verification, datetime formatting, data segment consolidation, signal validation, standardizing null data processing methods, and additional iterative processing specific to each dataset. This processing methodology allowed NREL to build out the encompassing dataset needed to complete an in-depth analysis of the all the zero-emission trucks deployed under ZECT II.

Performance Analysis Data for Kenworth ZECT Truck Prototype

The performance analysis of the Kenworth truck initially focused on building out summary data and overview plots as shown below in Figure 31. These plots are useful for detecting overall trends and spotting days of service with significant deviations in their performance profiles, such as outliers in daily distance accumulations. This analysis established trends more specific to the operator, TTSI, and the drayage duty cycle itself. Drayage duty cycle trends were determined by observing the operating time of day, distance traveled, key-on time, daily average speed, and kinetic intensity (quantifies intensity of drive cycle) as seen in Figure 32, Figure 33, Figure 34, and Figure 35, respectively.

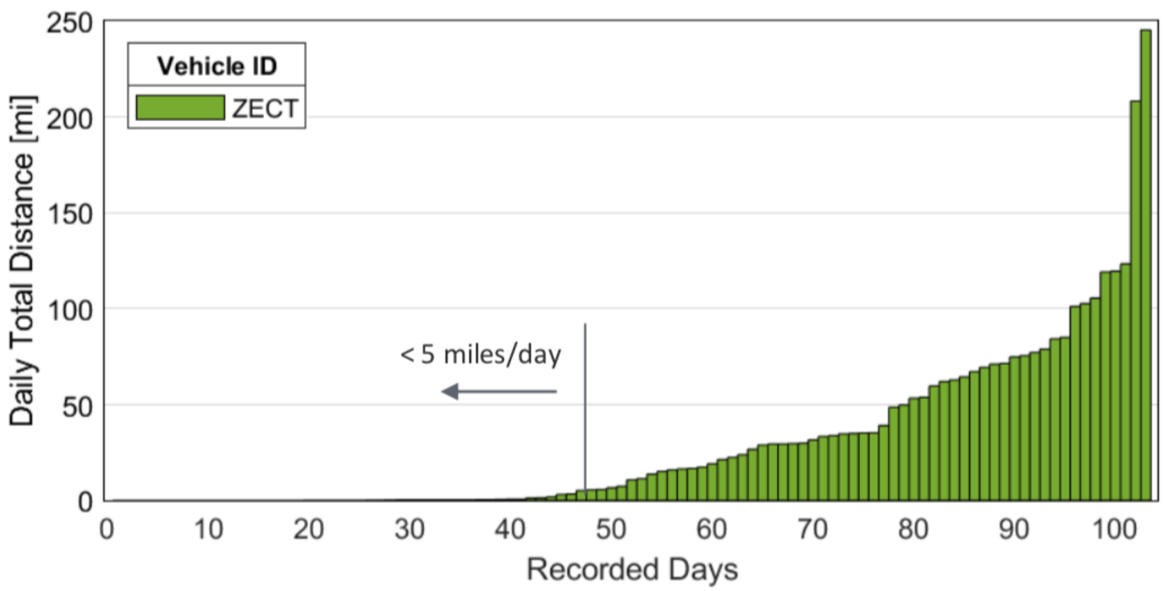


Figure 31. Daily Total Distance for Recorded Days

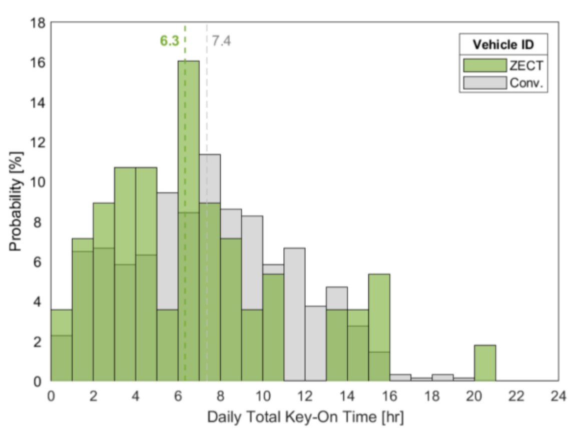


Figure 32. Daily Total Key-On Time Comparison

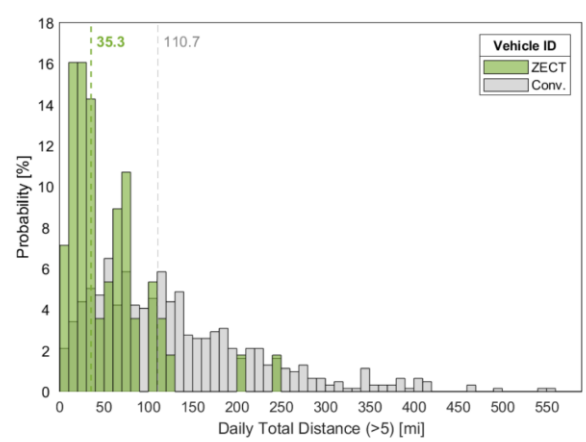


Figure 33. Daily Total Distance Comparison

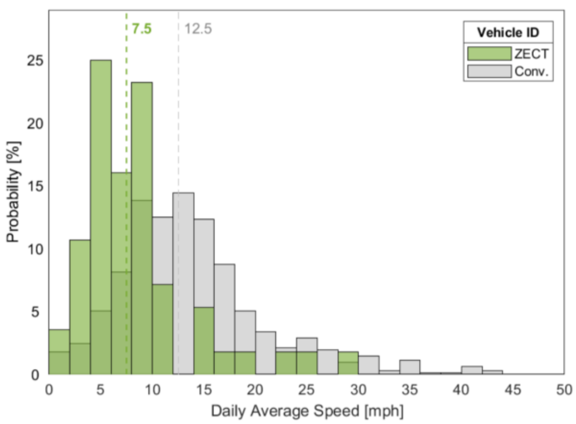


Figure 34. Daily Average Speed Comparison

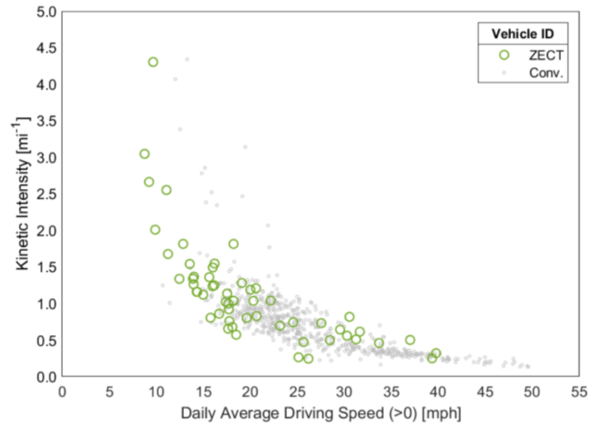


Figure 35. Daily Average Driving Speed Comparison

In addition to establishing operations and duty cycle trends, the data analysis team identified trends based on the specific performance characteristics of the vehicle. Figure 36 shows that Kenworth's fuel cell truck has a higher efficiency compared to the baseline vehicles. The Kenworth truck maintains this high efficiency at higher average speeds, in keeping with this same trend seen in conventional vehicles. However, Figure 37 reveals a lower-than-expected inverse correlation between kinetic intensity and fuel economy. This low negative correlation could suggest that this vehicle's efficiency is less susceptible to penalties by harsher drive cycles, whether induced by the driver or environment. Further analysis is needed to better understand what confounding variables could be at play here.

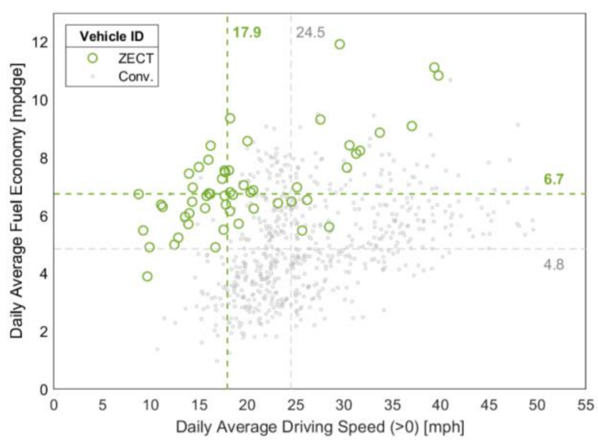


Figure 36. Speed vs. Fuel Economy - Comparison

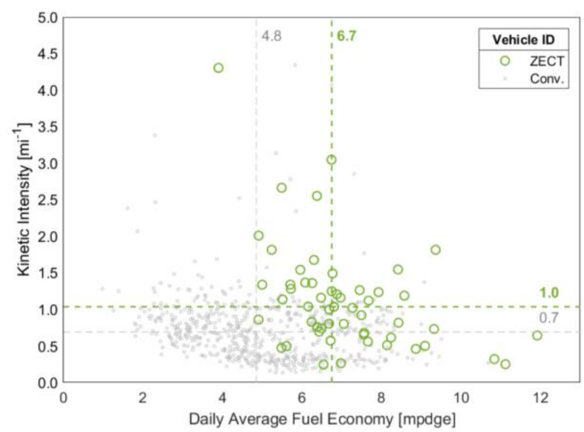


Figure 37. Fuel Economy vs. Kinetic Intensity - Comparison

After establishing baseline trends for the ZECT II Kenworth truck, NREL took a closer look at specific days of operation containing statistical anomalies. Figure 38 shows a day of service that captures the vehicle's response when maintaining highway speeds. The vehicle enters a charge depletion mode due to the inadequate power output of the fuel cell as it approaches a continuous speed of 60 mph. This charge depletion was anticipated by team; during the design phase, the vehicle's components and control logic were built around two critical design factors:

1. The available options for fuel cells were constrained by the required power and space available in the engine compartment;
2. The drayage duty cycle which rarely has to sustain highway speeds as seen in Figure 39.

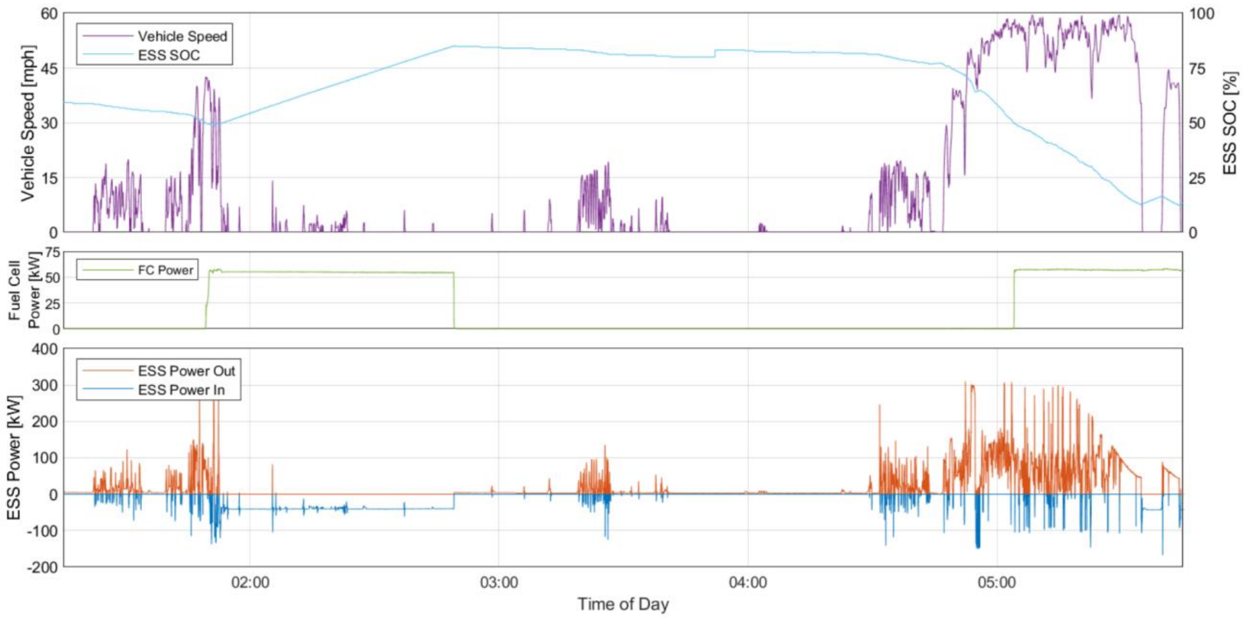


Figure 38. Vehicle Response During Highway Stretches

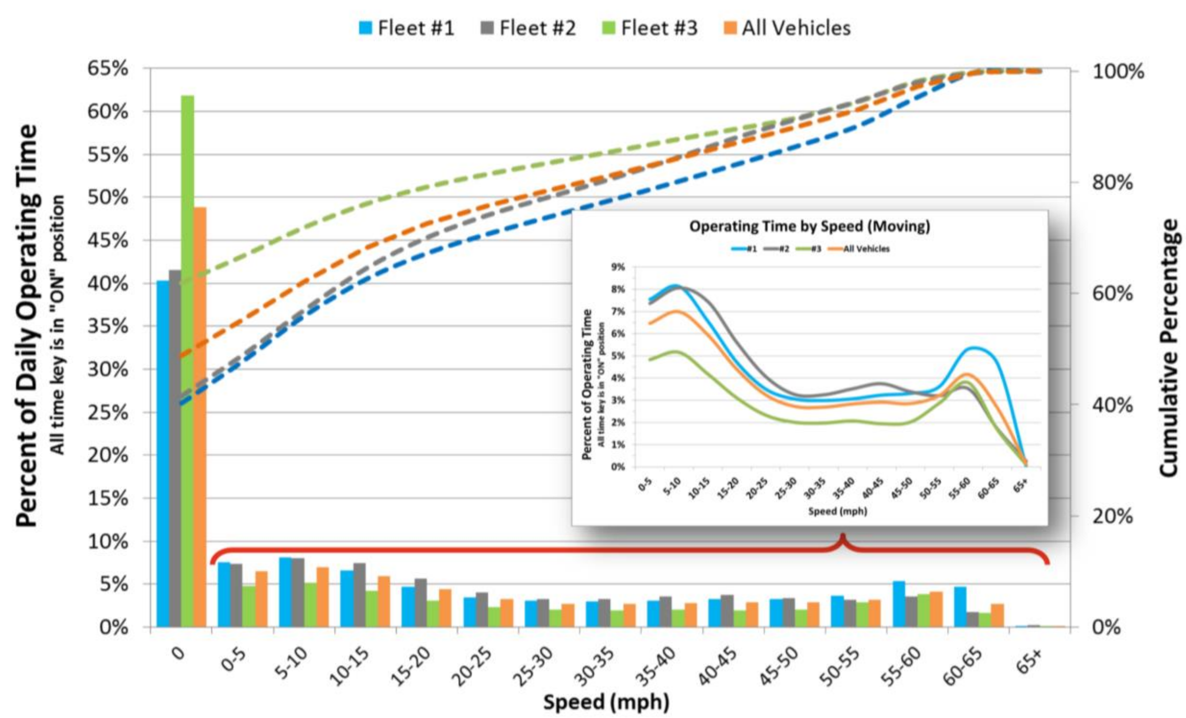


Figure 39. Operating Time by Speed for Drayage Duty Cycle

However, in some cases, this control mechanism resulted in derating events requiring the vehicle to pull over and stop to recharge the ESS as shown in the Figure 40, Figure 41, and Figure 42 below.

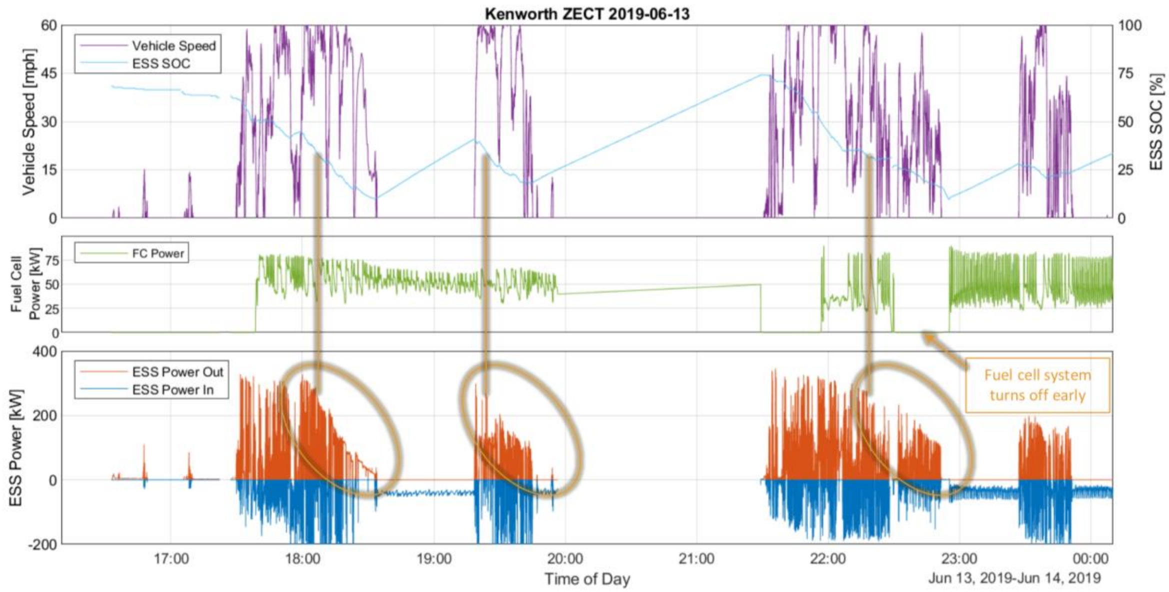


Figure 40. ESS Derate, Example 1

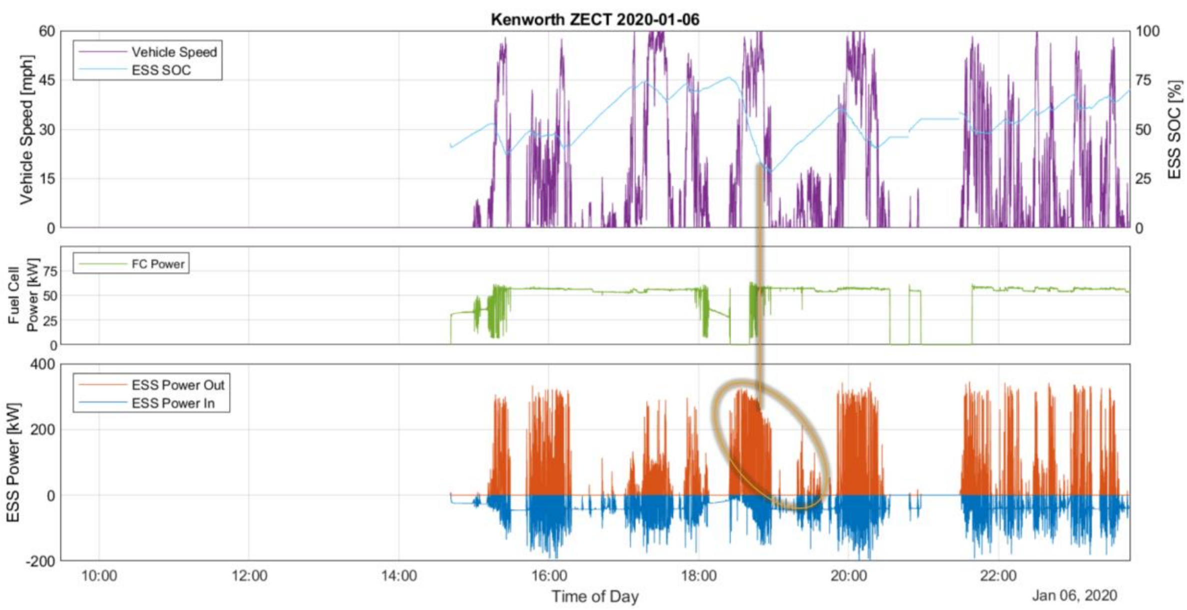


Figure 41. ESS Derate, Example 2

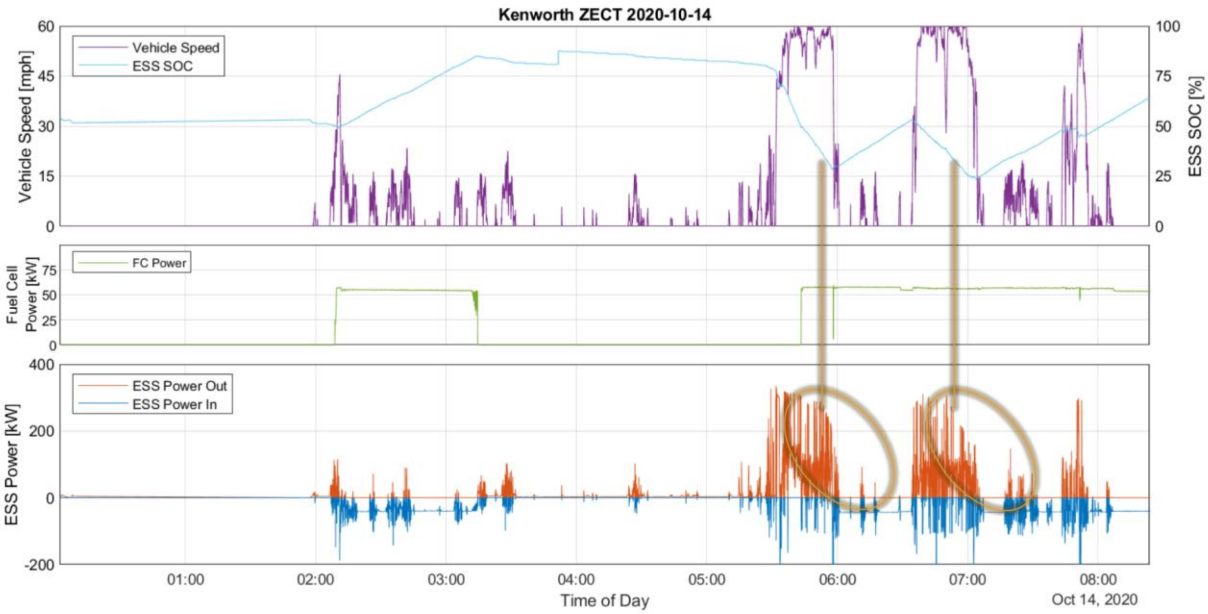
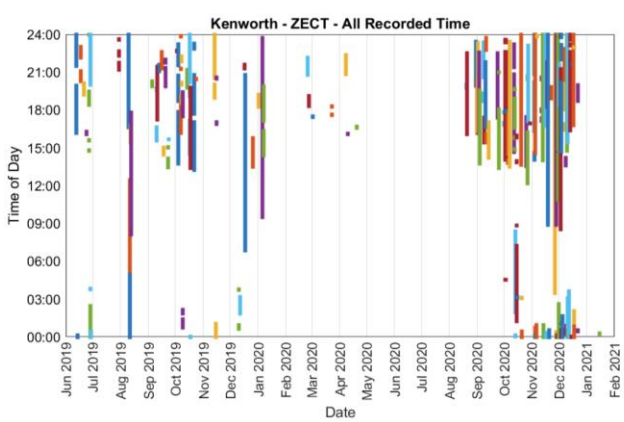


Figure 42. ESS Derate, Example 3

The hydrogen fuel cell drayage truck completed the 24-month demonstration period at TTSI on February 15, 2021. Table 3 and Table 4 summarize vehicle usage throughout the entire demonstration.

Table 3. Data Summary Table 1

Vehicle ID	First Date	Last Date	Total Days	Total Distance [mi]	Max Daily Distance [mi]	Total On Time [hr]	Max Daily On Time [hr]	Total Driving Time [hr]	Max Daily Driving Time [hr]
ZECT	6/13/2019	1/15/2021	103	3,039.8	245.2	455.4	20.9	148.2	6.6
HECT	—	—	—	—	—	—	—	—	—



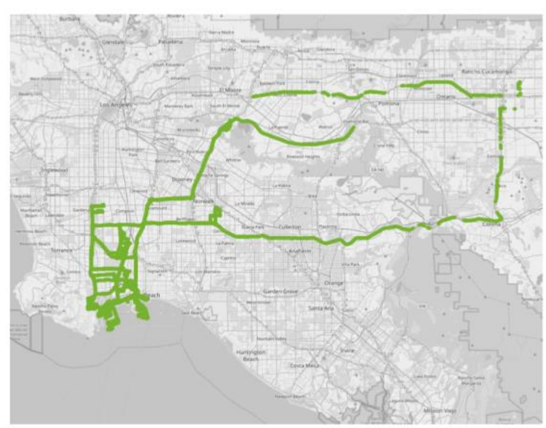


Table 4. Data Summary Table 2

Metric	Units	Baseline* Conventional	Kenworth ZECT
Date range		2014–2015	6/13/2019 – 1/15/2021
Number of total days recorded	#	557	103
In-service days with >5 miles	#	—	56
Max daily distance	mi	—	245.2
Avg daily distance	mi	127.9	53.9
Avg operating time (key-on)	hr	10.1	6.9
Avg driving time	hr	4.5	2.6
Avg speed	mph	14	8.4
Avg driving speed (speed>0)	mph	26.5	20.0
Kinetic intensity	1/mi	0.64	1.1
Avg stops/day	#/day	124.9	176.1
Avg stops/mi	#/mile	1.38	4.7
Median stop duration	sec	40.8	7.4
Avg daily fuel use (H_2)	kg	—	8.4
Avg daily fuel use (diesel equiv.)	gal	23.7	7.4
Avg fuel economy (diesel equiv.)	mi/gal	5.7	6.5
Avg fuel cell efficiency	%	—	52.1%

***ZECT II milestone report:** *Baseline Vehicle Data Collection and Analysis Report – Port Drayage*

NREL will provide further conclusions on the current state of heavy-duty zero-emission technology in its ZECT II final report at the end of 2021. An early conclusion from NREL is the need for more robust data collection standards in the zero-emission transportation industry. These standards would ensure that data being used to guide and inform the growth of the industry is reliable and comparable across a wide array of deployments. Currently, manufacturers are internally developing conflicting standards that result in large discrepancies in CAN data, including naming conventions, units, sampling rates, available onboard sensors, methodologies for calculated variables, and internal raw data processing procedures. It is imperative that standards are developed, codified, and enforced throughout the industry to build the foundations for quality data analysis as the industry continues to see increased deployments of advanced zero-emission technology.

Budget and Schedule Report

The project was completed in accordance with the contract budget and schedule, shown in Table 5.

Table 5. Overview of Project Budget and Schedule

Budget Period / Associated Tasks	SCAQMD & Partners Share	Minimum Contractor Share	Available Funds	Gate Review: Months from Contract
Budget Period One / Tasks: 1, 3, 4, 5, 6, 7	$2,011,295	$0	$2,011,295	12 Months
Budget Period Two / Tasks: 1, 2, 7, 8, 9, 10, 11, 12, 13	$2,923,115	$0	$2,923,115	24 Months
Budget Period Three / Tasks: 13	$1,098,848	$25,000	$1,123,848	36 Months
Budget Period Four / Tasks: 13, 2	$1,026,126	$25,000	$1,051,126	59 Months
Total:	$7,059,384	$50,000	$7,109,384	

Project Conclusions

The vehicles were maintained by the project team throughout the demonstration. The vehicle experienced typical issues for a demonstration project, and several examples were discussed previously in this report. The project team provided TTSI personnel with written documentation on vehicle operation and maintenance, as well as on-site training. TTSI personnel operated vehicles in typical revenue operations including fueling the vehicles. TTSI also performed periodic visual inspections of the vehicle systems.

The largest strides in Technology Readiness Level (TRL) were gained by the overall vehicle design and architecture. The hydrogen fuel cell drayage truck TRL prior to this project was at a strong Level 4 with several proof-of-concept vehicles constructed by previous researchers. Similarly, MRL of these vehicles was at Level 4- with identification of manufacturing concepts and fabrication of vehicles in laboratory or research environments. With this demonstration project, the research Team believes it has advanced the TRL of the hydrogen fuel cell drayage truck to a Level 7 (out of 10) with prototype demonstrations in operating environments.

Lessons Learned

The team achieved the primary goal of the project, which was to make significant strides developing zero-emission technologies for heavy-duty Class 8 trucks that would accelerate the improvement of air quality in southern California transportation corridors. The team also faced several challenges, some of which were described earlier in this report. Other specific development lessons learned include the following items:

- Supply base is not yet ready
- Routing design is integral to chassis layout
- Too many connections: High Voltage, Low Voltage, CAN, Cooling, etc.
- High Voltage Interlocks are vital for functional safety
- Minimizing to 2 voltages is difficult
- Cooling is a big challenge
- Battery technology is still evolving
- Battery Management Systems need self-diagnostics and auto-recovery
- Power electronics firmware must become more automated
- Human-Machine-Interface (HMI) is critical
- Procedures & infrastructure for vehicle testing are complex

Lack of standardization in componentry specific to zero-emission technologies is a high barrier to broad adoption of these technologies. To overcome this barrier, future vehicle designs will utilize proven, off-the-shelf components to avoid costs and risks associated with unstandardized system components. Using proven components also increases the technology readiness level (TRL) of the vehicle, improves vehicle reliability and performance, and allows for the emergence of the first commercial-ready ZECTs.

For example, the demonstration of the Kenworth truck ended with the inconsistent operation of the power steering pump. This pump is typically a belt-driven component, so the project team developed a custom power steering pump designed to run as a high voltage accessory specifically for this project. Future iterations will be able to integrate off-the-shelf components from tier 1 and 2 suppliers for all major components and avoid a large number of the issues experienced during this demonstration.

Additionally, successful prototype demonstrations such as this project contribute to commercialization of these technologies by making improvements to packaging of the battery, fuel cell, and hydrogen storage systems, by improving vehicle control strategies to increase efficiency, and by improving reliability across the board. Energy consumption reductions allow these vehicles to overcome higher capital costs associated with the zero-emission powertrain and operations by levelling total cost of ownership among all options.

Future projects may benefit by deploying a larger numbers of vehicles. Purchasing larger quantities of advanced technology vehicle components for these larger deployments enable certain supply chain benefits, such as economies-of-scale that allow for substantial cost reductions. Further, fuel cell, battery, and hydrogen storage system providers are now capable of filling large volume orders due to increased publicity and demand for zero-emission components. This supply expansion opens the door for future ZECTs to deliver a high-quality product at commercial volumes that fleet operators have come to expect from equipment providers.

Another area of focus for the project was ensuring reliable fueling. Air Products' mobile refueler performed consistently throughout the demonstration, but mobile fueling infrastructure adds cost, time, and risk that can only be justified for a small, temporary demonstration. An advantage for larger future deployments and for the heavy-duty vehicle market in general is investing in permanent on-site infrastructure. Permanent on-site fueling infrastructure contributes to the cost-reduction goals achieved by mass deployment and shared resources. Expanding fueling infrastructure also guarantees the demand that hydrogen suppliers require to lower costs. 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 heavy-duty fuel cell vehicle operator trying to maximize zero-emission range. Still, this issue is rapidly improving as the industry continues to grow. CTE is helping to mitigate this issue by identifying fueling protocol improvements, making recommendations to the SAE Standard J2601 fueling protocols subcommittee, and communicating demonstration and deployment project status with fueling providers.

A significant 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 Linde 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.

Next Steps and Conclusions

In addition to this final report, a couple of tasks will close out this project. The demonstration vehicle will be returned to Kenworth for vehicle disposition, according to DOE's contractual requirements. Data summaries generated from vehicle data will be aggregated with all ZECT II vehicles in NREL's in-depth analysis at the end of 2021.

Due to the success of this prototype demonstration, the project team recommends moving forward into a larger deployment of zero-emission Class 8 trucks as a means of developing and demonstrating the next iteration of vehicle design. Technical challenges are expected for all demonstration projects, but successful deployments of the next generation zero-emission trucks will require effective design updates, identification of higher-life failure modes, insights from data analysis, feedback from operators, and increased familiarity in zero-emission technology. Through the demonstration of its prototype vehicle, the project team gained invaluable experience and a successful model for the design, development, build, and deployment of fuel cell electric trucks.

Overall, the ZECT demonstration has laid the foundations for the commercialization of fuel cell electric heavy-duty trucks by successfully deploying the vehicle into TTSI's daily drayage operations. The lessons learned from demonstrating this prototype vehicle have informed improvements to both vehicle system design and manufacturing processes. By utilizing permanent on-site fueling infrastructure or existing public fueling infrastructure, increasing availability of off-the-shelf components, and achieving gains in efficiency of next generation technology, fuel cell electric trucks can enter the market at costs competitive with gasoline and diesel equivalents. The penetration of these zero-emission technologies into the heavy-duty market will maximize the impact to emissions reductions and help achieve local air quality targets on time.

Disclosures

CTE and its subcontractors produced the following items in connection with this project during the period:

- Publications
  - The KW Truck Company sponsored a booth at the 2018 CES and released a DOE and AQMD-approved statement to the press for this event. In addition, KW Truck also held a private Kenworth Dealer Meeting, showed the truck to the dealer group and shared the same information from the 2018 CES. Last, KW held an invitation only media event at the PACCAR Technical Center. The same information from the 2018 CES was again used to introduce the media editors to the test vehicle. The write ups from the host of editors are noted below in the Media Reports.
- Media Reports

  Test Drive: Zero Emissions, Positive Performance: Kenworth's ZECT NEW
  By Jim Park
  https://www.todaystrucking.com/zero-emissions-positive-performance-kenworths-zect/ (Today's Trucking)

  Special Report: Kenworth Offers Sneak Peek at Zero-Emissions Transport Truck
  By Jim Park
  http://www.truckinginfo.com/channel/fuel-smarts/news/story/2018/02/kenworth-offers-sneak-peek-at-zero-emissions-transport.aspx (HDT/Truckinginfo)

  Driving Kenworth's Zero Emissions Cargo Transport Truck (2:30-minute Video)
  By Jim Park
  http://www.truckinginfo.com/channel/fuel-smarts/video/detail/2018/02/watch-kenworth-s-new-zero-emissions-cargo-transport-truck-in-action-video.aspx (HDT/Truckinginfo)

  Photos: Kenworth's Zero Emissions Cargo Transport
  By Jim Park
  http://www.truckinginfo.com/photogallery/photos/863/photos-kenworth-s-zero-emissions-cargo-transport.aspx (HDT/Truckinginfo)

  Test drive: Kenworth's hydrogen fuel cell T680
  By Jason Cannon
  https://www.ccjdigital.com/test-drive-kenworths-hydrogen-fuel-cell-t680/ (CCJ)

  Is a fuel cell electric hybrid truck in your future?
  By Sean Kilcarr
  http://www.trucker.com/trucks/fuel-cell-electric-hybrid-truck-your-future (American Trucker)

Taking Kenworth's ZECT out for a drive (plus photos)
By Sean Kilcarr
http://www.trucker.com/trucks/photos-taking-kenworth-s-zect-out-drive
(American Trucker)

Testing Kenworth's ZECT fuel cell tractor
By Sean Kilcarr
http://www.fleetowner.com/running-green/testing-kenworth-s-zect-fuel-cell-tractor (Fleet Owner)

Taking a fuel cell-fired electric truck out for a spin
By Sean Kilcarr
http://www.fleetowner.com/trucks-work/taking-fuel-cell-fired-electric-truck-out-spin (Fleet Owner)

Kenworth ZECT Fuel Cell: Photo Gallery
By Sean Kilcarr
http://www.fleetowner.com/running-green/testing-kenworth-s-zect-fuel-cell-tractor/gallery?slide1 (Fleet Owner)

Kenworth hydrogen hybrid almost road-ready
By Elizabeth Bate
https://www.todaystrucking.com/kenworth-hydrogen-hybrid-almost-road-ready/

Kenworth showcases its Hybrid Electric Cargo Transport Truck
By Derek Clouthier
https://www.trucknews.com/equipment/kenworth-showcases-hybrid-electric-cargo-transport-truck/1003083466/ (Truck News)

Your first look at PACCAR's Zero Emissions Cargo Transport T680
By Tyson Fisher
https://tandemthoughts.landlinemag.com/tech-talk/first-look-paccars-zero-emissions-cargo-transport-t680/ (Land Line)

Kenworth Preps Hydrogen-Electric T680 for Drayage at SoCal Ports
By Roger Gilroy
http://www.ttnews.com/articles/kenworth-preps-hydrogen-electric-t680-drayage-socal-ports (Transport Topics)

Hydrogen, Batteries Power Kenworth Prototype
By Tom Berg

https://www.constructionequipment.com/hydrogen-batteries-power-kenworth-prototype (Construction Equipment)

Appendix A: Data Collection Parameters

VEHICLE PERFORMANCE PARAMETERS TO BE COLLECTED

EV Vehicle and Infrastructure Parameters		Driving	
	Units	Ideal Sample Rate	Minimum Sample Rate
Vehicle ID	n/a	Once per file	Once per file
Timestamp	dd/mm/yyyy hh:mm:ss.x	Every record	Full date/time once per file; seconds (with decimal) counter every record
Operation state	n/a	Every record	When changes
Vehicle speed	kph	5 Hz	1 Hz
Accelerator pedal position	%	5 Hz	1 Hz
Brake pedal position or force	% or N	5 Hz	1 Hz
Battery current	DC A	10 Hz	1 Hz
Battery voltage	DC V	10 Hz	1 Hz
Battery pack SOC	%	2 Hz	1 Hz
Battery pack DC discharge energy	DC Wh	1 Hz	Once per 5 sec
Battery pack DC charge energy	DC Wh	1 Hz	Once per 5 sec
Battery pack min cell voltage	V or mV	10 Hz	1 Hz
Battery pack max cell voltage	V or mV	10 Hz	1 Hz
Battery pack balance mode state	on/off	n/a	n/a
AC current	AC A	n/a	n/a
AC voltage	AC V	n/a	n/a
AC power factor		n/a	n/a
AC charge energy per event	AC Wh	n/a	n/a
AC discharge energy per event or cumulative	AC Wh	n/a	n/a
GPS latitude	degrees, minutes	2 Hz	1 Hz
GPS longitude	degrees, minutes	2 Hz	1 Hz
GPS altitude	m	2 Hz	1 Hz
Load (payload)	kg or lb	Once per file	Once per file
Ambient temperature	deg C	1 Hz	Once per 5 sec

VEHICLE PERFORMANCE PARAMETERS TO BE COLLECTED

EV Vehicle and Infrastructure Parameters		Driving	
	Units	Ideal Sample Rate	Minimum Sample Rate
Battery pack bulk temperature (e.g. Intake air or coolant temp)	deg C	1 Hz	Once per 5 sec
Battery pack min cell temperature	deg C	1 Hz	Once per 5 sec
Battery pack max cell temperature	deg C	1 Hz	Once per 5 sec
Motor temperature	deg C	1 Hz	Once per 5 sec
Power electronics temperature	deg C	1 Hz	Once per 5 sec
Charger temperature	deg C	1 Hz	Once per 5 sec
Motor speed	rpm	10 Hz	1 Hz
Motor torque	Nm	10 Hz	1 Hz
Motor power (electrical)	W	10 Hz	1 Hz
Air conditioner state	on/off	1 Hz	Once per 5 sec
Air conditioner compressor instantaneous power	W	1 Hz	1 Hz
Heater state	on/off	1 Hz	Once per 5 sec
Heater instantaneous power	W	1 Hz	Once per 5 sec
Other ancillary power demands (i.e. PTO or other)	W	1 Hz	1 Hz
Defroster state	on/off	1 Hz	Once per 5 sec
Shifter position (PRNDL)	n/a	1 Hz	When changes
Transmission gear state (if applicable)	n/a	1 Hz	When changes
Auxillary 12V battery current	V or mV	2 Hz	1 Hz
Auxillary 12V battery voltage	A or mA	2 Hz	1 Hz
Inverter DC bus current	V or mV	10 Hz	1 Hz
Inverter DC bus voltage	A or mA	10 Hz	1 Hz
Inverter three-phase PWM output voltage	V or mV	10 Hz	1 Hz
Inverter three-phase output currents	A or mA	10 Hz	1 Hz
Inverter coolant inlet pressure	kPa	2 Hz	1 Hz
Inverter coolant outlet pressure	kPa	2 Hz	1 Hz
Motor coolant inlet pressure	kPa	2 Hz	1 Hz
Motor coolant outlet pressure	kPa	2 Hz	1 Hz

FUEL CELL VEHICLE AND INFRASTRUCTURE PERFORMANCE

Component	Measurement	Units
Vehicle and Fueling Station	Time	Seconds (at least 1 data point per second)
	Ambient Temperature	Degrees C
Vehicle	Vehicle Speed	Miles/hour
	Odometer	Miles
On-Board Fuel Tank	Pressure	psig
	Temperature	Degrees C
	Tank Level	%
Fuel Cell Stack	Voltage	Volts
	Current Out	Amperes
	Stack Hours	Hours
	State	Example: 0=off, 1=on, 2=standby, 3=start, 4=shutdown
	H2 Mass Flowrate	g/s
On-Board Energy Storage	Voltage	Volts
	Current	Amperes (Positive = Current In, Negative = Current Out)
	State of Charge	% SOC
Traction Motor (Motoring and Regenerative)	Voltage	Volts
	Current	Amperes (Positive = Current In, Negative = Current Out)

FINAL REPORT

SCAQMD CONTRACT NUMBER 16022
GTI PROJECT NUMBER 21775 / 22911

Zero Emission Cargo Transport II Demonstration

Reporting Period:
December 2015 through October 2020

Report Issued:
January 2021

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Executive Summary

This research involved the development and demonstration of a Heavy Duty EV Truck with Near-Zero CNG Range Extender as a new option for heavy duty transport of goods with lower emissions of harmful pollutants and greater energy efficiency than with conventional diesel-powered trucks. The program was a result of funding and leadership provided by the Department of Energy (DOE) and South Coast Air Management District (SCAQMD) and it produced and successfully tested a compressed natural gas powered truck utilized by Total Transportation Services, Inc (TTSI) at the Port of Los Angeles, CA.

Zero emission technology is proving out in heavy duty transit bus applications, however due to the very high vehicle weights and potential for long runs at high speed, significant challenges exist in the class 8 drayage truck application. Additionally, high capital cost and operational cost of a zero-emission vehicles weigh heavily in on the economic viability of a given technology. Moreover, the new energy technologies come with a significant degree of infrastructure cost that must also be considered. While Near-Zero powertrains have been available for years, this project intended to further improve the performance, efficiency and environmental footprint by implementing a CNG-hybrid powertrain. The developed technical solution provided a well-balanced blend of all-battery and CNG engine to provide a system that can operate in a zero emissions (all-electric) mode and in a conventional hybrid-electric mode using CNG.

The Hybrid Electric Cargo Transport (HECT) Truck project sought to investigate the feasibility of the hybrid solution, and further the understanding of efficiency and emission benefits offered.

In order to achieve the necessary technical effectiveness and economic feasibility of the proposed solution, the team implemented a state-of-the-art hybrid technology with performance proven in tens of thousands of hours while fielded in other transit and maritime applications. By retaining the reliability and accessibility of conventional air, suspension, and brake systems from the Kenworth Body Builder series, the HECT Truck was easily maintained and operated by the fleet and a local Kenworth dealer. The extended range operation, exceeding all currently available zero-emission technologies, was accomplished by application of commercially available, mature CNG fueling technology and a Cummins-Westport L9N 9-liter natural gas near-zero NOx engine. Since approximately 10% of the drayage fleet at the Ports of Los Angeles and Long Beach operate on natural gas, the fueling infrastructure is well established and did not require additional investment.

Through the implementation of mature technologies and partners' expertise in high-volume applications, the vehicle demonstrated competitive performance and uptime.

If this technology is commercialized more widely in this application the public will benefit from lower emissions of criteria pollutants (primarily PM, hydrocarbons, and NOx) in and near the ports and along the roads that are used to transport goods from the ships to inland storage facilities. This should result in fewer illnesses and premature deaths, and other public health benefits, especially to the disadvantages communities directly surrounding the port.

Introduction

Despite major advances in air pollutant emissions performance, heavy-duty diesel trucks operating in dense urban areas continue to face pressure to achieve lower emission operation.
An area of significant focus is the Los Angeles Goods Movement and Industrial Corridor adjacent to the Ports of Long Beach and Los Angeles, the busiest port complex in North America. The area is in an industrial setting with diesel truck activity mingled with a variety of uses including residences, schools, daycares and senior centers. The area is also a known Environmental Justice Community made up of predominantly low-income and minority populations.

Approximately 10% of the drayage fleet at the Ports of Los Angeles and Long Beach operate on natural gas, with well-developed and accessible fueling infrastructure. These trucks currently represent the lowest emission vehicles in drayage operations, besides zero-emission prototypes. While zero emission technology is proving out in heavy duty transit bus applications, due to the very high vehicle weights and potential for long runs at high speed, significant technical challenges exist in the class 8 drayage truck application. Additionally, high capital cost and operational cost of a zero-emission vehicles weigh heavily in on the economic viability of a given technology. Moreover, the new energy technologies come with a significant degree of infrastructure cost that must also be considered.

An opportunity exists in integrating mature technologies such as battery-electric powertrain with a near-zero natural gas engine into a CNG-hybrid drayage truck, with a limited zero-emission capability. The range and performance of the truck is expected to exceed the performance of zero-emission vehicles, while offering lower emissions and better fuel economy than conventional diesel or CNG trucks. Additionally, an existing fueling infrastructure does not require expensive facility upgrades.

Objective

The primary objective for this project was to reduce criteria pollutants in the South Coast Air Basin by reducing diesel emissions from the transportation and movement of goods from the ports to intermodal and warehousing facilities throughout Southern California. The technical objective was to accelerate the introduction and penetration of hybrid technologies into the cargo transport sector which will help in achieving the primary objective of substantial reduction of criteria pollutants, and as a additional benefit reduce petroleum consumption and greenhouse gases. Despite major advances in air pollutant emissions performance, heavy-duty trucks operating in dense urban areas continue to face pressure to achieve lower emission operation.

The proposed technology, hybrid heavy duty trucks, faces many challenges in the process of commercialization: type of fuel and availability, battery and charging system; system integration and packaging of power train components and systems for safe, efficient and economical deployment of the technology are just a few of the challenges. Many options exist in designing the energy systems for this type of vehicle architecture – series- or parallel-hybrid configuration; sizing the battery for the required all electric range (AER); plug-in charging versus operation in charge-sustaining mode and the interface of the vehicle to refueling infrastructure. Considerations for the power requirements of vehicle under load and providing enough onboard energy to attain the range requirements for the drayage operation and duty cycles all come into play in the design of the energy storage and power systems. Another challenge is to design the energy and powertrain systems described above and then integrate them into a vehicle for safe and efficient operation that can be made economical in volume and series production.

The purpose of this project was to develop a near zero emission, compressed natural gas (CNG), hybrid cargo-transport prototype to evaluate the commercial viability of class 8 hybrid tractors. The goal is to reduce emissions in the South Coast Air Basin and surrounding communities along the goods movement corridors. GTI, Kenworth, BAE and CALSART developed set out to develop a battery electric truck with a CNG-powered range extender engine. The technical concept combines all-electric and CNG-based operation to provide a zero emissions (all-electric) mode and a conventional hybrid-electric mode. The detailed system architecture was designed in this project and it includes a drivetrain that can provide a combined propulsion power output of 320 kW integrated into a Kenworth T680 tractor.

The HECT truck is one of six advanced hybrid vehicles funded by the ZECT II (Zero Emission Cargo Transport) project, set out to design, build, operate, collect data from, and analyze the performance of hybrid electric technologies from several technology providers. The proposed technical concept provided a well-balanced blend of all-electric and CNG-engine operation to provide a system that can operate in a zero-emissions (all-electric) mode and in a conventional hybrid electric mode using CNG.

Comparison of Accomplishments versus Goals and Objectives

The project has accomplished the primary goals of developing, demonstrating and collecting data from the novel hybrid-electric class-8 vehicle, despite multiple issues encountered during execution of the project. Early challenges associated with the access to catenary technology and the test track have forced a redesign of the electrical architecture and an inclusion of on-board plug-in charger, in place of the catenary interface. The technical team has demonstrated a high quality pre-commercial product, that was extensively validated prior to the start of commercial service with the drayage fleet. In-service operation of the vehicle has been a huge success, with the drivers praising the comfort and performance of the truck, and the vehicle was reported one of the favorite and the most-used near-zero and zero-emission products in the fleet.

Figure 1 Completed HECT Truck

Numerous and extensive data sets have been collected, including detailed telematics information for NREL analysis, in-use emission data and fleet surveys. The emissions and fuel economy test results, while showing improvement over conventional technologies, are not as conclusive as expected and warrant further, detailed testing under controlled conditions and protocols.

Technical issues and COVID-19 outbreak have contributed to the project delay, however the project was completed within the budget and met its goal of demonstrating a hybrid truck. It also indicated an opportunity for higher efficiency and lower emissions than current, conventional drayage trucks. The process of designing, building, and testing the truck are described in this report.

The fleet surveys and an associated commercialization roadmap and scenario analysis provided several very important observations, primarily a very dynamic market fueled by the port and state regulations. While it is clear that the future of drayage transportation is zero-emission, it is not evident what role will the CNG and Near-Zero Emission technologies play in the transition.

Team Structure and Roles

The structure of the team and the roles are depicted in Figure 2

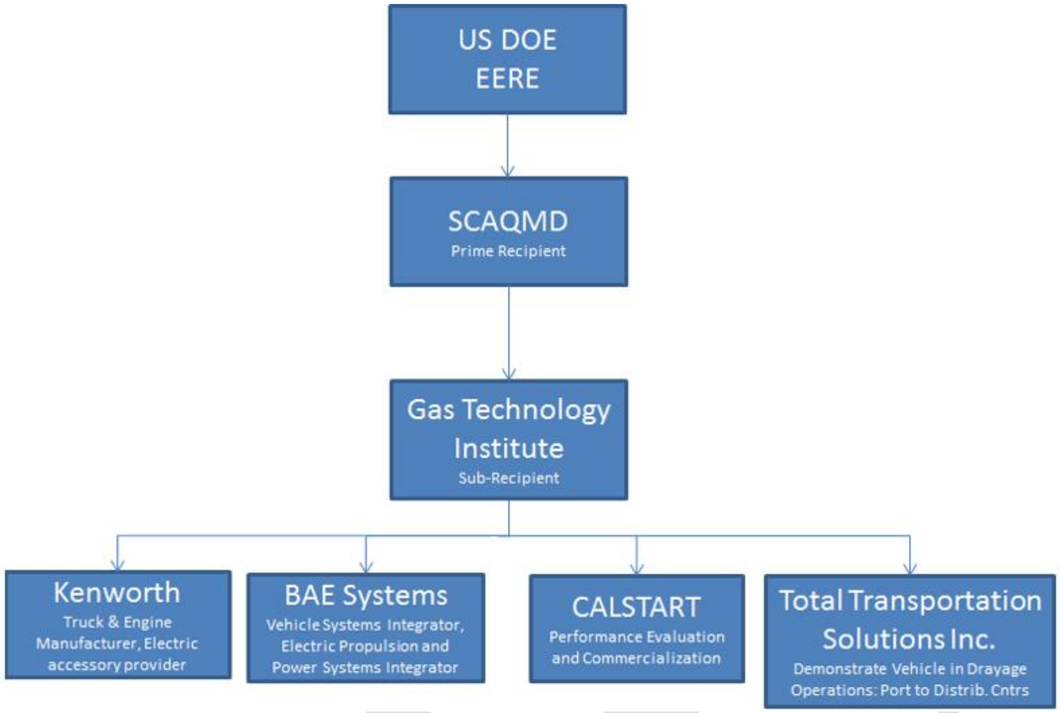


Figure 2 Team structure and roles

Summary of Project Activities

The project was divided into 10 tasks as listed below.

Task 1	–	Project Management
Task 2	–	Vehicle/System Design
Task 3	–	Long-Lead Items Procurement
Task 4	–	Laboratory Integration of Sub-System Components
Task 5	–	Vehicle Mechanical Integration
Task 6	–	Vehicle Electrical Integration
Task 7	–	Vehicle Testing and Validation
Task 8	–	Vehicle In-Service Operation
Task 9	–	Data Collection and Vehicle Performance Evaluation
Task 10	–	Commercialization Roadmap and Scenario Analysis

The procedures and accomplishments of Tasks 2 through 10 will be described in the following sections. In some cases, task descriptions are combined for clarity.

Task 2/3 - Vehicle/System Design and Procurement

This task involved the activities listed below for designing the HECT vehicle and propulsion system and procuring the advanced components and subsystems. These activities were conducted by BAE and Kenworth, with some being handled separately and some collaboratively.
Layout/design work and installation drawings:

- Vehicle system and platform requirements
- Electrical system architecture and design including electrical accessories
- Support of vehicle mechanical layout and mount design
- Power architecture design
- High Voltage Power Distribution Unit design and LV/HV wire harness design
- Software design and build; integration

Vehicle mechanical layout and accessory mounting designs

- High Voltage Power Distribution Unit design and LV/HV wire harness design
- Base chassis layout
- Base chassis harness design with preliminary hybrid accessory breakouts
- Tank assemblies and support
- Accessory Mount Designs
- Cooling system design – batteries; other
- Routing design (electrical, fuel, and cooling)
- Closures (fairings)
- Integration of team-generated designs into vehicle models

System Analysis

- High voltage harness hardware requirements
- Modeling and simulation
- Cooling system requirements definition
- Software requirements
- Internal Failure Mode and Effects Analysis (FMEA)

- Base simulation and controls Subcomponent Impact Analysis
- Rapid Control Prototyping (RCP) for subcomponent controls
- Base vehicle weight distribution analysis
- Complete vehicle/system design review

Vehicle Architecture Overview

The HECT (Hybrid Electric Cargo Transport) conceptual vehicle layout is shown in Figure 3. It is equipped with a Cummins-Westport L9N 9-liter natural gas near-zero NOx engine rated at 230 kW. The engine drives a generator intended to recharge the 100kWh battery pack as the vehicle system consumes power. Fuel is stored in Agility type IV CNG (Compressed Natural Gas) high-pressure (3600 psi) storage system with a 50 diesel-gallon-equivalent (DGE) capacity.

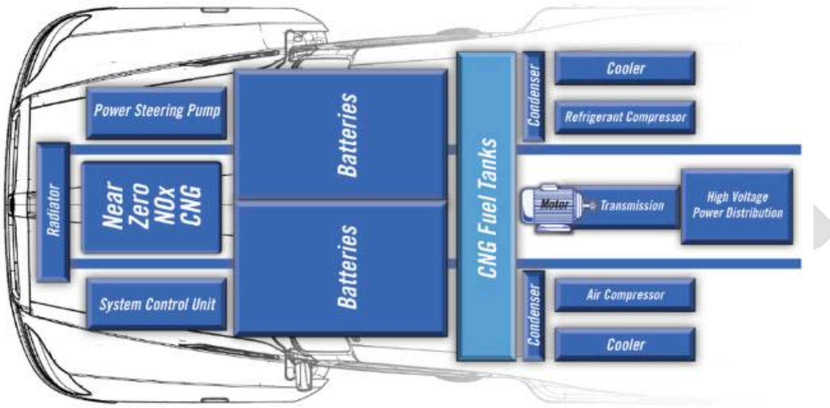


Figure 3 CNG Range-Extender Truck Layout

Major Components	Detailed Information
Chassis	Kenworth T680 Daycab
Control System	BAE
Traction Motor	AM Racing, 2 x 160kW
Energy Storage System	XALT, 100kWh, 650V
Range Extender	Cummins-Westport L9N, 230kW with BAE integrated starter-generator (ISG)
Transmission	4-speed Eaton Automated-Manual (AMT)

Table 1 Major Component Table

The Cummins-Westport L9N 9-liter natural gas near-zero NOx engine is pictured in
Figure 4.

Key Engine Attributes

- Certified to CARB’s Lowest Optional Low NOx Standard (0.02g/bhp-hr)
- 4 cycle, spark ignited, in-line 6 cylinder, turbocharged, CAC
- Displacement - 8.9 Liter (540 cu. In.)
- Exceeds 2017 EPA GHG requirements
- 2018 On-board Diagnostic (OBD) compliant
- Dedicated 100% natural gas engine
- Peak rating: 320 hp, 1000 lb-ft

Figure 4 Cummins-Westport L9N engine

HECT uses 2x160kW electric motors driving a common shaft into an Eaton 4-speed automated manual transmission with the following ratios;

1^{st} = 4.38:1
2^{nd} = 2.68:1
3^{rd} = 1.68:1
4^{th} = 1:1

From the transmission output, a conventional driveline is utilized to feed torque into a final drive ratio of 5.38:1. At a high level, the propulsion system operates as shown below in Figure 5Figure 5. Overall, power is provided by 3 sources at any given point in time: the Energy Storage System (ESS), the Traction Motors, and the CNG Engine. All power gets collected and disseminated to the appropriate loads, whether it’s for propulsion, ESS charging, or accessories. This power is distributed through power distribution units (PDU’s) where the power gets routed through easily accessible fuses, relays, and breakers. Low Voltage Power is distributed directly through the Electric Vehicle PCS (EVPCS) and High Voltage Power passes through a filter where it is cleaned and distributed to vehicle accessories including the air conditioner, charger, power steering, and the vehicle air compressor.

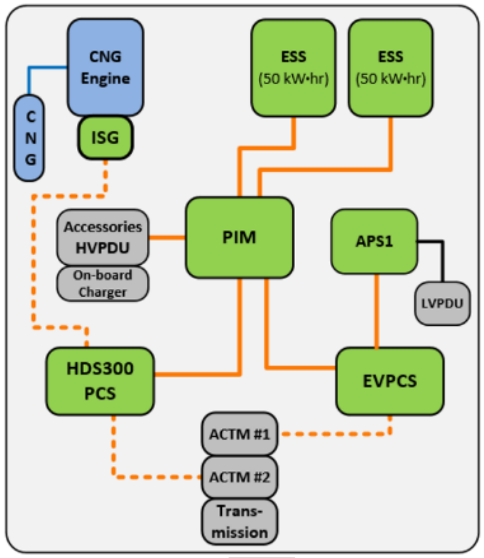


Figure 5 Diagram of Power Distribution Architecture

The Mechanical Layout of the propulsion system is shown below in Figure 6. These CAD models show the layout of the ESS, the Power Interface Module (PIM), the Propulsion Control System (PCS) as well as other ancillary devices including the HV Air Compressor, Power Steering Pump, and Coolant Compressor. Care was taken to position the heavier components, including the ESS, as low as possible to create a low center of gravity while maintaining the shortest run of high voltage cables to prevent losses in energy transfer. The PCS units are easily accessible and allow servicing of the inverters.

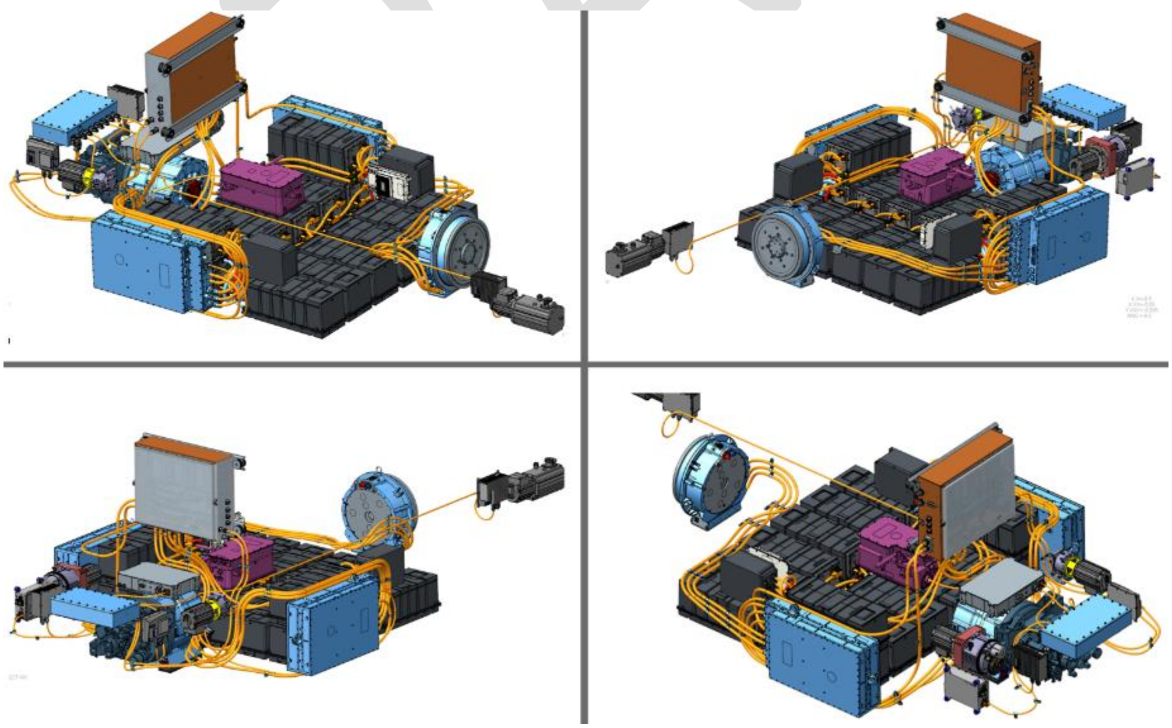


Figure 6 Mechanical layout of propulsion system

Cummins-Westport provided and supported their L9N Near Zero Emissions CNG engine, which was combined with the BAE Integrated Starter-Generator (ISG) to be the primary range-extender for this truck. All major sub-assemblies were designed and fabricated in parallel. These included the high voltage (650 volts) power steering pump, the HV air compressor, the AC compressor, the AC Traction Motor (ACTM), the Eaton 4-speed automated-manual transmission, the Eaton High Voltage Distribution Unit (HVDB), and the on-board CNG fuel storage system. All major cooling system components were procured while the sub-assemblies were being fabricated.

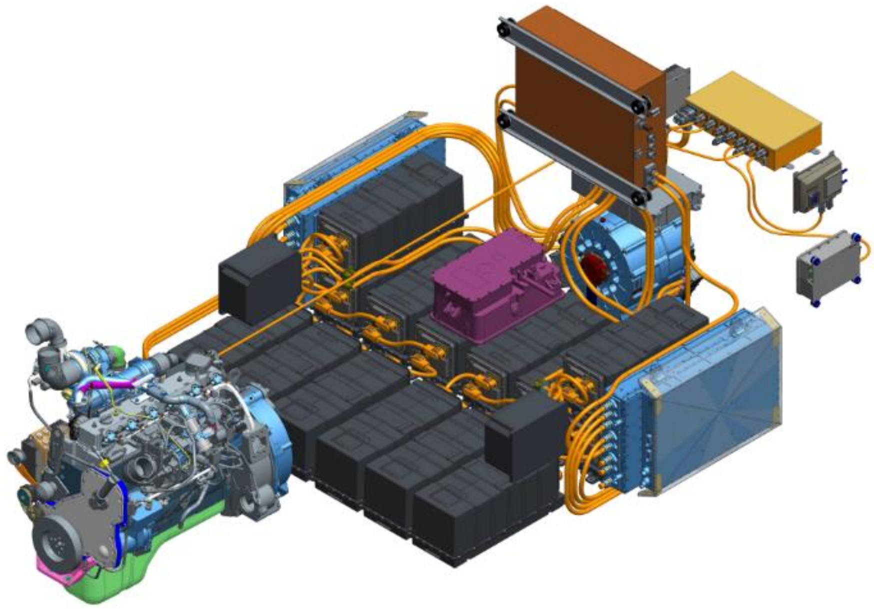
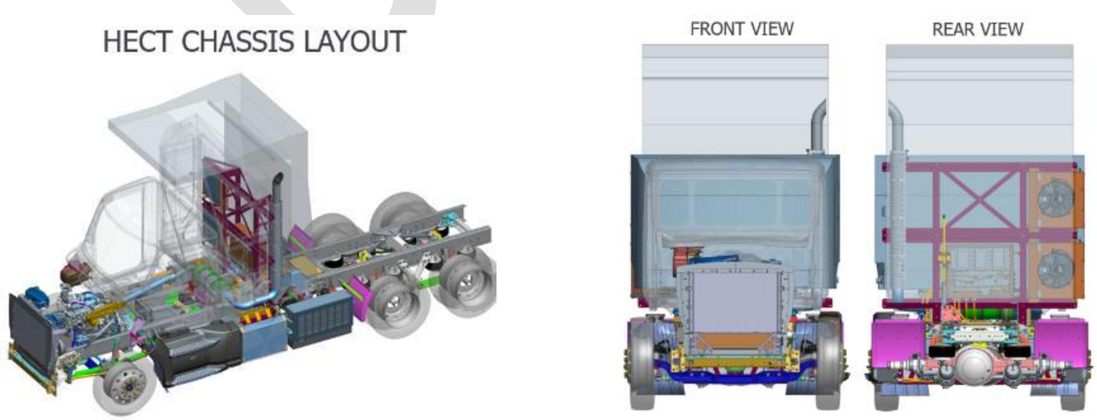


Figure 7 Main propulsion components and batteries; HV Hardware

The chassis layout is shown in the CAD Models in Figure 8. The orthographic views depict the layout of the components in the chassis. An estimated space claim for the pantograph was included to allow vehicle design to continue but it was never installed. Provisions were made in the CNG on-board storage cabinet to attach pantograph arm supports.



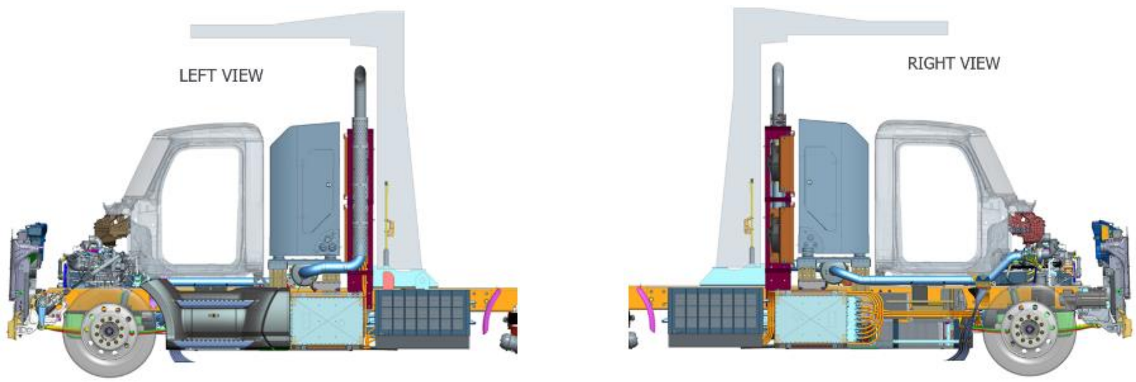


Figure 8 Model of chassis layout

Task 4 – Laboratory Integration of the Sub-System components

This Task involved subtasks that were conducted mainly at BAE as identified below.

- Subsystem lab integration
- Power electronics / PIM Test / integration
- Integrated system operational testing – Lab

The power electronics system lab at BAE was set up to test all the main components of the propulsion subsystem, including the Remy's (now BorgWarner) ACTMs (Alternating Current Traction Motor), Eaton Transmission, PIM (Power Interface Module), the PCS (Propulsion Control System), and the XPAND Battery Packs for Energy Storage. As shown below in Figure 9, the entire propulsion system was installed and characterized in BAE's Lab.

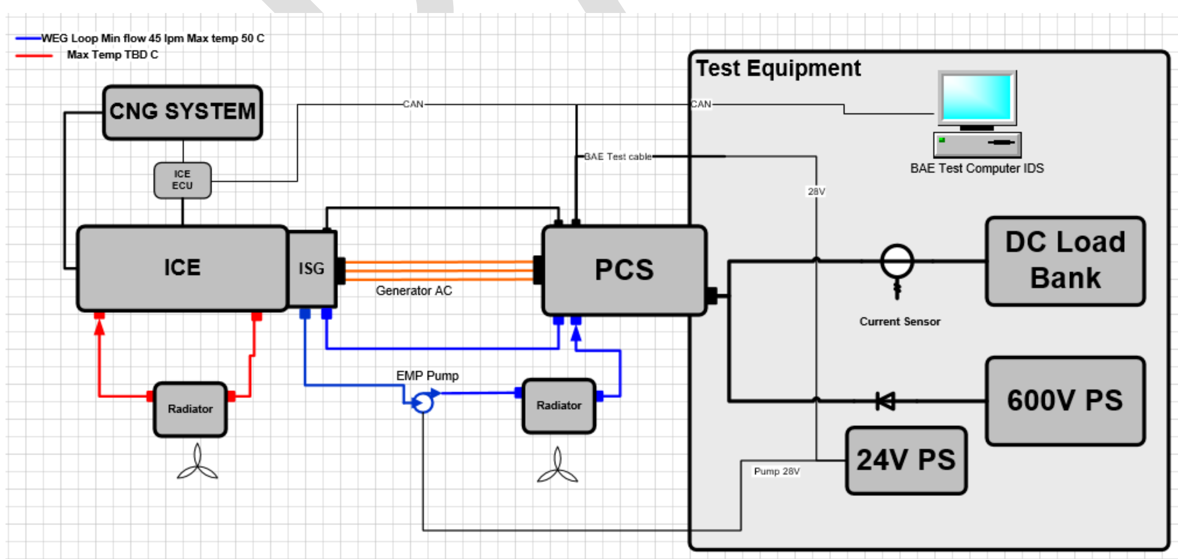


Figure 9 Lab test system schematic

The test block diagrams were created and executed per Figure 9. Here, the PCS and the PIM receive power from the ISG (Integrated Starter Generator) and send it to the DC Load Bank through a current sensor. Cooling loops were also characterized accurately.

The high-level test plan followed the information in Table 2**Error! Reference source not found.**.

	SUBSYSTEM TEST	TEST SCOPE
1	EXISTING DUAL REMY/TRANS	Motor Control Law Characterization
		Ensure Controls work with existing S6 version
2	XPAND Battery Packs	Integration into our Controls
3	AM RACING ACTM	Motor Validation with BAE Control laws & HW
		ARTIX 7 Cards Test/VAL & Tune Controls (FW)
		Perform Gear Shift tests with VECU
4	RUN SIMULATED DUTY CYCLES	Use Vehicle Dyno to simulate actual duty cycles

Table 2 Subsystem Tests in BAE Sim Lab

Overall, there four levels of testing were planned:

Component Testing

- BAE component testing for the PCS, SCU, ACTM, HVDP/Filter
- Supplier component testing for ESS

Subsystem Testing

- Controller/communication integration
- Hardware-in-the-Loop (HIL) Integration
    - Propulsion Subsystem Integration and Test
    - Transmission shifting

System Integration Testing

- Complete Propulsion System integration in the Laboratory (Endicott, NY)
- Vehicle Level Integration - Kenworth Dynamometer
    - CNG Engine/ISG Integration and Test
    - Full System Integration and Test

Vehicle Performance Testing – Test Track

- Vehicle Tuning and Optimization
- Final Performance Validation and Test

BAE provided the propulsion system components shown in Figure 10, including the system control unit (SCU), the Propulsion Control System Inverters (PCS), auxiliary power system (APS1), on-board charger for J1772 connection for depot charging, an integrated starter/generator (ISG), and the Energy Storage System (ESS). The Propulsion Control System (PCS) is utilized for both power processing and power management for the entire system. The PCS works in conjunction with the vehicle system's brain, the System Control Unit (SCU), which provides the operator interface, system monitoring, and control. These systems control the optimal flow of power to and from the traction motor, generator, and energy storage system. BAE’s PCS and SCU work in conjunction with the CNG Engine Controller to allow overall system performance to be customized to an operator’s specific requirements and provide diagnostic information to enhance truck maintenance.

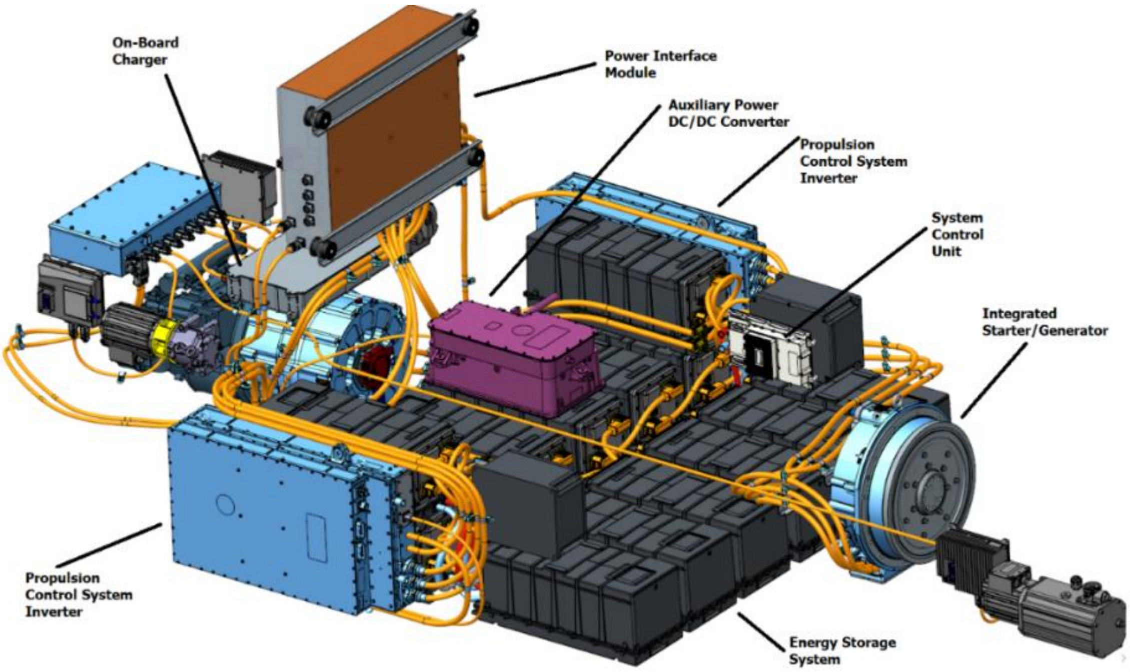


Figure 10 BAE Components of HECT Truck

The Vehicle Electronic Control Unit (VECU) was programmed to control all the sub-assemblies. The VECU and the different sub-assemblies, shown in Figure 11, were bench tested prior to mounting them on the truck.

Figure 11 650V Accessories

While lab testing scrutinized many of the potential issues, field testing and Kenworth Dynamometer testing at the Research & Development Center (RDC) were necessary to fully characterize the truck's duty cycle while on the track, enabling the truck to navigate the terrain for which it was designed. Figure 12 depicts BAE's lab setup, which included BAE's hybrid propulsion system, XALT Energy's XPAND (Battery) ESS, Remy traction motors and Transmission for power transmission to the simulated dyno motor.

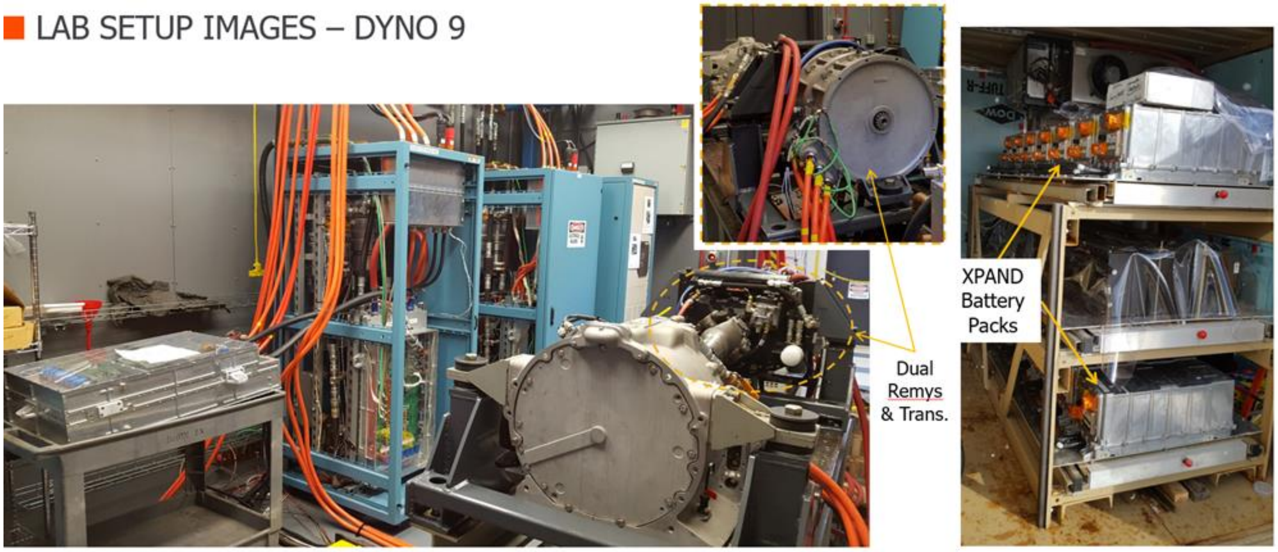


Figure 12 Lab Testing of HECT Truck Propulsion Components

This test setup simulated the duty cycle per the requirements set forth by Kenworth. Once lab testing was completed, the components were shipped for integration into the actual HECT Chassis.

The Kenworth team successfully demonstrated unit control of specific parts, inverters and sub-systems as shown in Figure 13, then repeated the process through the Vehicle Electronic Control Unit (VECU). The VECU controls motor speeds, pump speeds and inverter on/off/variability. Subsystem assemblies were built as the harnesses became available. The team built and tested the chassis-specific cooling loops, calibrated and logged all pumps used on the different systems, and fed this information back to the simulation teams to update models and recheck or confirm results.

The 650 V air compressor coupling was the last part required to complete the accessory subassembly and begin testing controls. Sub-system assembly verified the coupling design and identified an assembly opportunity for next generation components. Electrical harnesses were fabricated at Kenworth, including sub-system harnesses, pigtails to connect components to vehicle systems, and chassis harnesses with breakouts to minimize modifications during build and integration.

Figure 13 Chassis and sub-assemblies

Task 5/6 – Vehicle Mechanical and Electrical Integration

The task was performed primarily by Kenworth and involved integrating the following subsystems into the vehicle:

- electric propulsion and energy storage system (EPS and ESS)
- engine and CNG storage
- electrical accessories
- cooling system
- Fabrication, testing and installation of High Voltage harness on the vehicle
- Fabrication, testing and installation of Low Voltage harness on the vehicle

Task 7 – Vehicle Testing/Validation

The truck, with the hybrid propulsion system, was fabricated at Kenworth and preliminary characterization of the CNG engine and generator were completed prior to on-road testing. The truck was then subjected to closed track testing at the RDC at the Kenworth/PACCAR Training facility as shown below in Figure 14 R&D Test Center - Kenworth/PACCAR. Testing included both EV and hybrid (CNG/genset range extender) operating modes.

Figure 14 R&D Test Center - Kenworth/PACCAR

To satisfy the goals of the program the truck had to meet the performance parameters listed below in Table 2. These parameters include range, speed, and grade while carrying a worst-case payload of 80,000lbs.

Performance Parameter	Expected Performance*
Range	150 Miles
Top Speed	62 mph
Grade-ability	6.5% grade at 20 mph 5.0% grade at 30 mph
All-Electric Range	Up to 20 miles or 1 hour of operation depending on duty cycle and trailer load
Operating Temperatures	+16F (-9C) to +135F (57C)

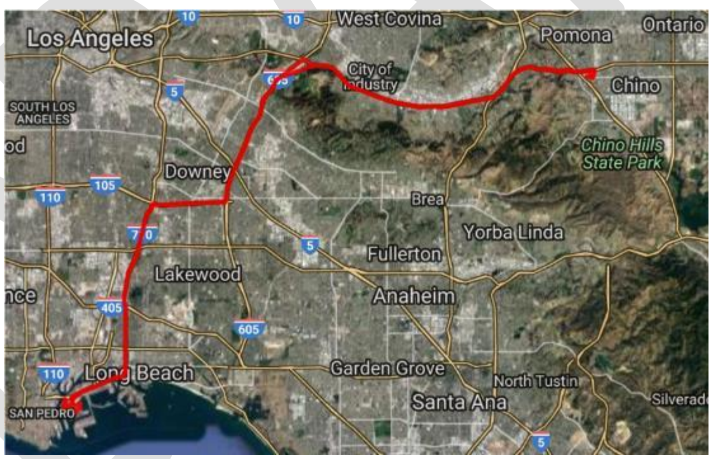
*Note: All performance parameters assume a GCWR of 80,000 lbs unless otherwise noted

Table 3 HECT Truck Expected Performance

Of special note, the gradeability tests the truck's ability to climb a steep incline, which requires the truck to navigate the steep approach to a couple of bridges while carrying 80,000 lbs of cargo. Figure 15 shows the bridges on its typical route at the Port of LA.

Figure 15 Bridge Overpasses

Testing at Kenworth/PACCAR consisted of a combination of test-track testing and simulations based on models that incorporated data from the component tests and the measured performance on the track. The typical route simulations are shown in Figure 16 and Figure 17.



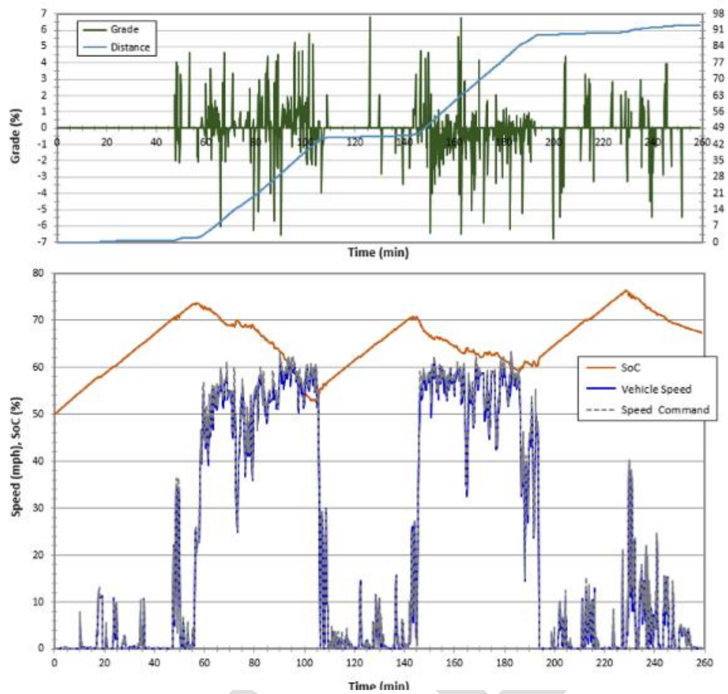


Figure 16 SIM #1 Route to Chino & Results

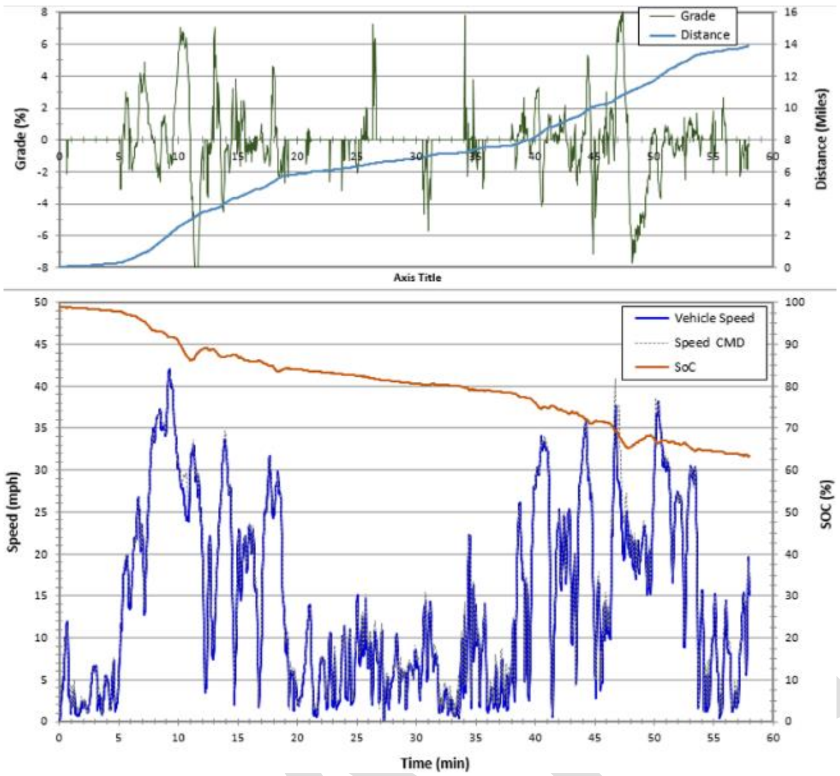


Figure 17 SIM #2 EV Mode in Port Area

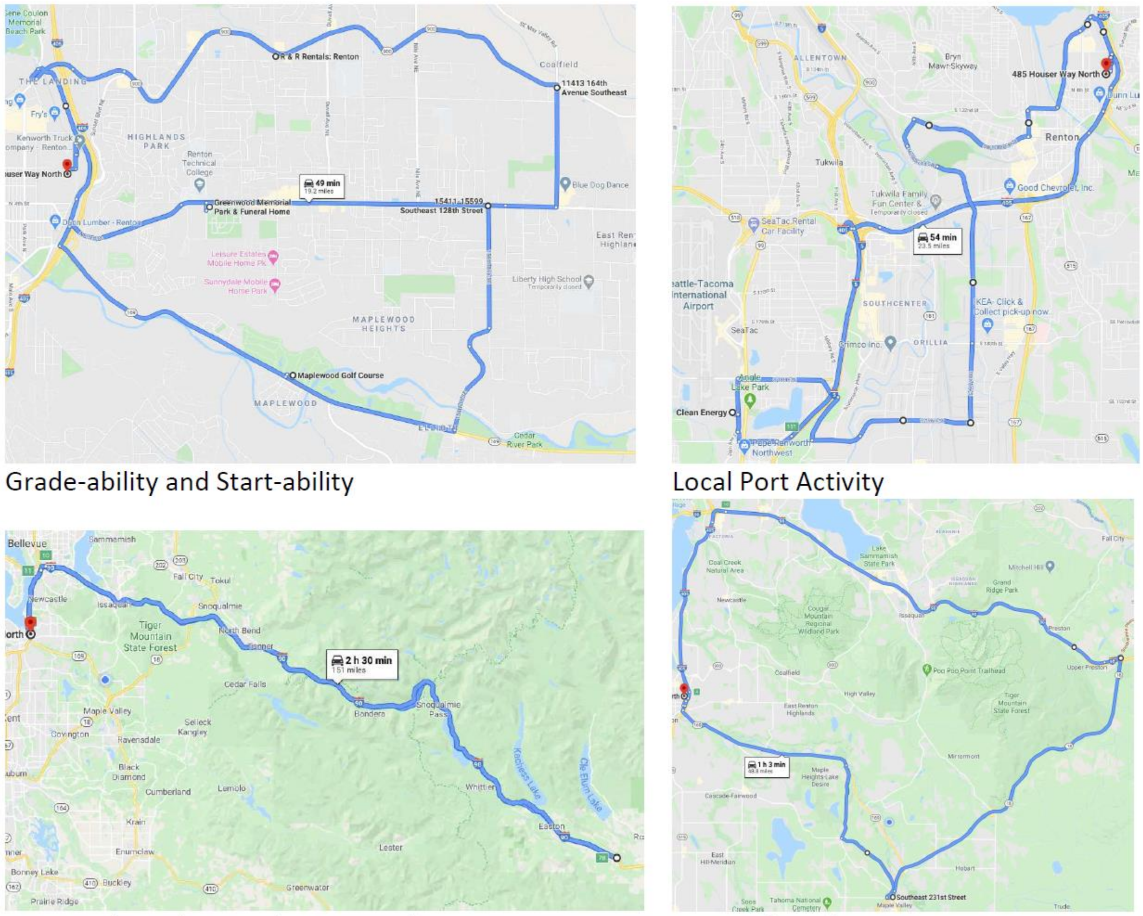
Weighing of the truck disclosed that the weight on the front axle marginally exceeded the rating for the front axle. To correct this, a higher rated axle was ordered, installed and tested on HECT before the truck was released for use on public roads. This higher weight also required a boost in the power of the power steering pump in order to facilitate turning of the wheels while stationary. Another issue identified in preliminary testing was an apparent pressurized air leak into the transmission. This leak manifested itself in spitting transmission oil out of the vent stack when gears were changed. The root cause was traced to a pinhole created during fabrication of one of the transmission actuators. This was corrected and the system shifted correctly without losing any transmission fluid. There were a number of unexpected minor electrical issues (bad contacts in connectors, harnesses mis-wired) that were caught during assembly. More sophisticated test harnesses would be able to exercise and test entire truck systems and minimize this problem, however this solution is practical only when multiple copies of the same truck are fabricated.

After preliminary testing at Renton R&D, the completed truck was moved to the PACCAR Test Center (PTC) for more extensive testing. This included testing with loads on the test track, as shown in Figure 18 and Figure 19, to verify that the truck met or exceeded all contractual requirements; and rapid mileage accumulation driving to verify reliability.

Figure 18 HECT Truck with flatbed trailer and load

Figure 19 PACCAR test track

A battery of tests was performed to test its operational readiness and reliability. These tests included all road conditions, including grade, incline and decline conditions, start/stop intervals and handling. Beyond the track testing, the vehicle was submitted to a battery of local routes that were found to contain all the obstacles this chassis would navigate through while in commercial service. As an example, local routes between the PACCAR Technical Center and the Kenworth R&D Center replicated near-port applications (Figure 3). A hill route with a 9% grade for more than a quarter mile and a mid point stop light tested the vehicle's ability to traverse the bridges around the Port of Los Angeles and Long Beach as well as start/stop conditions on the bridges. And our regional trips over Tiger Mountain and Snoqualmie pass tested the vehicles long haul and freeway runs. The regional loop contained multiple areas of sustained 5-6% grades, are a combination of near city operations in high traffic conditions and open highway runs at sustained high speeds.



Grade-ability and Start-ability

Local Port Activity

Sustained Grade at Highway Speed

Regional Haul

Figure 20 Selected routes representative of typical duty cycles

The tests were scaled to ensure the vehicle would survive a two year test period instead of ten years of commercial service. However, all DOT and FMVSS requirements were met to ensure certification for use on public roads. The testing took approximately 15 months and completed 3,700 miles of track and road testing in Washington before reliability targets were satisfied. It should be noted that all vehicle tests were conducted at near capacity loads of 80k lbs.

Field testing on the ZECT truck uncovered that the shore power connections and charging system needed to be upgraded. A more advanced "smart" shore power charging port was designed built, tested, and installed on the HECT truck, as shown in Figure 21. The new shore power system ensured that power is sent to the areas of the truck that need power and that fully charged or unused sections of the truck (such as battery heating on warm nights) do not draw power. The new system also made it easy to charge the High Voltage batteries to full power overnight. This means the truck starts the workday with a full battery charge, which extends its range for a single CNG fill.

Figure 21 Charging station for shore power

Testing of the truck with upgraded transmission software uncovered a condition that resulted in unsuccessful shifts. BAE and Kenworth controls teams struggled to manage a phase shift issue within the motor resolver. Two theories, software versus hardware issues, were vetted to determine the root cause of a motor fault that shut down operations. PTC conducted tests based on requests from the motor supplier, BAE, and Kenworth, none of which could identify a solution. Testing was stopped; the chassis was pulled from the test track and returned to KW R&D for a tear-down and inspection. The electric motor supplier completed the tear-down, component and assembly analysis and determined that the rotor assembly had not been properly torqued and was moving when introduced to extreme loads and operating conditions. The motors were reassembled with high strength fasteners, properly torqued and returned to KW for continued testing.

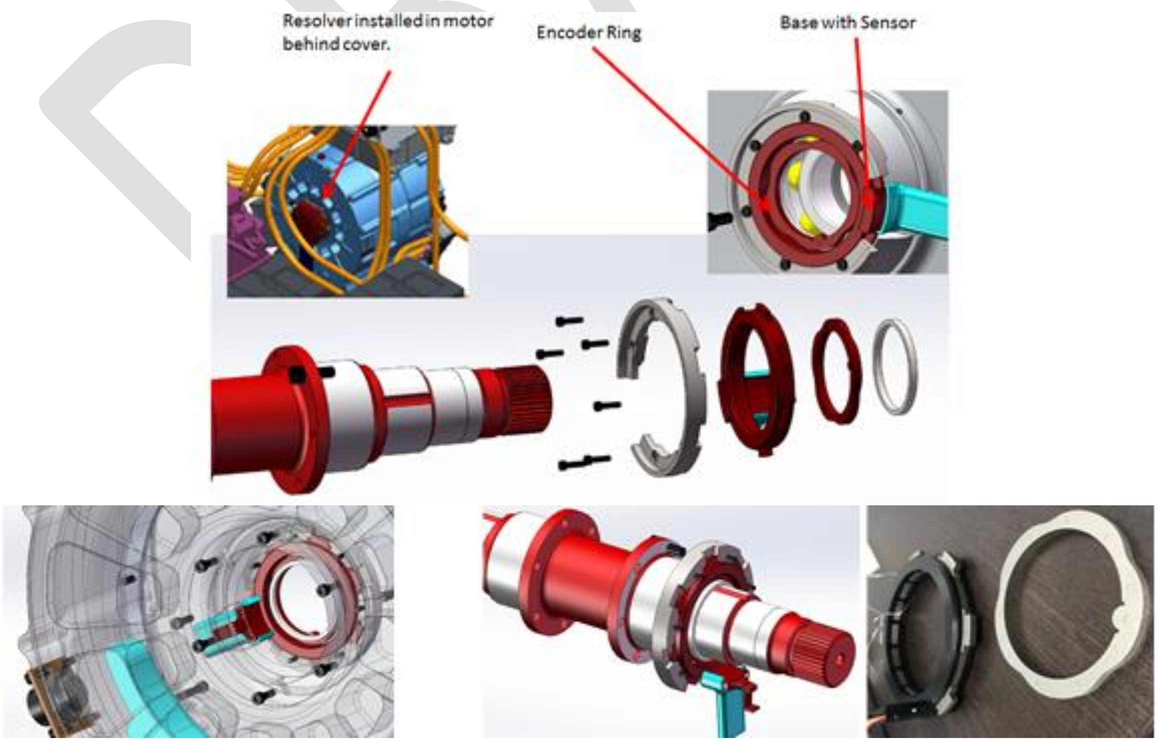


Figure 22 Resolver details

Another issue was an error in the #2 ACTM motor's resolver's offset. Each ACTM is made up of two motors, each with their own resolver (Figure 22). Specific component testing did not disclose the root cause of the issue. Software and firmware workarounds were attempted, worked for a period and long enough to promote efforts to the next level of analysis. However, the offset temporarily halted track testing. Transmission shifting was optimized and the resolver offset error was corrected.

A difficulty in conducting extended testing at PTC was the lack of a CNG fueling station within 75 miles of the test track. Rapid mile accumulation testing necessitated towing the truck to the fueling station in order to refill with CNG and then a return tow to the track. This effort continued until the chassis reliability was such that the vehicle was allowed to travel under its own power to and from the filling station.

Figure 23 HECT at refueling station

Another major issue was related to the high voltage distribution box (Figure 24). After several software modifications, the issues were traced to a firmware issue that prevented reliable power switching at the high voltage DPE's (digital power equipment). The root cause required several weeks of investigation, many test iterations and several destroyed DPE's before the issue was identified and resolved. The HVPD and DPE firmware was updated; the unit was reassembled, reinstalled in the chassis and functionally tested. The vehicle had to repeat a number of the performance tests to ensure the solution was reliable.

Figure 24 High Voltage Power Distribution (HVPD) box

The power steering assembly (Figure 25) faulted fuses in spite of software and firmware changes. The pump supplier was brought in to work with the team and help determine the root cause. One of the units was fitted with additional access ports such that engineers could add pressure sensors to different areas in the system and pull operating pressures while the vehicle conducted specific maneuvers.

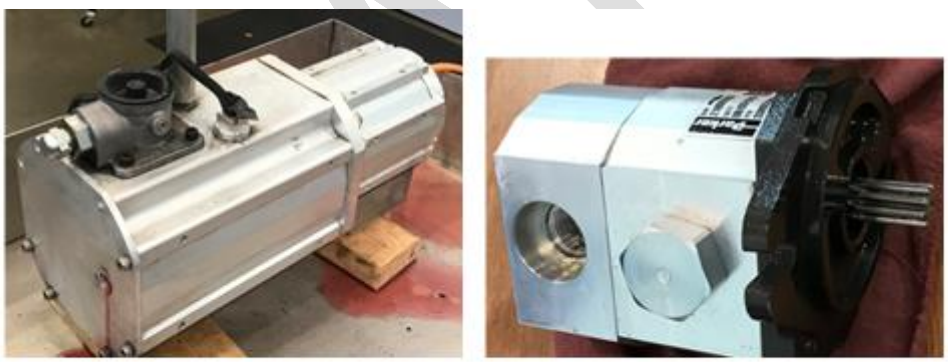


Figure 25 Power Steering sub-assemblies

Once the operating pressures were collected it was found that the pump pressures were lower than expected and had to be increased to resolve operation faults and improve steering effort during dry-park wheel turns. The pump supplier built and tested replacement pumps and had them delivered to Kenworth for testing.
Another major issue that caused an extended downtime was a loose HV connection that resulted with damage to Battery Disconnect Unit (BDU), shown in Figure 26.

Figure 26 Damaged Battery Disconnect Unit

Replacing the BDU addressed the immediate failure, but the system continued reporting HV grounding faults. Upon extensive investigation and troubleshooting, the issue was narrowed down to an internal fuse issue in one of the battery packs. All battery packs were removed from the chassis and fuses were inspected individually (Figure 27). Faulted fuses were replaced and the subsystems were assembled back into the vehicle.

Figure 27 Inspection of battery fuses

Track tests were invaluable in finding operational and performance issues prior to releasing the vehicle to TTSI. The KW team completed modifications to the HECT transmission shifting algorithms and feedback from the test engineers suggested the changes were a success. The key determination for success was the vehicle's ability to repeat the shifts for duration of a reliability test.

Kenworth team has performed a battery of other tests, typically associated with verification and validation of high-volume commercial vehicles. Those tests included:

Aero & Fuel Economy

Air flow was tested under bonnet, under fairing, and behind the cab. Fuel consumption was tested at steady speeds of 30, 45 and 60 mph using routes that simulated TIAX and port delivery profiles, and heavy-duty city circuit (HDCC).

Battery State-Of-Charge

When the vehicle's battery state of charge (SOC) is low it is critical to properly inform the driver of this state so the driver can respond appropriately. The truck has two indications of battery SOC, both of which clearly indicate the battery SOC to the driver. In the event a user ignores a depleting SOC, the vehicle will enter a derated performance mode. This derated mode significantly degrades available torque, but sufficient power remains to reach a safe location to stop the vehicle.

Electrical/Electronics

Component level tests included EMI/EMR, vibration & environmental testing, salt fog, water intrusion, freeze-thaw cycle, gravel, UV and fluid compatibility, low voltage systems, and high voltage specific test (1 k-Ohm). Charge limits were tested for shore-power charge, regenerative braking, and generator power generation.

Noise, Vibration & Ride

Baselines for drive-by noise and vehicle modal conditions when parked were developed, as were profiles for acceleration, braking, steering, and minimum vibration characteristics and a baseline for vehicle dynamics. Kenworth specifically measured differences during lane change conditions, ride & handling at multiple speeds, and modal points and excitation conditions.

Powertrain Validation

Powertrain efficiency and performance were tested. This included speed on various grades, maximum starting grade, and the maximum range in all-electric mode (EV).

Structural Evaluation & Durability

Tests also included compatible material evaluation for deionized Water Ethylene Glycol (WEG), FEA support to prevent infant mortality (IM) issues, and scaled durability track testing to verify/validate IM mitigation.

Thermal Management

Thermal management tests included cooling performance, system conditions under load, de-rate management under max load, and energy consumption. To test cooling performance, each cooling loop was checked for capacity and limitation as well as combined system level limitations. To test system conditions under load, temperature data was gathered under various load conditions and under various environmental conditions. De-rate management under max load was tested at ambient temperature & max output or during max regenerative braking. Energy consumption was reviewed during defrost, dehumidify, cold start at ambient temperature, and at high engine rpm when in vehicle creep mode.

While the HECT vehicle was on site key components were instrumented with thermocouples to provide guidance for calibrating thermal system models. The temperatures of these components were evaluated under stressed vehicle conditions. Figure 28 through Figure 32 provide visual representation of maximum temperatures reached at various locations under the stated conditions as follows:

- Ambient Temperature = 75 °F
- Dyno trailer applying load to maintain ~35 mph
- GCVW = 80,000 lb
- Location = High-Speed Track at PTC
- 100% Pedal Position for 25+ minutes continuously

Testing was repeated several times under the conditions listed above, varying the cab air conditioning on and off. Also included in testing was a hot shutdown and soak in which the truck was parked in direct sunlight. Then, a power failure was simulated by removing fuses for circulation pumps and fans to actively cool the vehicle systems post key-off while continuing to log thermal data. Figure 28 through Figure 32 illustrate the maximum temperatures of different components.

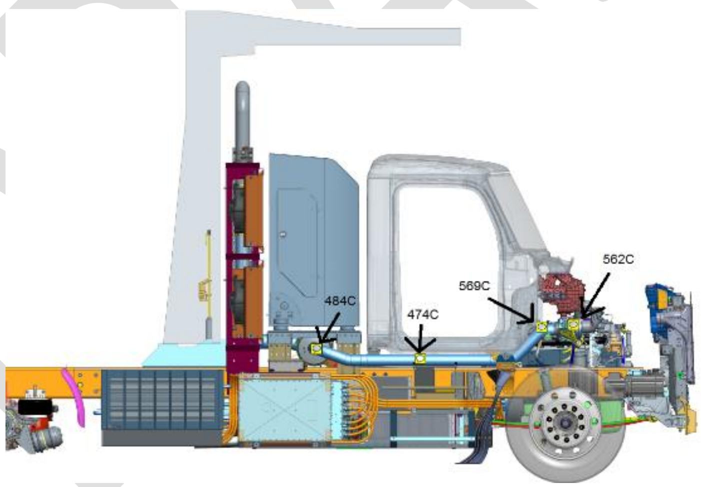


Figure 28 Component Temperatures

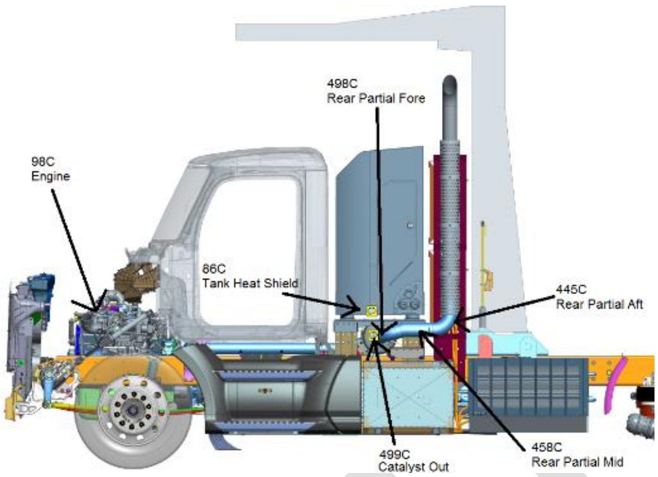


Figure 29 Component Temperatures

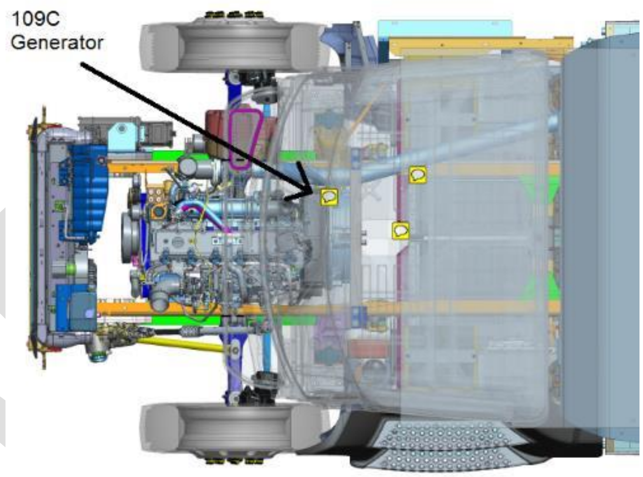


Figure 30 Component Temperatures

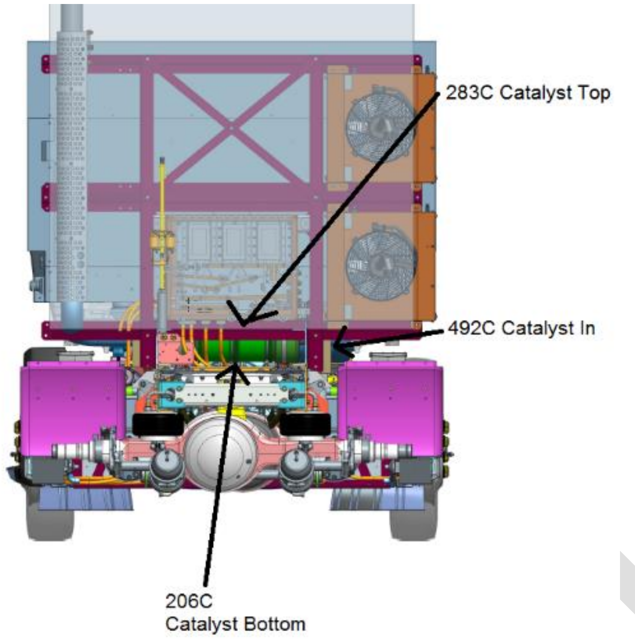


Figure 31 Component Temperatures

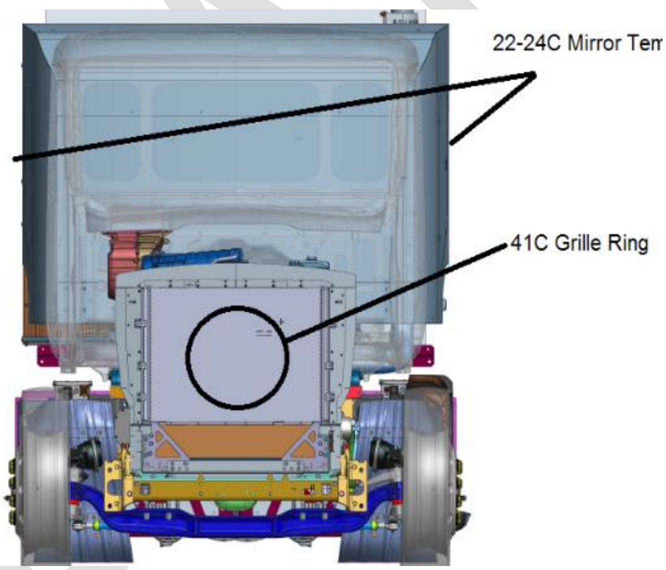


Figure 32 Component Temperatures

Vehicle Operations

Standard vehicle operations testing included key-on sequence, key-off sequence, E-Stop control, steering, braking (compressor performance and efficiency), acceleration, transmission shifting smoothness and accuracy.

Other Items and Compliance:

Compliance was checked for: SAE J2910, FMVSS 305, ISO 26262, and IEC 61580.

Overall vehicle performance achieved the targets presented.

Parameter	Target	Measured
Range Total	150 miles	284 miles*
Elec-Only	20 miles	26 miles
Top Speed	62 mph	65 mph

- Note: 80,000 lbs. GCW, *Measured from test track

Table 4 Performance Test Results

Key vehicle characteristics such as acceleration, range, and gradeability were verified to be sufficient for the intended service and largely competitive among conventional diesel products. Kenworth R&D's estimates of these vehicle traits were very close to tested actual results.

PTC identified a few areas of concern with the HECT vehicle. This was considered a key element of testing at PTC. The areas where opportunities for improvement exist are as follows:

- High-voltage (HV) fuse reliability for accessory loads
- Transmission shifting
- Electrified accessories

These areas rendered the vehicles untestable on multiple occasions, often ending a test prematurely or leaving the truck without the ability to continue moving under its own power. Often, this required PTC to swap out HV fuses. In-rush current for each of the accessories was greater than it was presumed to be, which resulted in many fuse replacements.

Task 8 – Vehicle In-service Operation

After completing the tests at PTC and accumulating 3,700 miles the HECT truck was released for on-road testing and delivered to TTSI on October 8th 2019. Training was conducted at TTSI and Inland Trucking regarding use and maintenance of the truck. A preliminary fault escalation plan was prepared and reviewed by the stakeholders. The documents underwent several iterations of modifications based on end user input.

After a delayed start of service due to issues with California Department of Motor Vehicles registration of the vehicle, the vehicle has accumulated over 3,000 trouble-free miles in the first quarter of 2020. Due to an outbreak of COVID-19 the Port of LA freight volumes deteriorated significantly, and the fleet operator has reduced the utilization of the vehicle. At the same time some minor issues (fuse failed during emissions test and fluid leak) have impacted the mileage accumulation, which was approx. 2,000 miles in the second quarter of 2020. With the increased freight demand and great reputation among the drivers, the vehicle was operated in the third quarter of 2020 with a couple more minor electrical issues.

The vehicle has accumulated 8,835 miles of commercial service through the conclusion of the project in November 2020.

Task 9 – Data collection and Vehicle Performance Evaluation

The team has performed two distinct data collection tasks.

In-service Data Collection

The first task was a collection of various performance parameters collected from the vehicle CAN networks as required by NREL and detailed in Figure 33and Figure 34:

		Driving		Charging	
EV Vehicle and Infrastructure Parameters	Units	Ideal sample rate	Minimum sample rate	Ideal sample rate	Minimum sample rate
Vehicle ID	n/a	Once per file	Once per file	same as Driving	
Timestamp	dd/mm/yyyy hh:mm:ss.x	Every record	Full date/time once per file; seconds (with decimal) counter every record	same as Driving	
Operation state	n/a	Every record	When changes	same as Driving	
Vehicle speed	kph	5hz	1 Hz	n/a	n/a
Accelerator pedal position	%	5hz	1 Hz	n/a	n/a
Brake pedal position or force	% or N	5hz	1 Hz	n/a	n/a
Battery current	DC A	10 Hz	1 Hz	once per 5 sec	once per 60 sec
Battery voltage	DC V	10 Hz	1 Hz	once per 5 sec	once per 60 sec
Battery pack SOC	%	2 Hz	1 Hz	once per 5 sec	once per 60 sec
Battery pack DC discharge energy	DC Wh	1 Hz	once per 5 sec	once per 5 sec	once per 60 sec
Battery pack DC charge energy	DC Wh	1 Hz	once per 5 sec	once per 5 sec	once per 60 sec
Battery pack min cell voltage	V or mV	10 Hz	1 Hz	once per 5 sec	once per 60 sec
Battery pack max cell voltage	V or mV	10 Hz	1 Hz	once per 5 sec	once per 60 sec
Battery pack balance mode state	on/off	n/a	n/a	1 Hz	When changes
AC current	AC A	n/a	n/a	once per 5 sec	once per 60 sec
AC voltage	AC V	n/a	n/a	once per 5 sec	once per 60 sec
AC power factor		n/a	n/a	once per 5 sec	once per 60 sec
AC charge energy per event	AC Wh	n/a	n/a	1 hz	1 hz
AC discharge energy per event or cumulative	AC Wh	n/a	n/a	once per 5 sec	once per 60 sec
GPS latitude	degrees, minutes	2 Hz	1 Hz	once per 60 sec	once per 60 sec
GPS longitude	degrees, minutes	2 Hz	1 Hz	once per 60 sec	once per 60 sec
GPS altitude	m	2 Hz	1 Hz	once per 60 sec	once per 60 sec
Load (payload)	kg or lb	Once per file	once per file	n/a	n/a
Ambient temperature	deg C	1 Hz	once per 5 sec	once per 60 sec	once per 600 sec
Battery pack bulk temperature (e.g. intake air or coolant temp)	deg C	1 Hz	once per 5 sec	once per 60 sec	once per 60 sec
Battery pack min cell temperature	deg C	1 Hz	once per 5 sec	once per 5 sec	once per 60 sec
Battery pack max cell temperature	deg C	1 Hz	once per 5 sec	once per 5 sec	once per 60 sec
Motor temperature	deg C	1 Hz	once per 5 sec	n/a	n/a
Power electronics temperature	deg C	1 Hz	once per 5 sec	once per 5 sec	once per 60 sec
Charger temperature	deg C	1 Hz	once per 5 sec	once per 5 sec	once per 60 sec
Motor speed	rpm	10 Hz	1 Hz	n/a	n/a
Motor torque	Nm	10 Hz	1 Hz	n/a	n/a
Motor power (electrical)	W	10 Hz	1 Hz	n/a	n/a
Air conditioner state	on/off	1 Hz	once per 5 sec	n/a	n/a
Air conditioner compressor instantaneous power	W	1hz	1 Hz	n/a	n/a
Heater state	on/off	1 Hz	once per 5 sec	n/a	n/a
Heater instantaneous power	W	1 Hz	once per 5 sec	n/a	n/a
other ancillary power demands (i.e. PTO or other)	W	1hz	1hz	n/a	n/a
Defroster state	on/off	1 Hz	once per 5 sec	n/a	n/a
Shifter position (PRNDL)	n/a	1 Hz	when changes	n/a	n/a
Transmission gear state (if applicable)	n/a	1 Hz	when changes	n/a	n/a
Auxiliary 12V battery current	V or mV	2 Hz	1 Hz	2 Hz	1 Hz
Auxiliary 12V battery voltage	A or mA	2 Hz	1 Hz	2 Hz	1 Hz
Inverter DC bus current	V or mV	10 Hz	1 Hz	n/a	n/a
Inverter DC bus voltage	A or mA	10 Hz	1 Hz	n/a	n/a
Inverter three-phase PWM output voltage	V or mV	10 Hz	1 Hz	n/a	n/a
Inverter three-phase output currents	A or mA	10 hz	1 Hz	n/a	n/a
Inverter coolant inlet pressure	kPa	2 Hz	1 Hz	n/a	n/a
Inverter coolant outlet pressure	kPa	2 Hz	1 Hz	n/a	n/a
Motor coolant inlet pressure	kPa	2 Hz	1 Hz	n/a	n/a
Motor coolant outlet pressure	kPa	2 Hz	1 Hz	n/a	n/a

Figure 33 Vehicle parameters collected for NREL

CNG Vehicle Parameters	Units
Engine speed	rpm
Engine torque @ reference points	Nm
Oil temp	deg C
Coolant temp	deg C
Intercooler temp	deg C
Crankcase pressure	kPa
Turbo boost	kPa
Intake temp	deg C
Intake pressure	kPa
Engine exhaust temp	deg C
Engine exhaust pressure	kPa
MIL lamp status	on/off
SCR tank level if equipped	%
Exhaust regen status if equipped	on/off
Aftertreatment fuel rate if equipped	L/h
Fan state	on/off
Fan speed	rpm
Nominal friction percent torque	%
Engine reference torque	Nm
Engine percent load	%
Engine air filter differential pressure	kPa
Compressor status	on/off
Pneumatic supply pressure	kPa
CNG tank pressure	kPa
CNG tank temperature	deg C
CNG delivery pressure	kPa
CNG delivery temperature	deg C
Fuel mass flow rate	g/s

Figure 34 Vehicle parameters collected for NREL

Data was tracked using the Aptiv Qualifier System Validation Service and transferred to PACCAR as a .mat file. Each run generated a new .mat file. PTC personnel regularly ran a script to filter all but the desired signals for the truck and saved the filtered data as a .csv file. The .csv file was stored on a BOX account, which was accessible to CALSTART and NREL. CALSTART has performed the analysis of operational data which is presented in an

Portable Emissions Measurement System Testing

CALSTART has performed in-use emissions testing with a Portable Emissions Measurement System (PEMS) supplied by Sensors, Inc (Figure 35

Figure 35 HECT truck with PEMS equipment installed

A separate summary of this testing was prepared by CALSTART and is included in Appendix A.

Task 10 – Commercialization Roadmap and Scenario Analysis

A commercialization roadmap and scenario analysis were prepared by CALSTART and are reported below in Appendix B

Discussion Of Results

In summary, the HECT vehicle has met or exceeded its performance attributes expected of a high-volume production vehicle. The tests performed by Kenworth team have not identified any shortcomings and qualified the truck as fully meeting the design and performance requirements. A few areas where opportunities for improvement exist are as follows:

- High-voltage (HV) fuse reliability for accessory loads
- Transmission shifting
- Electrified accessories

Throughout of the duration of the project the vehicle was subjected to extensive battery of tests. The most notable test results and observations are:

Commercial Service Operation

While not a test specifically, it was one of the critical goals of the project. The duty cycles in commercial operation were measured and characterized by CALSTART, and are reported in detail in Appendix A. Driver interviews and feedback from the fleet operator indicated that the vehicle was a preferred truck by the drivers, and valued for excellent performance and driver comfort. Unlike other advanced technology vehicles, the fleet management and the drivers were confident in reliability of the vehicle, which was evidenced by extensive mileage accumulated in service. The truck was also frequently sent on longer trips, with a record distance of 284 miles traveled in one day – unattainable by the current zero-emission vehicles.
The truck reliability was not without an issue, but the problems were not of systemic nature, and related to the novel components (sensors, fuses, electric air compressor). It is reasonable to expect that the issues can be easily eradicated with transition to series production, and more extensive operation of the trucks. The vehicle accumulated 8,835 miles of revenue service at the Port of LA without major incidents, operating from October 2019 through November 2020.

Emissions and Fuel Economy

The emissions and fuel economy test results, while showing improvement over the conventional technologies, are not as conclusive as expected and warrant further, detailed testing under controlled conditions and protocols. Additionally, the Cummins-Westport engine used in the vehicle is not certified or optimized for hybrid application, and it is presumed that optimization of the control system and engineering support from the Cummins would offer improvement of the emissions and fuel economy characteristics. More detailed discussion of the testing and results is covered in Appendix A.

Range

Performance Parameter	Expected Performance	Observed Performance
Range	150 miles	284 miles
Top Speed	62 mph	65 mph
Gradeability	6.5% grade at 20 mph 5% grade at 30 mph	~8.5%+ at 20 mph* ~5.5%+ at 30 mph* *(simulation results)
All-Electric Range	20 miles or 1 hour	26 miles
Startability	30% (stretch goal)	20%

Table 5 Performance targets and results

HECT's 230kW CNG engine can generate enough power to sustain the vehicle at 60mph. It is also important to note that this testing was primarily performed using flatbed, non-aerodynamic trailers on PTC's high-speed test track. The test rack is not completely flat and contains 4 distinct corners. No regenerative braking occurred throughout these tests.

Startability

Startability, defined as the vehicle's ability to launch on a grade, was also assessed. There are two large hills on-site at PTC, a 20% and a 30% grade. We made multiple attempts to launch the vehicles in various configurations on the 30% grade, all of which were unsuccessful. This was a bit of a stretch goal, as our target was the 20% hill. HECT successfully launched on the 20% grade while loaded to the target weights.

Top speed runs were also performed on our closed test track. Top speed targets were easily achieved. Battery temperatures were observed during max power testing in which a dyno trailer was used to apply enough load to require the HECT vehicle to exert maximum power for 25-minute sessions. This test was run at a steady speed of 35 mph in 75 °F ambient conditions on the PTC high-speed track.

Gradeability

A vehicle's ability to maintain speed while climbing a hill is defined as its gradeability. Since PTC was not able to take these vehicles off-site to perform sustained hill climbs, it relied on torque reporting and calculations to estimate the gradeability. Shown below in Figure 36 are the Power & Torque Curves reported by the vehicle under continuous maximum load across varying motor speeds.

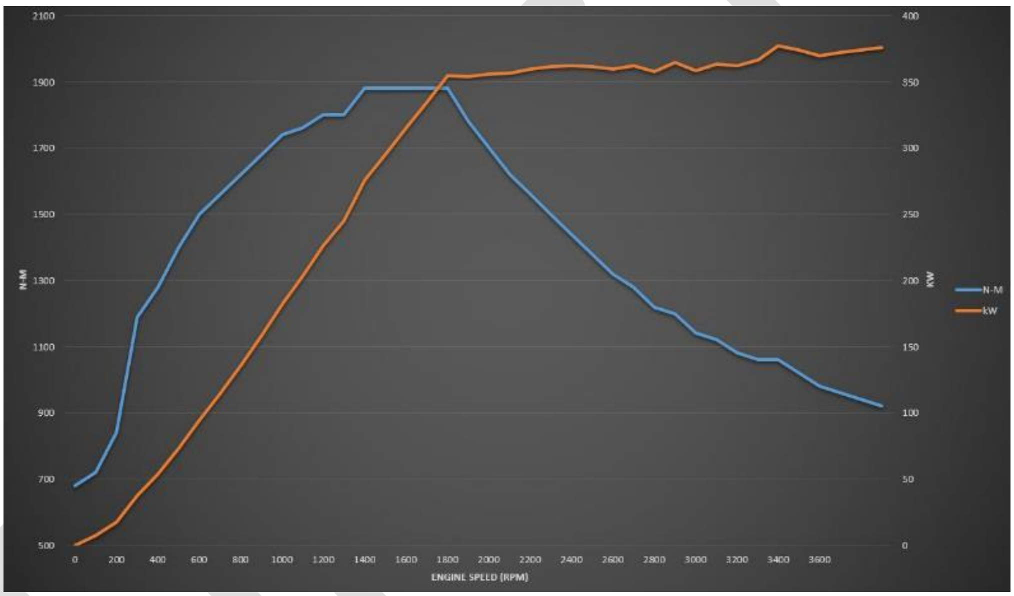


Figure 36 HECT Power and Torque Curves

Using these data an estimated maximum grades that the vehicle can ascend given a target vehicle speed were calculated. Assumptions include: estimated air resistance, estimated rolling resistance, estimated drivetrain efficiency values, and calculated tractive force. Gradeability by gear and vehicle speed is estimated in the graph below in Figure 37 and shows an acceptable performance.

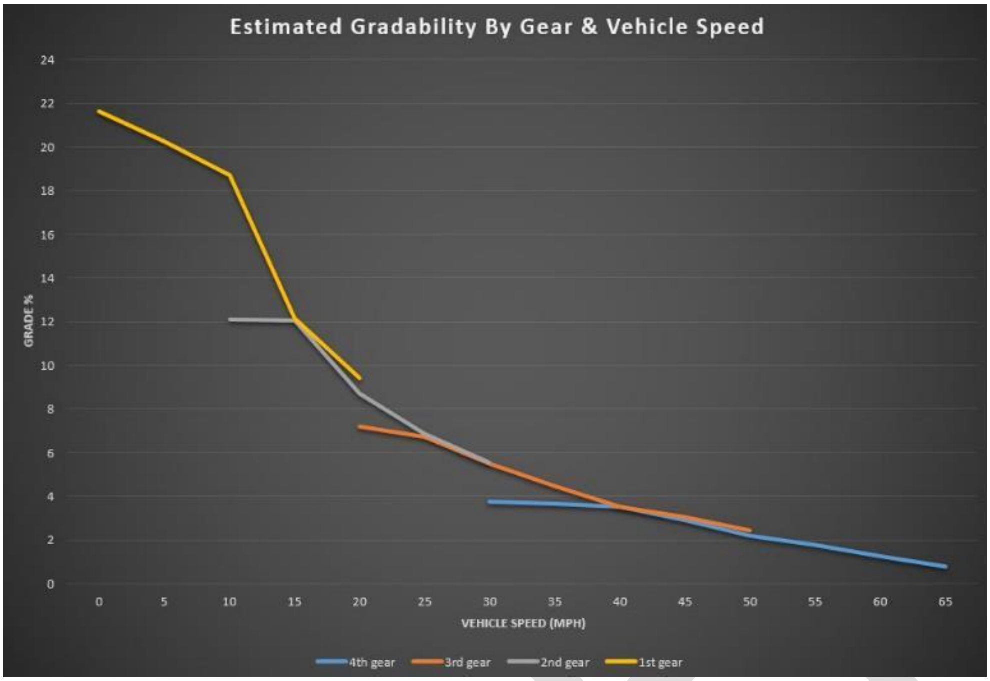


Figure 37 HECT Gradeability

Powertrain Systems Vehicle Acceleration Through Gears

Powertrain Systems Vehicle Acceleration Through Gears test, evaluates the acceleration performance of a loaded vehicle. This includes standing-start acceleration measurements to 30 and 60 mph, as well as time through a measured distance to ensure a loaded vehicle could adequately make it through an intersection prior to a light change. Acceleration was quite good and passed the evaluation. The HECT truck runs quite a bit faster than typical diesel trucks from 0 to 30 mph. Compared to an MX-11 engine-powered on-highway truck the HECT truck was nearly twice as fast. By 60 mph the difference had been mostly made up by the diesel truck. Table 3 shows the values and respective test weights for acceleration through the gears for the HECT truck as compared to truck 1706, an MX-11 engine-powered Kenworth T680 with 430 hp, 12-speed PACCAR AMT and 2.85 rear-axle ratio.

Vehicle	Transmission	Rear Axle Ratio:1	GVCW (lb)	0-30mph (s)	0-60mph (s)	45-60mph (s)	Thru Intersection (s)
HECT	4-speed AMT	5.38	78,140	16	74	37	12
1706 – 430 hp MX-11	12-speed PACCAR AMT	2.85	76280	25	79	33	17

Table 6 Acceleration Rates

Slow Speed Maneuverability

Slow speed maneuverability is a critical aspect for Class 8 trucks, especially trucks expected to operate within port facilities in and around foot traffic and heavy equipment. The slow-speed maneuverability evaluation is a subjective driver-feedback survey in which the driver is asked to perform several key tasks, all requiring precise vehicle control at slow speeds. Examples of this would be docking a trailer, dropping and hooking up to a trailer, and backing around a corner. In all situations with the HECT, driver confidence was high as drivers felt under full control of vehicle motion and were able to safely execute all maneuvers multiple times. Slow speed maneuvering is a distinct advantage for these vehicles as compared to a conventional diesel engine and transmission combination that relies on a clutch to provide vehicle motion.

Air System

Because of the critical dependence on the air system of a Class 8 truck the time required for the on-vehicle air compressor to fully charge the air system is of keen interest. To fully charge the air system conventional trucks, depending on vehicle specifications, range from 120 seconds to upwards of 180 seconds. The HECT vehicle required 148 seconds from 0 psi to governor cut-off at ~135 psi. One area of difference between a conventional product and the HECT truck is that in a diesel truck a user can manipulate engine speed through fast-idle-control (FIC) to cut the 180-second time in half. While the FIC is a benefit in conventional diesel trucks over the HECT truck, the inability to manipulate engine speed through FIC in HECT truck is not viewed as a significant detriment.

Engine Retarder versus Regenerative Braking

The benefits of electrified powertrains are numerous and real, but not without compromise. One area of concern that must be appropriately handled is the transition from the reliance of a diesel engine brake to safely descend a grade to depending solely on regenerative braking. As electrified powertrains gain popularity and begin to penetrate the Class 8 truck segment, maintaining vehicle control down a grade is critical to vehicle adoption rates in applications where trucks are expected to operate on hilly terrains. The intended routes for these proof-of-concept trucks will include some long steep hills, although likely not many. Because of the generous size of their battery packs, there is significant regeneration potential on these trucks. A 100 kWh of energy storage onboard would provide a considerable amount of regenerative braking potential. Regenerative braking force was experienced on the PTC high-speed track and seemed sufficient at the test weights that were employed (80,000 lbs and 65,000 lbs). Unfortunately, regenerative braking-system performance on off-site downgrades could not be verified at PTC.

Aerodynamics

Air flow was tested under bonnet, under fairing, and behind the cab and did not indicate any issues.

Electrical/Electronics

Component level tests included EMI/EMR, vibration & environmental testing, salt fog, water intrusion, freeze-thaw cycle, gravel, UV and fluid compatibility, low voltage systems, and high voltage specific test (1 k-Ohm). Charge limits were tested for shore-power charge, regenerative braking, and generator power generation and no issues were reported.

Noise, Vibration & Ride

Baselines for drive-by noise and vehicle modal conditions when parked were developed, as were profiles for acceleration, braking, steering, and minimum vibration characteristics and a baseline for vehicle dynamics. Kenworth specifically measured differences during lane change conditions, ride & handling at multiple speeds, and modal points and excitation conditions.

Powertrain Validation

Powertrain efficiency and performance were tested. This included speed on various grades, maximum starting grade, and the maximum range in all-electric mode (EV). The vehicle met or exceeded powertrain performance of conventional vehicles.

Structural Evaluation & Durability

Tests also included compatible material evaluation for deionized Water Ethylene Glycol (WEG), FEA support to prevent infant mortality (IM) issues, and scaled durability track testing to verify/validate IM mitigation.

Thermal Management

Thermal management tests included cooling performance, system conditions under load, de-rate management under max load, and energy consumption.

Conclusions and Recommendations

In conclusion, this program has been a very successful demonstration of integrating mature technologies into a viable near-zero emission drayage truck, with a limited zero-emission capability. The technology presents a huge opportunity for reduction of harmful diesel emissions, petroleum consumption, and greenhouse gases in the South Coast Air Basin, especially in the surrounding communities along the goods movement corridors that are impacted by heavy diesel traffic and the associated air pollution and health risks in real world drayage operation.

While it is expected that the drayage transportation will transition to zero-emission in the long-term, there are no stop-gap technologies that can bridge the cost and performance barriers associated with currently contemplated zero-emission technologies. CNG-hybrid vehicles have the potential to be developed and commercially available in the short term, while offering improved emissions, fuel economy and availability of fueling infrastructure.

The great performance of the vehicle and feedback from the fleet suggests that the technology has a potential for good acceptance amongst the operators and quick transition, however the hardware cost would require incentives to offset the incremental expense.

Fuel economy and emissions measured during the limited testing proved inconclusive, and it is recommended that more focused effort is put forth towards characterization of the CNG-hybrid operation. An in-depth transient emissions testing on controlled test routes, or chassis dyno cycles are the most appropriate tool to evaluate the actual performance and identify the opportunities for further optimization of the technology.

List of Acronyms

Acronym	Description
ACTM	Alternating Current Traction Motor
AER	All Electric Range
AMT	Automated-Manual Transmission
APS	Auxiliary Power System
BDU	Battery Disconnect Unit
CNG	Compressed Natural Gas
DGE	Diesel Gallon Equivalent
DOE	Department of Energy
DOT	Department of Transportation
DPE	Digital Power Equipment
ESS	Energy Storage System
EV	Electric Vehicle
EVPCS	Electric Vehicle Propulsion Control System
FMVSS	Federal Motor Vehicle Safety Standards
GHG	Greenhouse Gas
GTI	Gas Technology Institute
HDCC	Heavy Duty City Circuit
HECT	Hybrid Electric Cargo Transport
HIL	Hardware in the Loop
HV	High Voltage
HVDB	High Voltage Distribution Box
HW	Hardware
IM	Infant Mortality
ISG	Integrated Starter Generator
LV	Low Voltage
NREL	National Renewable Energy Laboratory
PCS	Propulsion Control System
PCT	PACCAR Test Center
PDU	Power Distribution Unit
PEMS	Portable Emissions Measurement System
PIM	Power Interface Module
PM	Particulate Matter
R&D	Research and Development
RCP	Rapid Control Prototyping
SCU	System Control Unit
SOC	State of Charge
VECU	Vehicle Electronic Control Unit
WEG	Water Ethylene Glycol
ZECT	Zero Emission Cargo Transport

END OF REPORT

Appendix A
Kenworth Plug-In Hybrid CNG Demonstration Data Collection Summary Report

Appendix B
Drayage Truck Commercialization Roadmap and Scenario Analysis

Appendix C
2-page synopsis

APPENDIX B
Kenworth Plug-In Hybrid CNG Demonstration Data Collection Summary Report

Prepared by: CALSTART, Inc.

November 2020

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ACKNOWLEDGEMENTS

This report could not have been possible without the support of SoCalGas, GTI, Kenworth, TTSI, BAE, and others. SoCalGas and GTI provided financial support for the work as well as insightful feedback. Kenworth oversaw the vehicle build, troubleshooting, and deployment phases while providing useful perspective on the truck's design and functioning. Kenworth also provided data collected on board the truck. TTSI ran the truck as part of its normal service routes for month, providing us with valuable real-world usage data, and also made themselves available for scheduling site visits, PEMS testing, and interviews. BAE provided the hybrid driveline for the truck and integrated their systems with those of Kenworth. The CALSTART team would like to acknowledge and thank the following for their assistance, without which this report would not have been possible.

E. EXECUTIVE SUMMARY

The Kenworth Plug-in Hybrid Demonstration project began after the Department of Energy (DOE) issued a Funding Opportunity Announcement for Zero Emission Cargo transport focusing on reducing emissions in and around the Port of Los Angeles, and the heavily traveled I-710 Corridor. This is an ideal target for alternative fuel technologies. The I-710 corridor runs through a heavily populated area and the pollutants emitted by the drayage vehicles has significant consequences on the people living near it. The drayage duty cycle is a prime duty cycle for alternative fuels as well, consisting, in part, of long periods of idling and waiting long lines for freight. The project deployed and demonstrated a plug-in hybrid electric CNG Class 8 drayage vehicle. The vehicle was studied both for its ability to complete the drayage duty cycle, and its emissions reductions.

Unfortunately, the project ran into a number of problems and issues throughout its lifespan. Firstly, the vehicle was only driven using the CNG engine to charge the battery, and never was charged using grid energy, which is not the normal operating procedure of this Plug-In hybrid vehicle. Secondly, the project was subject to many delays, shortening the testing period from twenty-four months, as originally planned, to thirteen months. Thirdly, there were multiple issues with the dataloggers, some that caused further delays, and others that could never be resolved. Finally, Portable Emissions Measurement System (PEMS) testing was not done under completely ideal conditions. These issues must be taken into account as this report is read.

The vehicle was tested against two baseline vehicles, a PACCAR CNG vehicle and a Mack Diesel vehicle. Three major data streams were collected in order to evaluate the vehicle's performance, emissions, and user acceptance. Performance data on the Plug-In Hybrid was collected by Kenworth's own telematics system, while data for the two baseline vehicles was collected from a DataHub provided by ViriCiti. Together, these two data streams provided performance data which allowed us to analyze the vehicle's ability to perform its duty cycle. Sensors Inc. conducted PEMS testing on each of the project vehicles and determined the emissions of each vehicles, so they could be compared properly. Finally, User Acceptance Interviews were conducted with some of the vehicle operators and management, in order to understand how the vehicle was perceived and used.

From this data, we were able to draw conclusions on the performance and emissions of the Plug-In Hybrid. The Plug-In Hybrid was able to adequately perform the standard drayage duty cycle. The vehicle was able to complete most trips, that the baseline vehicles were able to, reaching a maximum daily range of 284.61 miles. This is short of the maximum daily mileage of the CNG vehicle, which could reach up to 400 miles per day, but the Plug-In Hybrid would be able to complete the majority of the duty cycle. The Plug-In Hybrid was also somewhat more fuel efficient than the baseline CNG vehicle, having averaged more miles per diesel gasoline equivalent than the CNG vehicle. The results of the PEMS testing were somewhat inconclusive, owing partially to the difficulties in testing the vehicles. The Plug-In Hybrid vehicle performed averagely on this test. Finally, the vehicle was very popular with the drivers and was heavily praised during the user acceptance interviews. Due to the inclusive nature of some of the result and the issues faced during the demonstration, further testing and evaluation is recommended.

1. PROJECT OVERVIEW

1.1 INTRODUCTION

In 2014, the Department of Energy issued a Funding Opportunity Announcement for Zero Emission Cargo Transport, focusing on the development and demonstration of technologies that will reduce emissions in and around the Port of Los Angeles. The Kenworth Plug-In Hybrid Demonstration project aims to do exactly that: demonstrate a low-emission alternative to traditional diesel and compressed natural gas (CNG) drayage trucks. The project chose to deploy a plug-in hybrid electric CNG Class 8 drayage truck, rather than a fully electric model, due to concerns over limited range and inability to handle the demanding payload. The union of a CNG range extender engine together with an electric motor mitigates those issues. The CNG engine allows the truck to comfortably complete extended drayage duty cycles while the electric motor and associated regenerative braking system significantly reduce emissions by allowing for a clean idle at the port and energy recovery from slowing the vehicle.

This project examines the performance of one of these trucks and compares its emissions, performance, and user acceptance, to that of baseline CNG Class 8 heavy duty drayage trucks. The hybrid truck was operated on a normal drayage route over a thirteen-month testing period, along with a pair of baseline trucks (one diesel and one CNG). This analysis included performance data, detailing how the trucks operated, emissions testing that quantified greenhouse gas emissions and particulate matter from the trucks, and surveys that tracked the opinion of operators and fleet managers. CALSTART analyzed and compared the data across technology types to understand the viability of the hybrid EV compared to the baseline across the three metrics that data was collected for. Using this data, this report provides conclusions, learnings, and recommendations for the future of this technology.

1.2 BACKGROUND

The ports of Los Angeles and Long Beach are the busiest ports in the entire United States, and the I-710 is one the most well-travelled shipping lanes from those ports. It is the most direct path from the Port of Los Angeles to the various warehouses, shipping centers, railway stations, and other transportation terminals in the region. Thousands of drayage trucks make multiple five to fifty-mile trips to and from the port along this corridor and are crucial to the shipping industry of not only Los Angeles, but the whole country. The importance and traffic of this corridor is poised only to grow and is predicted to double by the year 2035.[1]

These drayage vehicles often run on CNG or diesel fuels, which not only contribute to anthropogenic climate change, but also heavily impact the air quality of the surrounding communities. Particulate matter concentration in these neighborhoods averages 36% higher than the rest of LA county,[2] leading to significant, pervasive health

[1] https://www.bloomberg.com/news/articles/2018-03-12/why-l-a-s-710-freeway-won-t-get-wider-after-all
[2] https://usc.data.socrata.com/stories/s/Community-Health-in-the-I-710-Corridor/xygk-aaaq

problems in the surrounding communities, such as asthma, heart disease, and decreased lung function. Additionally, the communities surrounding the I-710 are some of the most vulnerable in Los Angeles, both having more minority residents and more low-income residents. In fact, in 2017, residents of communities near the I-710 visited the hospital for asthma-related issues twice as often as residents of neighborhoods that are more affluent and have fewer minorities. Poor air quality caused by the emissions of vehicles travelling along the I-710 is not only a pressing public health issue, but also an important social equity issue as well. The drivers of these vehicles are also affected since they have to spend long hours behind the wheel and at the port breathing in harmful emissions, which negatively impacts their long-term health more directly. In order to help combat these systemic issues, the Ports of Long Beach and Los Angeles and the fleets that operate there have begun looking into the use of fuels other than CNG and diesel for their drayage trucks.

Drayage truck duty cycles are unique and a prime target for alternative fuels and electrification. The duty cycle primarily consists of two elements: first, long periods of idle time at the port as the trucks wait in long lines for freight to be loaded onto the truck. Second, long periods of highway driving up and down the I-710 corridor, delivering their cargo to distribution centers and warehouses. The first segment of this duty cycle (at the ports with short bursts of movement) is ideal for electrification, with few concerns over range limitations and ample opportunity to reduce emissions. The second portion of the duty cycle (trips from the port of Los Angeles to their destination) is a bit more difficult for electric vehicles due to the range required to make multiple trips to and from the port on a single charge.[3]

The addition of the CNG range extender solves many of the issues of range and still allows the drayage truck to be a near-zero emissions vehicle. The electric drive train would significantly reduce emissions while the truck idles at the port. The added range allows the truck to complete multiple trips along the I-710 that pure electric trucks would struggle to while still being cheaper than a fully electric model. Although the CNG range extender would produce more emissions than a fully electric vehicle, it would still be expected to be cleaner than a traditional diesel or CNG model. With both the ability to complete the necessary duty cycle adequately and the promise of reduced tailpipe emissions, a hybrid truck with a CNG range extender was examined in more detail for this project.

1.3 PROJECT GOALS

This project primarily studied whether the Plug-In Hybrid with CNG range extender technology is a viable alternative to traditional CNG class-8 drayage trucks. The truck was evaluated based on its ability to complete the duty cycle of a traditional drayage truck and any reduction in emissions from using the plug-in hybrid technology. To answer both questions, CALSTART collected data from two main streams. First, over a thirteen-month period, data was collected on the performance of both the demonstration hybrid vehicle and the baseline comparison vehicles. CALSTART examined and compared the distance traveled, the energy efficiency, and the operating time of all three vehicles, to determine the ability of the hybrid vehicle to complete the necessary duty cycle. Second, emissions testing was conducted, and the resulting data was analyzed to determine if the electric drive train reduced the overall emissions of the vehicle. This report details the methodology used to compile and analyze

[3] Check with jon's com report on this para

this data and the results of the analysis, endeavoring to determine if the Plug-In Hybrid vehicle is a reasonable alternative to the current baseline drayage trucks and if it helps ameliorate the problem of poor air quality on the I-710.

1.4 PROJECT TEAM

Kenworth Truck Company is an American truck manufacturing company, that specializes in class 8 Heavy Duty and Class 5-7 medium duty commercial vehicles and is at the forefront of the industry. For the Kenworth Heavy Duty Plug-In Hybrid CNG Demonstration project, Kenworth produced and manufactured the truck based on the Kenworth Model T680 and integrated the hybrid system onto the vehicle. Kenworth also provided the electric accessories.

BAE Systems Inc. is an international aerospace, information security, and electronics equipment company. BAE systems specializes in advanced electric technologies with a plethora of patents and systems across the globes. In this project, BAE Systems provided integration for the vehicle systems, electric propulsion, and power systems.

Total Transportation Services, Inc. (TTSI) was the fleet that operated the vehicles for the duration of the demonstration project. TTSI operates out of Los Angeles and specializes in local port drayage, local, and regional trips. TTSI operated all three vehicles in this project, the demonstration vehicle, as well as both baseline vehicles.

ViriCiti is an international company that operates a cloud-based vehicle monitoring tool called the DataHub. ViriCiti's DataHub was installed on both baseline vehicles and provided valuable data to compare the demonstration vehicle.

Sensors, Inc. is a leader in providing emissions measurement solutions and analytical emissions reports. Sensors, Inc. conducted the PEMS testing on this project and measured the emissions for each of the vehicles. They then provided a detailed report that was used to produce this report.

CALSTART is non-profit member supported organization that promotes the growth of advanced, clean transportation technologies. CALSTART performed project management duties as a third party, and compiled and completed this report, as well as an accompanying commercialization report.

1.5 PROJECT ISSUES

Unfortunately, a number of substantial issues occurred during the course of this project. Firstly, and most importantly, the operators of the vehicle did not have charging infrastructure installed as part of this project and they were not able to plug it in. The vehicle was solely driven using the CNG engine to charge the battery and did not charge using grid energy. These are not optimal operating conditions for a plug-in hybrid. Fuel consumption and therefore emissions of the truck are higher relative to what could have been achieved with regular charging, because all of the energy used came from the CNG fuel tank. This also changes how the truck performed in every metric. It is very important to keep this in mind as the report is read, as it significantly effects the interpretation of the analysis.

Additionally, significant delays afflicted the project throughout its lifetime. Originally, this project was slated to be competed in Q4 of 2018, having been initiated back in Q3 of 2015. Instead, delays in production of the vehicle delayed the deployment of the vehicle until October 2019 and the completion of the project was delayed until Q4 2020 (a project delay of two years). This meant instead of the originally planned twenty-four months of data, only thirteen months of commercial revenue service data was able to be collected. Further delays were incurred with some of the data loggers on the baseline truck.

Certain issues permeated the data collection process and were not able to be resolved. ViriCiti supplied the data loggers that were to be used to record the performance of the baseline vehicles for this project. However, there were delays with installation of the loggers and multiple attempts had to be made by ViriCiti to ensure the loggers were properly connected and recording data. Despite eventually collecting data adequately for the baseline CNG vehicle, the logger could not properly read data from the CAN bus of the diesel vehicle. Key parameters were not broadcast in alignment with J1939 standards, so only data on the total distance driven by the vehicle could be collected, and not the energy parameters that would be needed for a comprehensive comparison. Multiple attempts were made to properly configure the data logger and contact the vehicle manufacturer to find a correct implementation of the key signals, but a solution was not found.

PEMs testing was also not completed under ideal conditions. The data collected was valid, but each truck was driven on a different route and with a different payload, making the results difficult to properly compare. This was expected because the in-use testing had to be completed while the fleet responded to the business needs of the day. Multiple attempts were made to locate the data on the weight of payloads carried by each vehicle during testing, but the fleet did not supply the data. Although far from ideal experimental circumstances, the testing was successful, and a comparison was able to be made.

2. DATA COLLECTION

2.1 DATA COLLECTION OVERVIEW

Throughout this project, data was collected via four main data streams, before being compiled and analyzed.

1. On-Route Performance Data – Performance data for the truck was collected and streamed from a telematics system owned and installed by Kenworth. This system collects data and wirelessly sends it to Kenworth. They subsequently upload this data to an online Box server on a weekly basis. From this server, the data was accessed by CALSTART, downloaded, cleaned, compiled, and analyzed for this report. This data contained key metrics such as distance traveled, average speed, energy used, and was used to derive other key metrics, such as energy efficiency.
2. Baseline Performance Data – Data was also collected on two baseline trucks, one diesel and one CNG. ViriCiti DataHub data logging systems were used to collect performance data for each of the baseline

trucks. Similar to the CNG-hybrid truck, the DataHub collected key metrics such as average speed, energy used, distance traveled, and was used to derive other metrics such as efficiency. Unfortunately, only very limited data was able to be collected for the diesel vehicle because it used non-standard signals.

3. Emissions Testing – Each of the three trucks underwent Portable Emissions Measurement System (PEMS) testing in order to evaluate the amount of reductions in emissions that came from adopting the hybrid technology. CALSTART partnered with Sensors, Inc. to administer PEMS testing on each of the trucks and received a report with results.
4. User Acceptance Data – Interviews were conducted by CALSTART with TTSI. CALSTART interviewed two truck drivers and TTSI executive on their experiences with the truck and the future of the technology.

Each of these different streams were combined and consolidated to create the analysis presented in the report. The first section of analysis details the results from the performance data from both the hybrid demonstration vehicle and the two baseline comparison vehicles. The second section details the results of the PEMS testing on each vehicle, and the third analysis section discusses the results of the User Acceptance interviews.

2.VEHICLE SPECIFICATIONS

The specifications for each vehicle in this project are outlined in the table below. Each vehicle was owned and operated by TTSI. The CNG and diesel vehicles were both old vehicles that have been part of TTSI's fleet for multiple years.

Figure 1: Demonstration Vehicles

Kenworth Plug-In Hybrid

Peterbilt CNG

Mack Diesel

Table 1: Vehicle Specifications

	PLUG-IN HYBRID	CNG	Diesel
Type/Description	T680	CECNG01, CXU613	TEC 050, CXU613
Make	PACCAR	PACCAR/RUSH	MACK TRUCKS, INC
Model	8.9L ISL G 320	11.9L, ISX12-G	12,8L, MP8-415C
Model Year	2017	2013	2015
Rating	320bhp/2100 RPM	400 bhp/1800 RPM	415 bhp/1500 RPM

3. PERFORMANCE ANALYSIS

3.1 METHODOLOGY

Data was downloaded from a Box server maintained by Kenworth. The data provided was in the format of individual trips each collected into a single file. A trip is defined as the period from when the vehicle was turned on to when it was turned off. Parameters were recorded each second, giving us extremely detailed and granular data. This data was downloaded manually and aggregated into a single master data set, which was used to complete the analysis. Similarly, for the two baseline vehicles, data was collected by ViriCiti's DataHub system and uploaded to their data portal. Per second data was downloaded from ViriCiti's data portal for both the diesel and the CNG baseline truck and each truck's data was aggregated for analysis.

After data was downloaded and aggregated, it was cleaned. CALSTART removed data that was either captured incorrectly or was a trip too short to be part of the vehicle's actual duty cycle. These included trips where the vehicle was turned on but never moved, trips where the vehicle moved but data was not properly recorded, and trips that were less than a minute long. Any trip that met any of these criteria was removed from the dataset in order to make sure we were capturing only data that was accurate and only trips that were part of a normal drayage duty cycle. Data was then converted from metric units, to imperial units, and grams of CNG was converted to diesel gallon equivalents. The only parameter that was not collected was the efficiency values, which were calculated using the following formula:

$$MPDGE = \frac{Distance\ Traveled}{Fuel\ Consumed} * DGE$$

The data for the diesel vehicle was handled slightly differently. The only parameters that were recorded by the DataHub for diesel vehicles was Distance Driven per Day and Time. Using these two variables, the Time Operated per Day was calculated, and then divided together to get the Average Speed per day.

This combined and cleaned dataset was then sorted and aggregated by day and analyzed. The following table details the parameters that were analyzed by CALSTART to evaluate the performance of each of the vehicles.

Table 2: Parameters Analyzed

PARAMETER	UNITS	Description
Date	-	The date when the trip took place.
Time Operated per Day	hours, minutes, seconds	Total time the truck was operated over the course of a day.
Distance Traveled per Day	Miles/day	Total distance traveled by the vehicle over the course of the day
Average Speed	Miles/hr	Average speed of the vehicle throughout the course of the day.
Number of Trips per Day	-	Trips taken by the vehicle per day.
Energy per Day	kWh	Total energy used by the vehicle per day
Fuel Consumed per Day	dge	Total CNG or diesel fuel used by the vehicle per day.
Idle Time per Day	Hours, minutes, seconds	Total time the vehicle spent turned on, but not moving.
Average Efficiency	Miles/dge	The average efficiency of the vehicle per day.

3.2 ANALYSIS

The performance analysis considered five major parameters to determine the ability of the hybrid vehicles to perform the drayage duty cycle compared to a CNG baseline. The following parameters were defined as operational parameters: Time Operated, Distance Traveled, and Average Speed, and the following were defined as fuel consumption parameters: Fuel Consumption and Efficiency. The operational parameters show the ability of the hybrid vehicle to perform the drayage duty cycle by measuring whether or not the vehicle can perform as well as the baseline vehicles. The Fuel Consumption parameters show whether or not the vehicle can do so efficiently. Together, these five parameters paint an accurate picture of the vehicle's performance over the demonstration period.

Unfortunately, only time operated and distance traveled data was collected for the diesel vehicle, and no data related to fuel consumption. We have calculated the overall average speed value from those two parameters. Table 3 summarizes the parameters that have been analyzed and this section discusses them in further detail.

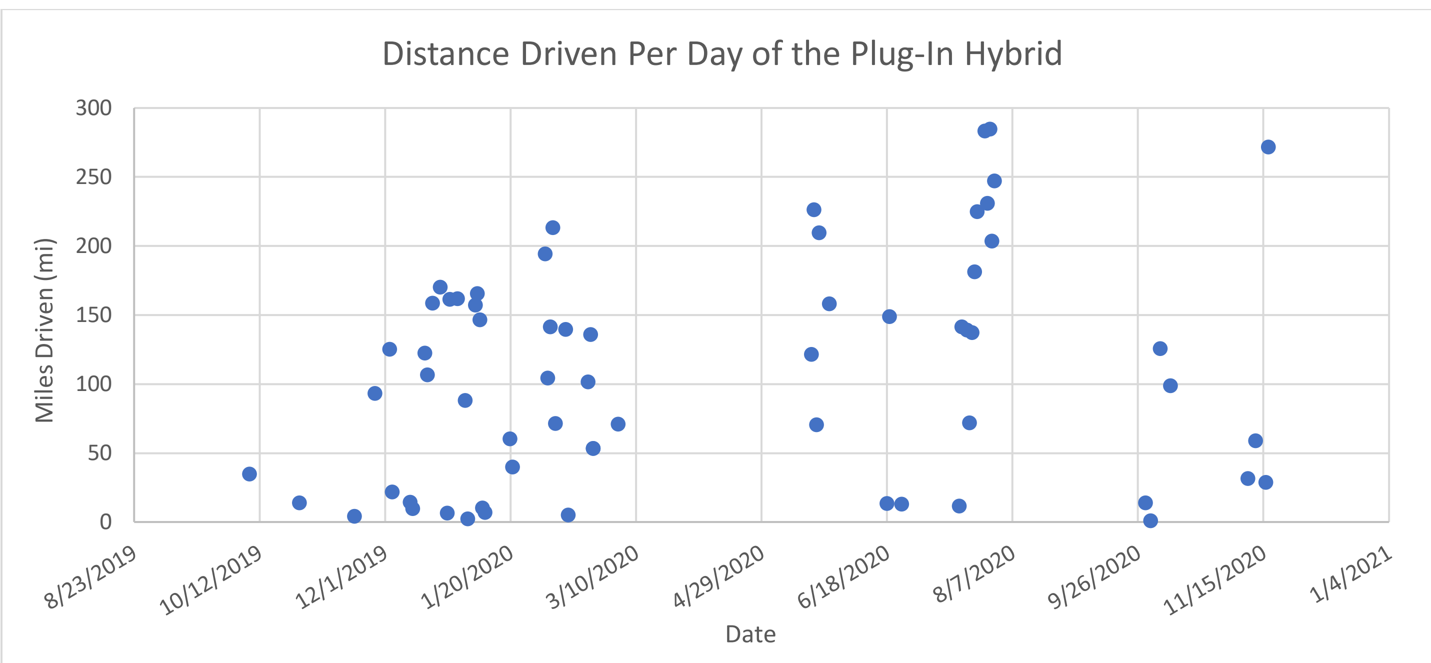
Table 3: Average Daily Summary of Results of Performance Demonstration

	Total Days in Operation	Avg. Time Operated	Avg. Distance Traveled	Average Speed	Avg. Fuel Consumed	Avg. Efficiency
Plug-In Hybrid	64 Days	8.50 hrs	141.75 mi	18.43 mph	20.72 dge	6.62 mi/dge
CNG	38 Days	6.35 hrs	218.59 mi	32.79 mph	15.36 dge	5.1 mi/dge
Diesel	52 Days	10.38 hrs	91.59 mi	8.64 mph	n/a	n/a

3.1.1 OPERATIONAL PARAMETERS

This section summarizes the performance results of the demonstration test for operational parameters Together, these parameters, Time Operated per Day, Distance Traveled per Day, and Average Speed per Day, paint a picture of how well the hybrid vehicle performed the duty cycle, compared to the baseline vehicles.

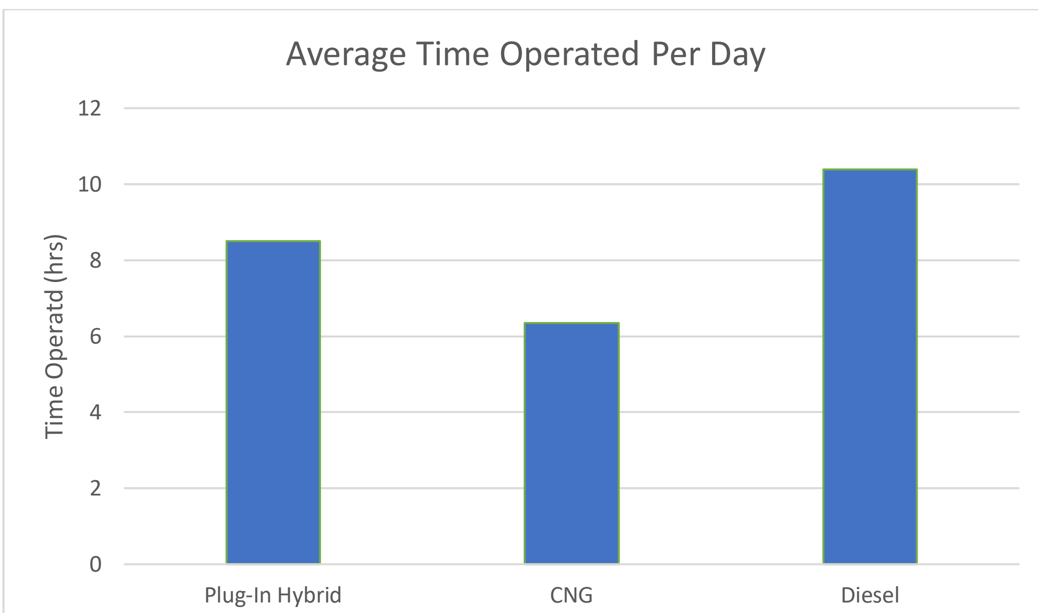
Figure 2: Distance Driven per Day of the Plug-In Hybrid



This scatterplot graphs the duty cycle of the Plug-In Hybrid vehicle over the past thirteen months, with sixty-four days of operation. From this plot we can draw a number of interesting conclusions:

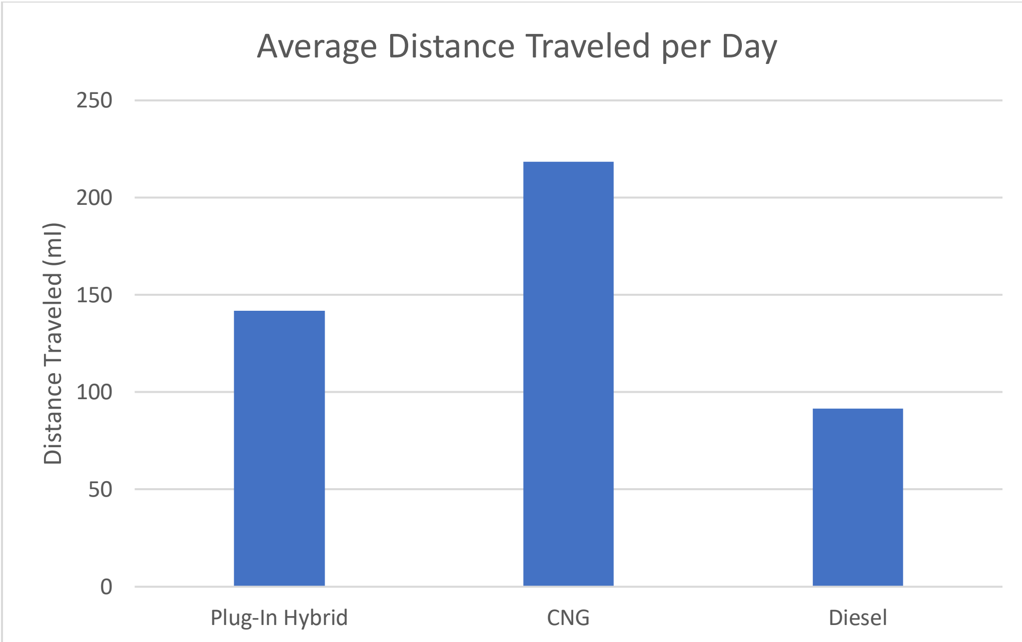
- The demonstration vehicle was operated sixty-four times throughout the demonstration period. During the demonstration period it made trips that spanned the entire breadth of the drayage duty cycle, giving us an excellent snapshot on how the vehicle performs.
- The Plug-In Hybrid is capable of making long trips and does not suffer from the same issues of range that many fully electric trucks do. The maximum distance the Plug-In Hybrid vehicle drove in one day was 284.62 miles on July 29th. It drove similarly long distances on July 28th and November 16th. Nineteen days (29.69 % of days operated) during the demonstration period saw more than 150 miles of driving in a single day. This shows the hybrid truck is able to perform the long-distance trips that are required in the drayage duty cycle consistently.
- The drayage duty cycle has many days where the truck did not drive many miles. Twenty-one days (32.81% of days operated) featured less than 50 miles of driving per day. These days were local trips in and around the Port of Los Angeles and were ideal for the electric drive train of the Plug-In Hybrid.
- There are two noticeable gaps in the demonstration period. The first gap, in late March and April was due to the changes in TTSI's operations due to the Covid-19 Pandemic. The second gap, in August and September, was due to a maintenance issue that put the vehicle out of service for some time. With these two exceptions, the truck was able to drive throughout the entirety of the testing period.

Figure 3: Average Time Operated per Day (Hours)



This bar graph shows the average time operated per day, in hours, over the demonstration period. The diesel vehicle had, on average, the longest days on the road, with ten hours and twenty-three minutes on the road. The Plug-In hybrid averaged eight hours and thirty minutes on the road, and the CNG vehicle averaged only six hours and twenty-one minutes on the road.

Figure 4: Average Distance Traveled per Day (mi)



This bar graph shows the average distance traveled by each vehicle per day. The CNG vehicle drove the furthest on average: 218.59 miles per day. The Plug-In Hybrid drove a total 141.75 miles per day, while the diesel vehicle drove the least, only 91.59 miles per day.

Taken together, these two graphs show the typical duty cycle that each vehicle undertook. The diesel vehicle, driving long days, but short distances, tended to spend long hours at the port and make local trips, that had long idle times, but short distances, while the CNG truck took long trips with large stretches of freeway and highway driving. The Plug-In Hybrid, on the other hand, took a more average and balanced duty cycle and was able to perform both extremes.

More importantly, it shows that the Plug-In Hybrid vehicle did not lag behind either of the baseline vehicles, in either metric. It was able to complete the duty cycles just as well as both the CNG and the diesel vehicle, and no glaring performance issues presented themselves in the data.

Table 4: Minimum and Maximum Distance Traveled per Day

	Minimum Distance Traveled	Mean Distance Traveled	Maximum Distance Traveled
Plug-In Hybrid	2.09 mi	141.75 mi	284.61 mi
CNG	4.2 mi	236.81	406.65 mi
Diesel	7.18 mi	80.76 mi	266.81 mi

This table shows the minimum and maximum distance traveled per day for each vehicle. The CNG vehicle did drive, on average much further than the demonstration vehicle and had a greater maximum daily range than the Plug-In Hybrid vehicle had. The CNG vehicle had a maximum range of 406.65 miles, compared to the Plug-In Hybrid's maximum of only 284.51 miles. This means that there may be some extremely long trips that can only be completed by a baseline vehicle. However, the Plug-In Hybrid compared favorably to the diesel vehicle, and would have been able to complete each trip that the diesel vehicle completed.

Overall, the data collected supports the ability of the Plug-In Hybrid Vehicle to perform the drayage duty cycle well. The vehicle was able to regularly drive more than 150 miles per day, without much issue. Every daily distance that was completed by the diesel vehicle could also be completed by the demonstration vehicle. The main concern would be for trips that are very long; over 300 miles per day, which may not be able to be completed by this vehicle. However, these trips do not make up a large majority of the trips undertaken by the baseline vehicles.

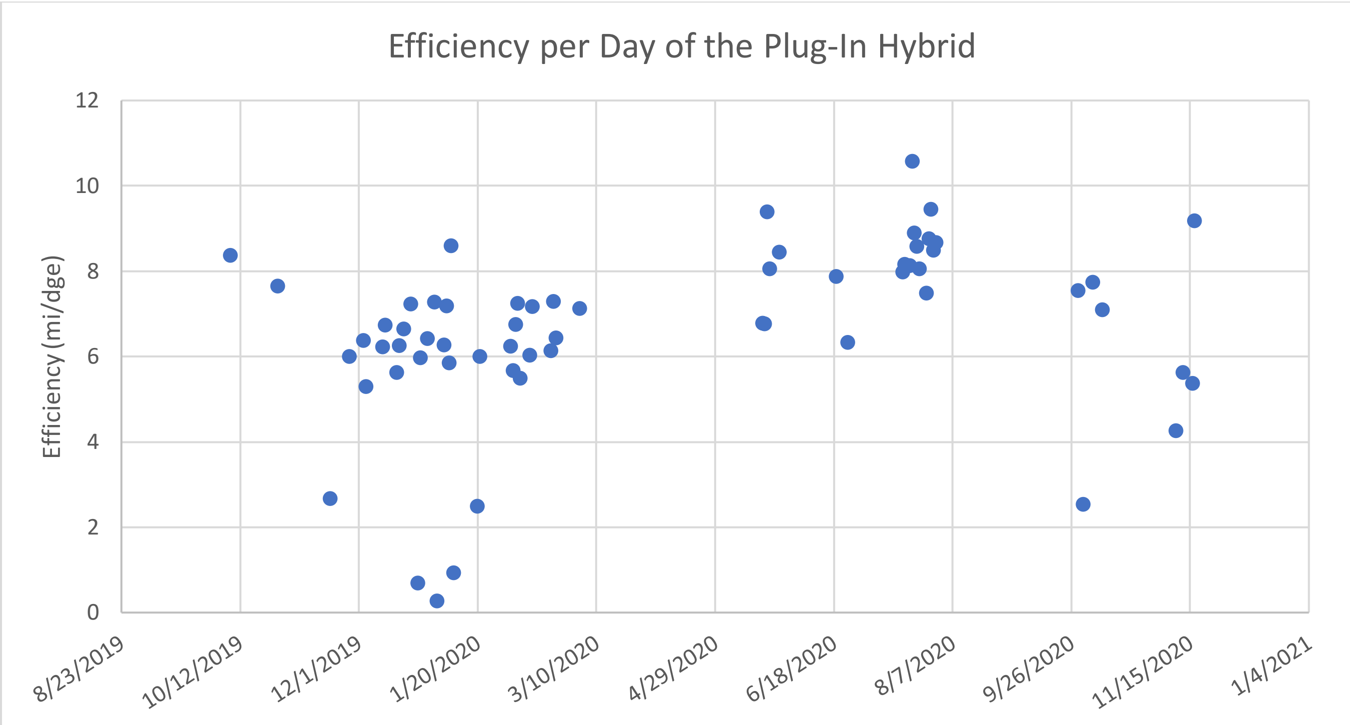
3.1.2 FUEL CONSUMPTION AND FUEL EFFICIENCY

This section summarizes the results of the fuel consumption and fuel efficiency parameters. These parameters look at what the fuel economy of the Plug-In Hybrid vehicle was and how it compares to the baseline CNG vehicle. The following table shows a summary of results that will be explored in detail in this section. As mentioned before, the diesel vehicle was unable to collect fuel usage data and will not feature in this section.

Table 5: Average Daily Fuel Efficiency and Fuel Consumed

	Total Days in Operation	Avg. Fuel Consumed	Avg. Efficiency
Plug-In Hybrid	64 Days	20.72 dge	6.62 mi/dge
CNG	38 Days	15.36 dge	5.1 mi/dge
Diesel	52 Days	n/a	n/a

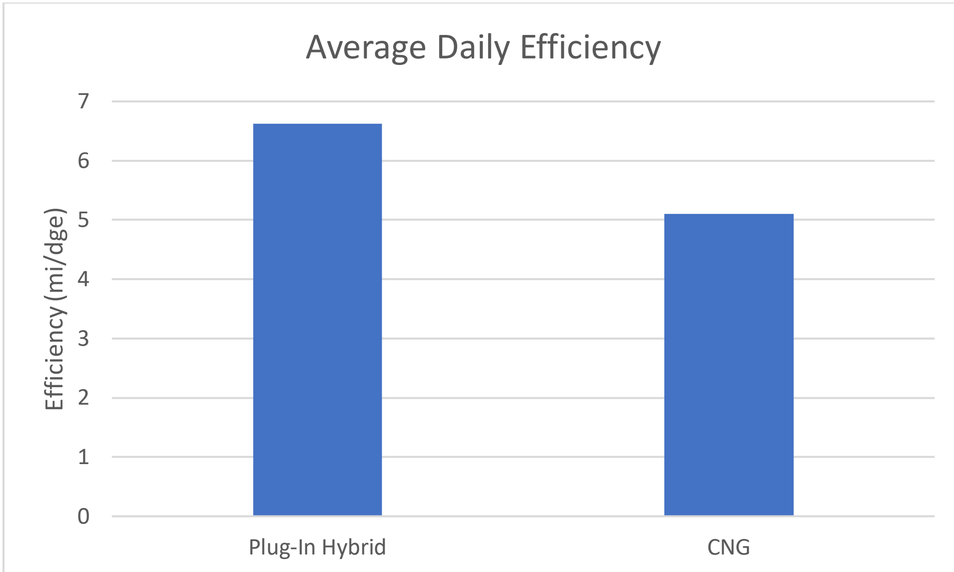
Figure 5: Efficiency per Day of the Plug-In Hybrid (mi/dge)



This scatterplot shows the efficiency of the Plug-In Hybrid over the course of the demonstration period. From this data, we can note some interesting trends over the course of the demonstration period.

- There are two main clusters of data, one, less efficient period during the winter, and a more efficient set of trips during the summer. This is due to the slightly longer distances the truck drove during the summer months. The higher values are what we would expect most often going forward.
- There are small clusters of days with very low efficiency. These days consists of long periods of idle time, presumably at the port, that brought down the daily efficiency of the vehicle. The days clustered higher consist of more highway and freeway driving.

Figure 6: Average Efficiency per Day (mi/dge)



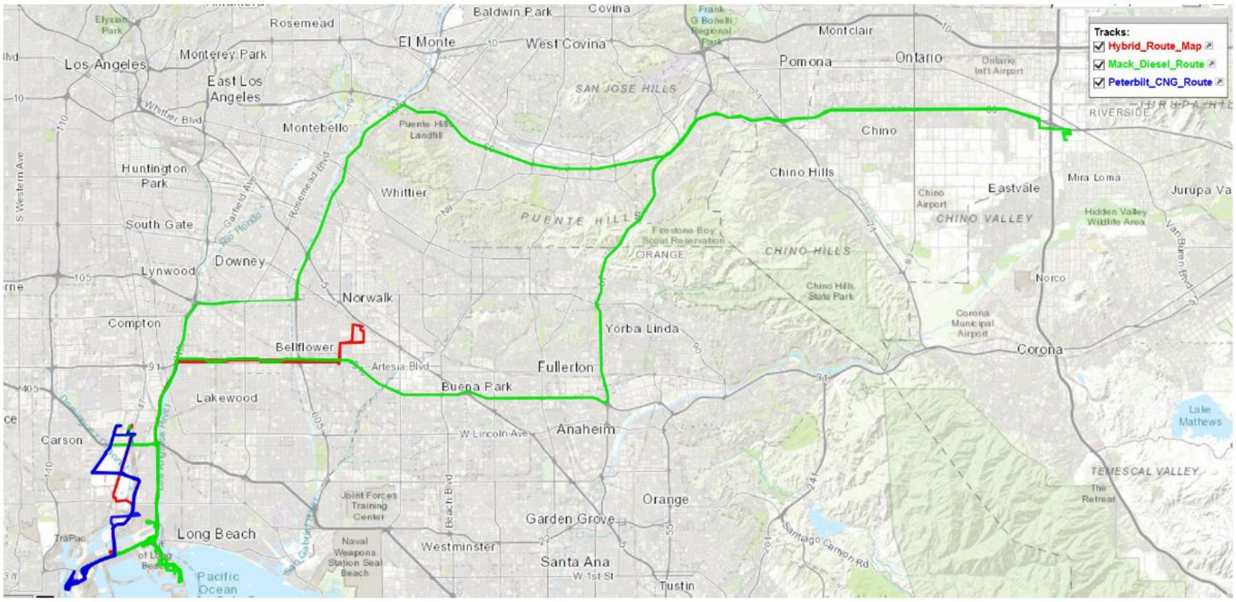
This simple bar chart shows the average daily efficiency of both vehicles, represented graphically for easy comprehension. We can see that the Plug-In Hybrid was more fuel efficient than the CNG vehicle. This is mainly due to the little idle time of the demonstration vehicle. Overall, this is encouraging for the Plug-In Hybrid vehicle.

4. PEMS TESTING ANALYSIS

Portable Emissions Measurement Systems (PEMS) testing of the demonstration vehicle and both baselines was conducted by Sensors, Inc. Testing occurred over a four-day period, between 3/2/2020 and 3/6/2020. The testing measured the levels of particulate matter (PM) and five different gaseous pollutants emitted by each vehicle: Carbon Dioxide (CO2), Carbon Monoxide (CO), Nitrous Oxide (NOx), Total Hydrocarbons (THC), and Methane (CH4).

Testing occurred not on a prebuilt testing track, but instead under actual operating conditions. Each vehicle conducted a single actual trip as part of its duty cycle, and the emissions given off during those trips were collected and measured. This was preferred to testing on an experimental track, because those controlled experiments fail to adequately capture real operating conditions as well as real routes. However, as previously explained, there is wide variation in operating conditions due to the business needs of the fleet.

Figure 7: Map of the Routes Taken During PEMS Testing



The diesel vehicle, shown here in green, drove an extremely long route from the port to Riverside, over long stretches of freeway. The hybrid demonstration vehicle, shown in red drove a much shorter route, from the ports, to Norwalk, with some freeway driving, but much less than the diesel vehicle. The Peterbilt CNG vehicle, on the other hand, drove a local route, with no freeway driving, and solely drove over surface streets. Generally, vehicles are less efficient when driving on surface streets due to heavier traffic, lower speeds, and more frequent stops. This also translates to higher emissions. Driving over surface streets emits more emission per mile than driving over freeways. Due to the extreme variation in the routes driven, a simple grams per mile presentation of the data is not applicable and would not be a good comparison.

Instead, results from the PEMS testing are presented in grams per brake horsepower-hour (bhp-hr). Bhp-hr is a measure of work conducted by the vehicle and represents how demanding the trip was, accounting somewhat for frequent stops, topography, different loads pulled, and high speeds. Due to the difference in testing routes, this measure is a much better comparison than comparing by distance. While this is not ideal, and better results may be had by testing on similar routes, g/bhb-hr is a common way to compare emissions from vehicles across different fleets, routes and loads.[4] Results from the PEMs testing in g/bhp-hr is shown below.

Table 6: Results of PEMS Testing

	Plug-In Hybrid	CNG	Diesel
Total Distance Traveled (mi)	41.4	49.7	58.9
Total Fuel Consumed (gal)	7.2	8.3	8.1

[4] https://archive.epa.gov/international/air/web/pdf/stds-eng.pdf

Overall Fuel Economy (mpdge)	5.8	6.0	7.3
CO2 (g/bhp-hr)	458.7	559.0	506.1
CO (g/bhp-hr)	1.05	0.42	1.53
kNOx (g/bhp-hr)	0.23	0.08	1.95
THC (g/bhp-hr)	0.19	0.14	0.01
CH4 (g/bhp-hr)	0.17	0.13	NA

A number of interesting things can be gleaned from the results of the PEMS testing. First, both the CNG and diesel were more fuel efficient than the Plug-In Hybrid truck on a pure per mile basis. However, during the longer performance evaluation, the Plug-In Hybrid vehicle was more fuel efficient, on average. There is variation expected in the efficiency of vehicles based on factors such as the route driven, load pulled, and time of day. Therefore, some days, like the PEMS testing day, will not match the general trend. One day of data, generally, is not enough to make significant conclusions from if we normalize fuel consumption by mileage. More focus should be given to the g/bhp-hr values.

The emissions values are presented in g/bhp-hr, which is a better comparison than a per mile basis given the variation in test routes as described above. On this basis, the Plug-In Hybrid emitted 20% less CO_2 than the CNG baseline and 10% less than the diesel baseline, a fairly significant decrease over the other vehicles. However, the other emissions paint a more muddled picture. While emitting less than the diesel vehicle, the Plug-In Hybrid vehicle emitted more CO and NO_x than the standard CNG vehicle and emitted the most THC and CH_4 of all three vehicles. Taken together, when normalized by work done, the Plug-In Hybrid vehicle is the most efficient, although when normalized by distance it was the least. This may suggest that it may have had a more demanding test cycle of the three vehicles.

We assume that the results from the Plug-In Hybrid vehicle in the PEMS testing would have been better if the vehicle was not relying solely on the CNG range extender. Instead of operating as a true plug-in hybrid vehicle, the truck operated under the power of CNG alone. A battery fully charged by the grid would have decreased the amount of CNG fuel used during the test. While the significant reduction in CO_2 is promising, the results of this testing are a mixed bag. Despite not appearing in headlines as much as CO_2, the other gaseous pollutants such as NO_x and CH_4 are significant contributors to poor air quality in the region and climate change. We can therefore conclude that, the Plug-In Hybrid vehicle, when operated like it was in this test, is overall a cleaner vehicle than the CNG and diesel baselines, but further testing under more similar conditions and different operational procedures is recommended.

5. USER ACCEPTANCE DATA

CALSTART conducted three user acceptance interviews with members of TTSI staff, two with truck operators, and a third with a TTSI executive. The interviews were designed to understand how the operators and drivers felt about the hybrid truck, to capture any safety, maintenance or other issues that could not be captured by the data, and to gauge how the operators felt about the future of the technology and the drayage industry.

Overall, the operators interviewed were very pleased with the operation of the vehicle, citing the smoother, cleaner, and quieter ride of the hybrid truck. The vehicle drives without the excessive shaking and rattling that characterizes the baseline vehicle, does not smell of diesel, and has a much quieter drivetrain than the baseline vehicles' engines. These factors make the ride much more enjoyable and comfortable to operate. However, one driver pointed out that even though he enjoys the hybrid vehicle much more than the older diesel vehicles, many other drivers are used to driving the diesel vehicles and are not likely to want to change. In fact, the only complaint the operator seemed to have about the vehicle is that he could not drive it at the time of the interview because the air compressor was being repaired.

Both the operators and the TTSI executives noted the health and safety measures that the hybrid vehicle provides. Old diesel vehicle would cover drivers in a layer of soot, significantly impacting the health of the driver, but the cleaner hybrid does not smell or cover operators in a layer of particulate matter. The operators enjoy the added safety features, like the lack of a back window, which is less safe to use than the truck's mirrors.

The interviewees did note certain issues with fueling the vehicle and its range. Most trips were under 200-miles round trip and perfectly doable with the hybrid vehicle. While TTSI believes that future technologies and future expansion will alleviate some of these problems, they do not believe that fully battery electric vehicles will be viable for their operations in the near future. However, TTSI does believe that there is a chance that they will lease more hybrid CNG vehicles in the next lease cycle.

6. CONCLUSIONS

This report provided invaluable insight on the performance, fuel efficiency, emissions, and user acceptance of the Plug-In Hybrid class-8 heavy duty drayage truck. A number of conclusions can be drawn on the overall performance of the demonstration vehicle:

- **The Plug-In Hybrid Vehicle can adequately perform the standard drayage duty cycle.** The vehicle was able to complete days with both long driving distances, and shorter distances, without much issue, reaching a maximum daily range of 284.61 miles. However, the CNG vehicle showed that part of TTSI's operations include extremely long days of up to 400 miles per day, much further than the daily range of the demonstration vehicle. The Plug-In Hybrid would be able to complete the majority of trips required but some days would require a conventional vehicle.
- **The Plug-In Hybrid is somewhat more fuel efficient than the baseline CNG vehicle.** The Plug-In Hybrid averaged more miles per diesel-gallon equivalent than the baseline CNG over the course of the demonstration period, making it a better value compared to that vehicle.
- **The Plug-In Hybrid performed averagely on the emissions test.** For each metric, the Plug-In Hybrid vehicle performed averagely, putting it in between the baseline diesel and CNG. It did not show large overall

emissions reductions. This is partially due to issues in the operation of the vehicle and the way the test was conducted but should be looked into further.

- **The demonstration vehicle was very popular with the drivers.** A litany of quality of life enhancements for the driver, such as reduced noise, lack of smell, and smoother driving conditions made the Plug-In Hybrid very popular amongst the truck operators at TTSI. Overall, the operators interviewed were extremely pleased with the demonstration vehicle and were keen on continuing to drive it.
- **Further testing under better operating conditions would be ideal.** Issues in the baseline data collection and how the vehicle operated colored the full demonstration project, and makes the conclusions drawn here somewhat difficult to properly characterize and contextualize. Further research into the technology to correct for these issues is recommended.

Overall, the vehicle seems to have exceeded expectations in some regards but fallen short in others. While the demonstration vehicle was able to adequately perform the drayage duty cycle, the technology is not yet able to completely replace baseline vehicles. The vehicle has the capability to replace the majority of trips undertaken by the baseline, but some baseline vehicles are needed to complete the extremely long days of driving that are part of the drayage duty cycle. Fortunately, it can do so more efficiently than the baseline CNG vehicles, saving fleets money on fueling in the long run.

Overall, the vehicle did reduce emissions compared to baselines on the basis of work done by the powertrain. The nature of the testing and lack of experimental controls still makes it unclear how much widespread adoption of this vehicle will affect air quality on the I-710 corridor, the main issue of concern when this project was being drafted. In order to properly combat that issue, technologies that have greater reductions in emissions would be recommended.

Lastly, the vehicle pleasantly surprised by being very popular with the truck operators who drove it. They praised the quality of life features it added and were keen on keeping the vehicle around. This was not a factor that was majorly considered in the drafting of this project but ended up being one the biggest selling point of the vehicle when the project had concluded.

APPENDIX B
Drayage Truck
Commercialization Roadmap

Prepared for: South Coast Air Quality Management District

Prepared by: CALSTART, Inc.

November 2020

Jon Gordon, Baha Al-Alawi PhD, Chase LeCroy, *CALSTART*

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E. EXECUTIVE SUMMARY

CALSTART, under funding from SoCal Gas, performed this study to provide the San Pedro Bay Ports' drayage community an overview of the current drayage market and a prediction of how the market may evolve by 2035. It begins by exploring the critical role heavy-duty trucks play in the Ports' and California's air pollution and emissions reductions goals. Heavy-duty trucks are the primary source of greenhouse gas emissions at the Ports and the second leading source of smog-forming NO_x, a respiratory irritant that Los Angeles is notorious for.[1] This section specifically discusses the disproportionately harmful effects that pollution emitted by heavy-duty trucks has on low-income and disadvantaged communities located near the Ports of Los Angeles and Long Beach.

Section 2 begins with an overview of the drayage market and the role that independent owner operators (IOOs) play in the industry. Drayage trucks are Class 7 and 8 trucks that ferry inbound and outbound cargo between port terminals and train yards, warehouses, and distribution centers. Because drayage trucks travel the shortest distances among heavy-duty trucks and usually domicile in the same location, drayage trucks have been targeted as a beachhead industry to electrify first among the heavy-duty sector. [2] Over half of trucks operating at the Ports are owned by independent owner operators, or individuals that own their own vehicles and contract their drayage services.

The IOO business model faces multiple challenges from regulation. California's AB5, which is currently being contested in the courts, may end the IOO model altogether. Other legislation, like the Ports' Clean Truck Program and the California Air Resources Board's Advanced Clean Fleet Rule, place bans on older drayage trucks and mandate the adoption of newer, cleaner vehicles. High capital costs, limited range, and the complexities of charging / fueling infrastructure all pose difficulties to the current IOO business model.

The section goes on to define the drayage truck duty cycles that alternative fuel vehicles will need to meet to allow a successful transition to zero and near-zero emission vehicles. Over half of all drayage trips at the San Pedro Bay Ports are within 50 miles of the Ports with a maximum distance of 150 miles. Drayage trucks often complete two or three trips per day, leading many fleet managers to demand a 300 mile minimum range from alternative fuel vehicles.

Section 2.3 examines the available drayage trucks by fuel segment, including diesel, compressed natural gas (CNG), battery electric (BE), and fuel cell (FC) trucks. It discusses their respective pros and cons, commercial readiness, and emissions produced. Right now, about 96% of drayage trucks in operation at the Ports run on diesel, and the vast majority of the remaining 4% are CNG vehicles. CNG vehicles entered the market around a decade ago and, after establishing an early reputation for being unreliable, are now highly integrated and valued by operators.[3]

The future of this lower-emission technology remains unclear as new regulations, such as Governor Newsom's Executive Order (N-79-20) which mandates that all drayage sales be zero-emission starting in 2035, indicate a

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[1] New satellite measurements show how dirty Los Angeles' air really is. November 2019. https://www.latimes.com/environment/story/2019-11-15/nox-pollution-los-angeles-air-quality#:~:text=When%20the%20scientists%20looked%20at,in%20third%2C%20with%204%20quadrillion. Accessed November 2020.

[2] Di Filippo, J. et al. Zero-Emission Drayage Trucks. October 2019. https://innovation.luskin.ucla.edu/wp-content/uploads/2019/10/Zero_Emission_Drayage_Trucks.pdf Accessed October 2020.

[3] A Case Study in CNG: What Not to Do. October 2014. https://www.government-fleet.com/155710/a-case-study-in-cng-what-not-to-do Accessed November 2020.

clear desire for zero-emission drayage. Right now, many fleets are enjoying their investments in low-emission CNG vehicles, including Kenworth's CNG plug-in hybrid electric trucks. In addition, when running on renewable natural gas (RNG), these vehicles can actually have negative carbon intensities, beating out battery electric and fuel cell trucks on a greenhouse gas emissions basis.

Battery electric drayage trucks are in the early stages of commercialization and, with sales fueled by regulations promoting zero-emission vehicles, are expected to penetrate a significant share of the market over the next decade. Still, they face many roadblocks to largescale adoption including limited range, slow charging times, high capital costs, and complexities with installing charging infrastructure. Fuel cell drayage trucks are a few years behind BE truck commercialization but are expected to solve many of the operational limitations of BE trucks with their longer range, quick refueling, and scalable fueling infrastructure.

Section 2 ends with the findings of interviews conducted in late 2020 with fleet managers and drayage stakeholders. The interviews explore the stakeholders' views on the future of IOOs in the drayage market, the key drivers and roadblocks of battery electric, hydrogen fuel cell, and CNG technology. It ends with a discussion on their experiences with installing and utilizing charging / fueling infrastructure.

Section 3 examines the key regulations that will influence the future of drayage adoption. They signify a clear shift towards zero-emission drayage operations. The Ports' Clean Truck Program only allows model year (MY) 14 trucks to enter the Port Drayage Truck Registry as of 2018 and will likely begin charging a $10-per-container throughput (TEU) surcharge in 2021 for drayage trucks that are not zero or near-zero emission vehicles. Starting in 2020, California's Truck and Bus Regulation restricts the DMV from registering trucks and buses with model years older than 2010.

The Heavy-Duty Omnibus Regulation, if passed, would set stricter limits on NO_x emissions vehicles starting in 2024. The Advanced Clean Truck Rule will require original equipment manufacturers (OEMs) to begin selling an annually-increasing percentage of zero-emission drayage trucks and will be accompanied with Advanced Clean Fleets that will mandate fleets to purchase those zero-emission vehicles. As mentioned above, Governor Newsom's executive order will increase the required percentage of zero-emission drayage sales in 2035 from 40%, as mandated by the Advanced Clean Truck Rule, to 100%.

Section 3 also covers six of the major incentives available to drayage fleets to help them adopt alternative fuel vehicles. These include capital cost discounts offered by HVIP, the VW Mitigation Trust, and the Carl Moyer Program. Other incentives, like the CEC's Block Grant and Southern California Edison's Charge Ready Transport Program, offer funding for the purchase of charging and fueling infrastructure. Finally, California's Low Carbon Fuel Standard provides credits to entities managing the distribution of alternative fuels based on their carbon intensity.

Section 4 reviews the methodology and results of a CALSTART model that was used to analyze three Scenarios based on California legislation outcomes. Scenario 1 investigates the drayage market between 2020 and 2035 if the San Pedro Bay Ports were able to meet Governor Newsom's Executive Order (N-79-20) goal of 100% ZE drayage sales by 2035. Scenario 2 explores what 75% ZE sales by 2035 would look like, and Scenario 3 looks at 40% ZE sales by 2035 as mandated in the Advanced Clean Truck Rule.

For each of these Scenarios, the model explores how the drayage markets in Los Angeles and Orange Counties may look with regard to diesel, CNG, BEVs, and FCBEVs. It includes percent adoption by fuel type between 2020 and 2035 and the cumulative number of vehicles by fuel type in the two counties. It also includes estimates for gallons of diesel saved and the amount of CO_2 and NO_x emissions avoided under each scenario. Finally, the report concludes with the major takeaways and lessons learned from writing this report.

1. INTRODUCTION

1.1 REPORT PURPOSE AND SCOPE

In December 2014, CALSTART released the "Near Zero-Emission Heavy-duty Truck Commercialization Study." This study was part of a larger California Energy Commission project for Kenworth Truck Company that identified the business case for electric heavy-duty trucks with range extenders. The study also identified the roll out plan, early adopters of near zero-emission heavy-duty trucks, and plans for expansion into other applications.

This study serves to update those findings and provide a comprehensive analysis of how the drayage truck market may look by 2035 depending on how a variety of factors play out. CALSTART used three fundamental approaches as part of the analysis to answer this question.

First, all the port drayage fleets registered in the Clean Truck Program in the Summer of 2016 were contacted for an in-depth survey. The goal of the survey was to collect general information about port drayage fleet operation, gauge fleet interest in advanced technology trucks, and identify trends and market barriers impacting the commercialization of advanced technology trucks.

Second, the influence of policy on the heavy-duty truck market was researched. By investigating legislation from as far back as 2008, CALSTART was able to synthesize the guiderails that helped shape the market as it exists today in late 2020. Legislation expected through the mid-2020's was also studied to predict how future incentives and regulations may influence the market by 2035. Finally, a drayage truck market projection was conducted, analyzing three scenarios that could represent the market penetration of battery electric, fuel cell, CNG, and diesel drayage trucks by 2035.

As this report will describe, heavy-duty trucking has a significant impact on the health of local populations and the global climate crisis. The number of trucks transporting goods from the Ports of Los Angeles and Long Beach is increasing steadily year over year. If Southern California is to achieve federal air quality standards, improve the health of millions of residents, and reduce carbon dioxide emissions to meet port and state goals, then understanding and actively shaping the future of the heavy-duty truck market will be essential.

1.2 SIGNIFICANCE OF HEAVY-DUTY TRUCKING

The Ports of Los Angeles (LA) and Long Beach (LB) are the first and second busiest Ports in the United States, accounting for a combined 25.6% of the North American market share in 2017.[4] In 2019, the San Pedro Bay Ports handled over 17.3 million TEUs, or twenty-foot equivalent units of cargo. While the Ports of LA and LB help support an estimated 1.86 million jobs in Southern California, they are also the largest fixed source of air pollution in the region.[5]

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[4] The largest and busiest Ports in the US, May 2017. https://www.icontainers.com/us/2017/05/16/top-10-us-ports/ Accessed September 2020.

[5] Port Facts and FAQs https://www.polb.com/port-info/port-facts-faqs/#facts-at-a-glance Accessed September 2020.

Facts and Figure https://kentico.portoflosangeles.org/getmedia/a43d3038-7713-4ebd-8c6a-dc72195a65f1/2019-facts-figures. Accessed September 2020.

As of 2018, over 17,500 Class 8 trucks were registered in the San Pedro Bay Ports' drayage fleet. On any given day, approximately 11,000 to 13,000 drayage trucks perform drayage activities at the Ports.[6] Heavy-duty vehicles constitute the largest source of greenhouse gasses at the Ports, emitting over 42% of the 933.5 total tonnes of CO_2e.[7] The following sections will detail the effects of heavy-duty trucks on local populations and global climate emissions.

1.3 EFFECTS ON LOCAL POPULATIONS

Enacting change on the heavy-duty vehicle market in Southern California will be critical to improving the lives of millions of local residents currently living in areas with air quality worse than what is prescribed by Federal standards. The San Joaquin Valley and Southern California continue to have the worst air quality in the country, both in terms of smog and particulate pollution.

Smog, or ground level ozone, is formed from a chemical reaction between Nitrogen Oxides (NO_x) and volatile organic compounds (VOCs) in the presence of heat and sunlight. Heavy-duty trucks are a key source of both NO_x and VOCs.[8] In fact, trucks are responsible for about one-third of California's smog-forming nitrogen oxides.[9] The LA County area is especially vulnerable to the effects of photochemical smog because of a combination of warm weather that enables the chemical reaction for the formation of smog, and the calm winds and surrounding mountains which do not allow smog to escape.

According to the American Lung Association's 2019 "State of the Air" report, Los Angeles and Long Beach were ranked first in the nation for most ozone pollution, fifth for year-round particle pollution, and seventh for short-term particle pollution. Small particles emitted by diesel combustion can lodge in lung tissue. Both this particle pollution and ozone can contribute to lung inflammation and asthma attacks. In the long term, particles lodged in the lungs could lead to heart attacks, stroke, and cancer. California air quality and health experts linked 2,400 premature deaths per year to noxious emissions produced by the Ports in 2007.[10]

Importantly, truck pollution has been shown to negatively impact disadvantaged communities at higher rates in California. According to a 2020 study by the Union of Concerned Scientists, the areas along the I-10 freeway from LA to Riverside and the area bounded by the I-605 and I-110 freeways from the Port of LB through LA are most affected. Communities like Lynwood, Huntington Park, and Wilmington are surrounded by two major freeways,

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Clean Port https://www.aqmd.gov/nav/about/initiatives/clean-port#:~:text=The%20twin%20ports%20of%20Los,air%20pollution%20in%20Southern%20California. Accessed September 2020.

[6] https://cleanairactionplan.org/documents/final-drayage-truck-feasibility-assessment.pdf/

[7] Port of Los Angeles Inventory of Air Emissions – 2018, September 2019 https://kentico.portoflosangeles.org/getmedia/0e10199c-173e-4c70-9d1d-c87b9f3738b1/2018_Air_Emissions_Inventory. Accessed September 2020

[8] Jaworski, A. *Ozone (Smog),* Environmental Law and Policy Center. http://elpc.org/issues/clean-air/ozone-smog/ Accessed October 2020.

[9] Editorial: California is leading again on cleaner air, LA Times, August 2020. https://www.latimes.com/opinion/story/2020-08-30/clean-trucks-california#:~:text=Today%2C%20trucks%20are%20responsible%20for,2027%20than%20models%20sold%20today. Accessed October 2020.

[10] Lin, R. 100-truck convoy planned on Harbor Freeway this morning, June 2007. https://www.latimes.com/archives/la-xpm-2007-jun-27-me-convoy27-story.html Accessed November 2020.

five oil-refineries, and two of the country's busiest Ports which all emit toxic air pollution.[11] These communities are also predominately populated by minority groups. While 39% of California's total population is Latinx, this group makes up 61% of those most exposed to truck pollution.[12] As a specific example, Wilmington has a population that is 97% people of color and a pollution burden score of 100 (the highest possible level) according to the California EPA. Port emissions are not just an issue of human health, but also of racial equity.

Heavy-duty trucks are one of the main sources of these harmful pollutants. While the air quality near the Ports is still not in line with Federal standards, significant emissions reductions have been made over the past 15 years. The following figure displays the NO_x produced from the Port's largest emissions sources in 2005 and 2019.

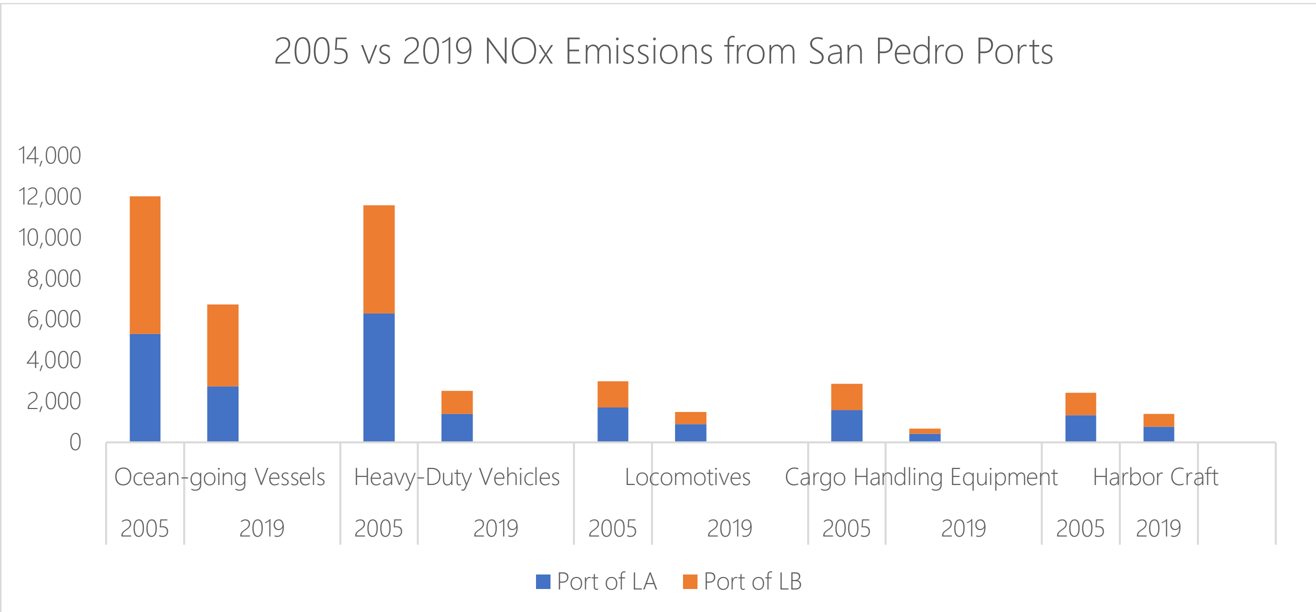

Figure 1: NO_x Emissions from the largest emissions sources at San Pedro Bay Ports in 2005 and 2019 [9]

As shown in Figure 1, all five emissions sources experienced drastic decreases in NO_x. This ranged between a 43% reduction in harbor craft emissions to a 78% reduction in heavy-duty vehicle emissions. Ocean-going vessels remained the largest source of NO_x in 2019, constituting more than all the other sectors combined. Notably, the emissions from each port are nearly equal in both 2005 and 2019, indicating that the reductions initiatives from both Ports are working at around the same pace. It is also noteworthy that these NO_x reductions occurred while container throughput continued to grow. The table below compares the number of TEUs, or twenty-foot equivalent units used to describe cargo capacity, with NO_x emissions.

[11] Lavelle, P. Extreme Air Pollution Choking Wilmington, California. January 2020. https://america.cgtn.com/2019/01/11/extreme-air-pollution-choking-wilmington-california#:~:text=Wilmington%2C%20California%20is%20surrounded%20by,That's%20the%20highest%20level%20possible. Accessed November 2020.

[12] Cooke, D. California Moves Forward to Address Pollution from Heavy-Duty Trucks. August 2020. https://blog.ucsusa.org/dave-cooke/california-moves-forward-to-address-pollution-from-heavy-duty-trucks Accessed November 2020.

Table 1: Comparison of TEU throughput (TEU) and NO_x emissions from heavy-duty vehicles at the San Pedro Ports between 2005 and 2019.[13]

	Container Throughput (TEU)			NO_x Emissions		
	2005	2019	Percent Growth (%)	2005	2019	Percent Decrease (%)
Port of LA	7,484,625	9,337,632	24.8	6,307	1,382	-78.1
Port of LB	6,709,818	7,632,032	13.7	5,273	1,127	-78.6
Total	14,194,443	16,969,664	19.6	11,580	2,509	-78.3

As displayed in the table, the combined number of TEUs grew roughly 20% between 2005 and 2019. In that same period, NO_x emissions were reduced by about 60% from all sectors. Reducing air pollution can be achieved without posing a barrier to economic growth at the Ports. These results were largely the effect of the San Pedro Bay Port's Clean Truck Program. This Program and other progressive mandates intended to reduce air pollution and greenhouse gas emissions will be discussed further in Section 3.

1.4 EFFECTS ON GLOBAL CLIMATE EMISSIONS

Harmful emissions from heavy-duty trucks not only pose a threat to local residents, but the greenhouse gases they emit are also significant contributors to global climate change. About 99.4% of the vehicle miles traveled by heavy-duty trucks in 2019 were from on-road vehicles rather than on-terminal. This means that converting drayage trucks and other on-road heavy-duty vehicles will have the most significant impact on reducing carbon emissions. Unlike air pollutants such as NO_x, significant CO_{2e} reductions have not yet been realized at the Ports. The following table displays the change in $CO2_e$ by source at the San Pedro Ports between 2005 and 2019.

[13] 2019 Air Emissions Inventory, Port of Long Beach. https://safety4sea.com/wp-content/uploads/2020/10/Port-of-Long-Beach-Air-Emissions-Inventory-2019-2020_10.pdf Accessed October 2020.
2019 Air Emissions Inventory, Port of Los Angeles. https://kentico.portoflosangeles.org/getmedia/4696ff1a-a441-4ee8-95ad-abe1d4cddf5e/2019_Air_Emissions_Inventory Accessed October 2020.

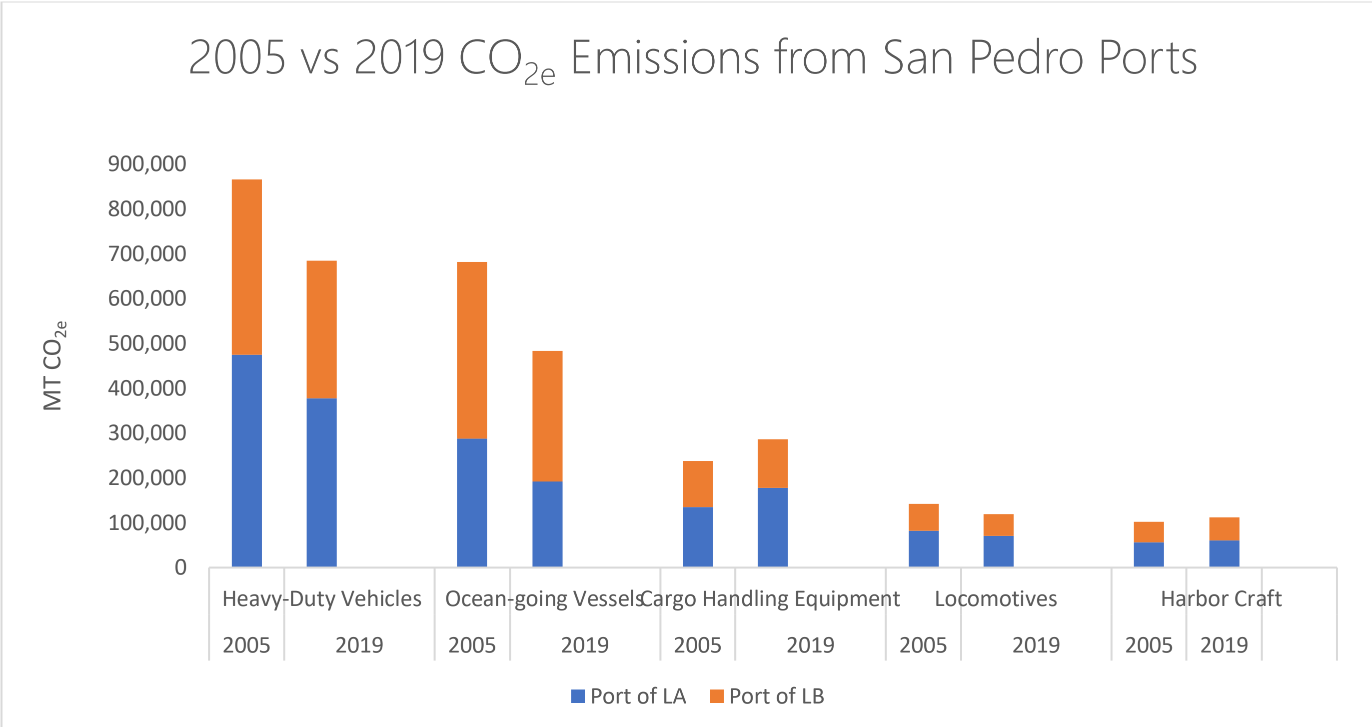

Figure 2: Change in CO_{2e} emissions from the largest sources at San Pedro Bay Ports in 2005 and 2019

As displayed in the figure above, heavy-duty vehicles remain the largest source of CO_{2e} despite some reductions in the past fourteen years. Figure 2 reveals the significant impact that converting to zero and near-zero emission trucks would have on the Ports' greenhouse gas emissions. Even after a 21% decrease in emissions between 2005 and 2019, the combined 685,119 metric tons of CO_{2e} released from heavy-duty trucks at both Ports last year is equivalent to burning over 750 million pounds of coal or 77 million gallons of gasoline.

As the largest source of greenhouse gas emissions and the second largest source of NO_x emissions at the Ports, transitioning heavy-duty vehicles to zero-emission is a key focus at the state government and port management level. To better understand the zero and near-zero emission truck technology available to fleets, the following section will discuss the drayage industry, the drayage duty cycle, the different fuel types available for drayage trucks and the emissions produced by each, as well as the perspective of four major fleet stakeholders on the future of the industry. The paper will then explore the different regulations and incentives that play a role in the adoption of alternative fuel drayage trucks. Finally, this report will describe the methodology and results of CALSTART's analysis predicting the market penetration of alternative fuel trucks in the San Pedro Bay Port drayage market under three scenarios by 2035.

2. DRAYAGE TECHNOLOGY, FUEL TYPE ASSESMENT, AND INDUSTRY INTERVIEWS

2.1 THE DRAYAGE INDUSTRY

Electrifying the heavy-duty vehicles operating at the Ports will play a critical role in meeting our air pollution and climate goals. Heavy-duty trucking is often broken up into three distinct categories with increasing average distances per trip: drayage, regional delivery, and long-haul trucking. Drayage trucks ferry inbound and outbound cargo between port terminals and train yards, warehouses, and distribution centers. Because drayage trucks usually travel the shortest distances and generally domicile in the same location every night, they have been targeted as the easiest heavy-duty vehicles to electrify first.[14]

CARB has adopted the beachhead model developed by CALSTART to identify the markets in each transportation sector that are most suited to electrification, acting as a foothold for other markets in that sector. Drayage trucks are identified as beachhead markets in the heavy regional freight sector and will lead the path towards electrification for regional, refuse, and long-haul trucking.[15]

CALSTART surveyed 25 port drayage fleets in 2016 to better understand the market. When asked if they provided other trucking services in addition to port drayage, 84% of the respondents said yes. The following figure highlights the most common other services offered by these fleets.

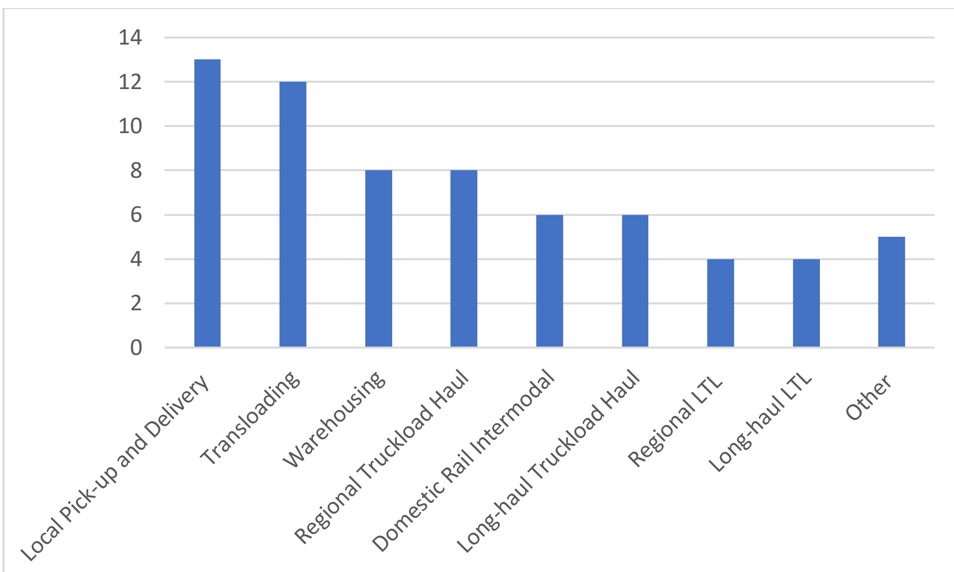

Figure 3: Other services offered by surveyed drayage fleets

Many of these services, like regional and long-haul trucking, have longer-range duty cycles. Historically, fleets operated the same vehicles for longer range services and then converted trucks for drayage when they had high

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[14] Di Filippo, J. et al. Zero-Emission Drayage Trucks. October 2019. https://innovation.luskin.ucla.edu/wp-content/uploads/2019/10/Zero_Emission_Drayage_Trucks.pdf Accessed October 2020.

[15] Welch, D. The Beachhead Model. October 2020. https://globaldrivetozero.org/public/The_Beachhead_Model.pdf Accessed November 2020.

mileage. As regulation pushes fleets to operate newer vehicles for drayage, some fleets may decide not to continue offering both long range and drayage services.

Drayage trucking firms are licensed motor carriers (LMCs) who often have a combination of their own drivers and contracted independent owner operators (IOOs). LMCs are contracted to move cargo to or from a port, and then the drayage companies dispatch either their drivers or IOOs to perform the service. LMCs provide trucks for their own drivers, but IOOs are generally responsible for purchasing their own trucks. The figure below displays the distribution of company-owned and driver-owned vehicles in the 25 port drayage fleets surveyed by CALSTART in 2016.

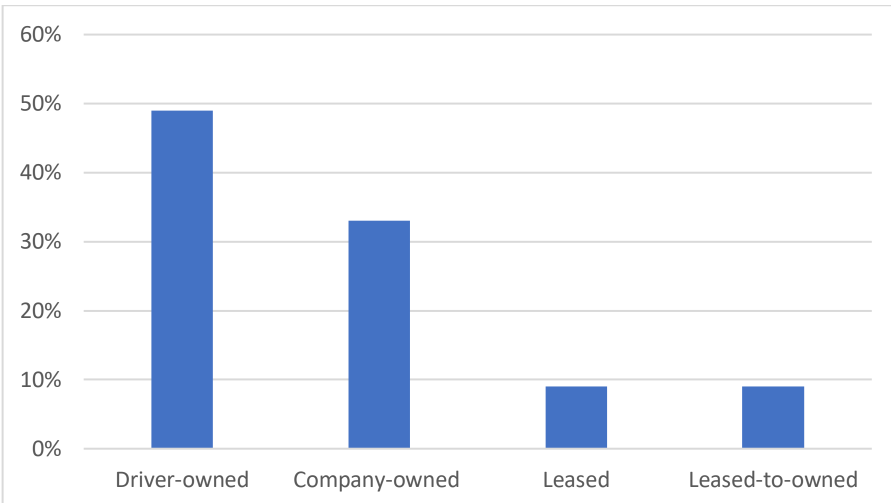

Figure 4: 2016 CALSTART survey response to the question, "Please tell us how many trucks you have in your port drayage fleet by truck ownership."

According to Figure 4, about 50% of vehicles in these fleets were driver-owned, or IOOs. Fleets owned 33% of their vehicles, and an additional 18% were leased or being leased-to-owned by the fleet. The independent owner operator model has been controversial in recent years. Table 2 presents the fleet's opinions, back in 2016, about the future of IOOs in their fleets.

Table 2: 2016 CALSTART survey response to the question, "How do you expect the driver status situation of your company to change in the future?"

	Employee-Driver Only Fleet	Independent-Driver Only Fleet	Mixed-Driver Fleet
Will have more employee drivers	83% (10 responses)	0% (0 responses)	44% (4 responses)
Will stay the same	17% (2 responses)	0% (0 responses)	22% (2 responses)
Will have more independent drivers	0% (0 responses)	75% (3 responses)	22% (2 responses)
Don't know	0% (0 responses)	25% (1 responses)	12% (1 responses)

Table 2 indicates that employee-driver only fleets expect to continue employing drivers at more or the same numbers, and independent-driver only fleets will likely continue to hire independent drivers. For mixed fleets, there is a mix of employing more of their own drivers and employing more independent drivers.

The future of the independent owner operator model has been in doubt since confusion over this arrangement has the been the source of legal action. A variety of misclassification lawsuits arose from the lease-to-own model noted in Figure 4. The Port's Clean Truck Program mandated in 2008 that trucks older than Model Year (MY) 1989 not be allowed to enter the San Pedro Bay Ports, followed by a 2012 ban on trucks that did not meet 2007 emission standards. Many IOOs were unable to afford the high capital costs of financing newer trucks.[16] Fleets stepped in and offered IOOs a lease-to-own model where fleets lease trucks of their choosing to IOOs. This led IOOs to become more reliant on hundreds of drayage fleets in Southern California. Misclassification lawsuits arose from the Teamsters union and private sector attorneys representing drivers charging motor carriers of, among other things, "avoiding paying fair wages, medical insurance, unemployment compensation, and other benefits normally afforded to employees." [17]

In September 2019, California adopted Assembly Bill (AB) 5 aimed at combatting the misclassification of workers, including IOOs. Under the bill, the independent owner operator model would essentially be outlawed and current IOOs would either need to be acquired by fleets as employees or let go.[18] AB5 was set to take effect January 1, but in response to a request from the California Trucking Association, a U.S. district judge granted a temporary restraining order. Soon after, the judge enacted a preliminary injunction to halt enforcement of AB5 against motor carriers. As of the writing of this report, the fate of AB5 and independent owner operators is still to be determined by the courts.[19] Of the three fleets CALSTART interviewed in October 2020, one made the decision to preemptively remove all IOOs from their service.

The authors of this report have no opinion over the outcome of AB5, however it is noteworthy that the IOO model makes it harder to transition towards zero-emission vehicles for three key reasons. First, as future regulations like Advanced Clean Fleets and updates to the Clean Truck Program require investment in new, higher cost trucks, IOOs are more likely to be unable to afford these emissions-reductions measures. Second, many IOOs park their trucks at their houses without space to install charging infrastructure. This makes transitioning to battery electric vehicles (BEVs) more difficult. FCBEVs may offer a zero-emission alternative that fits better into the IOO structure. Third, the pay structure for IOOs is often different than employee drivers and does not fit well with the current limitations of zero-emission technology. According to results from CALSTART's 2016 survey, 81% of fleet employees are paid hourly / salary, and 19% are paid based on the number of hauls made. On the contrary, no IOOs were paid hourly / salary. Instead, nearly three quarters of IOOs were paid primarily based on number of hauls or distance driven. Zero-emission technology that is currently range limited makes it difficult for IOOs to maintain current wages when payment is based on the number of hauls or distance driven. Understanding the

[16] Clean Truck Program. https://www.portoflosangeles.org/environment/air-quality/clean-truck-program. Accessed October 2020.

[17] Mongelluzo, B. LA-LB harbor truck drivers sue to secure employee status, February 2018. https://www.joc.com/trucking-logistics/la-lb-harbor-truck-drivers-sue-secure-employee-status_20180226.html. Accessed October 2020.

[18] McNicholas, C and Poydock, M. How California's AB5 protects workers from misclassification, November 2019. https://www.epi.org/publication/how-californias-ab5-protects-workers-from-misclassification/. Accessed October 2020.

[19] Kingston, J. Judicial panel hears why AB5 should be kept out of California trucking sector, September 2020. https://www.freightwaves.com/news/judicial-panel-hears-why-ab5-should-be-kept-out-of-california-trucking-sector. Accessed October 2020.

duty cycles of drayage trucks will be critical for both fleets and IOOs to transition towards zero-emission technology.

2.2 DRAYAGE DUTY CYCLE

To better understand the drayage duty cycle, the 2016 survey was supplemented by 2020 interviews with four major drayage fleets and trucking associations. These included questions related to how long trucks stay in service, trip distances, number of trips per day, and domicile location. Table 3 shows findings from the 2020 interviews.

Table 3: Approximate number of trucks and years in service for fleets and associated IOOs interviewed by CALSTART in late 2020

	Approximate Number of Company-Owned Trucks	Approximate Number of IOO Trucks	Company-Owned Truck Years in Service	IOO Truck Years in Service
Fleet 1	100	0	7 – buy new	N/A
Fleet 2	65	500	5 – buy new	Up to 550,000 miles, although some likely operate for longer. Must be CNG
Fleet 3	60	300	3 – lease new	Must meet Clean Truck Program regulations

As shown in Table 3, fleets have adopted a few different structures for truck years of service. Fleets 1 and 2 buy their vehicles new every 5 or 7 years, while fleet 3 chooses to lease new vehicles every 3 years. The fleets that still utilize IOOs appear to be less structured with their IOOs. Fleet 2 has mandated that all IOOs operate CNG vehicles and fleet 3 just requires them to meet the Clean Truck Program regulations. In general, IOO vehicles tend to stay in service longer than company owned vehicles. None of the fleets interviewed helped IOOs finance their trucks. The following figure taken from the Port of Long Beach's 2019-2020 Air Emissions Inventory provides a snapshot of the current model year distribution of trucks entering both Ports.

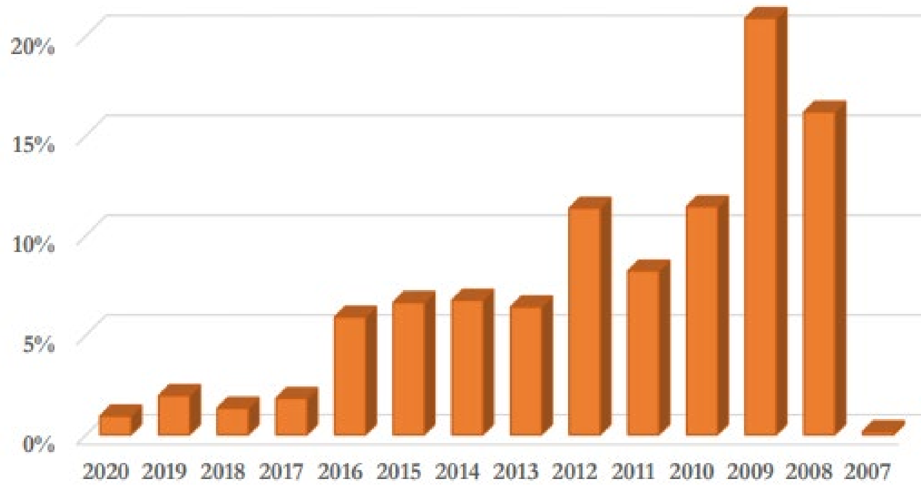

Figure 5: 2019 Model Year Distribution of HDV vehicles entering the Ports[20]

According to the 2019 report, the call weighted average age of the trucks was about 7.6 years. Notably, the very low number of MY2007 vehicles is a result of the Clean Truck Program's requirement for trucks to be MY2008 or newer. OEMs of zero-emission vehicles would be advised to set manufacturing timelines that correspond with the Clean Truck Program's future model year regulations, especially because many drayage fleets only purchase new vehicles once per decade. The table below explores the average distances of port drayage trips for employees and IOOs.

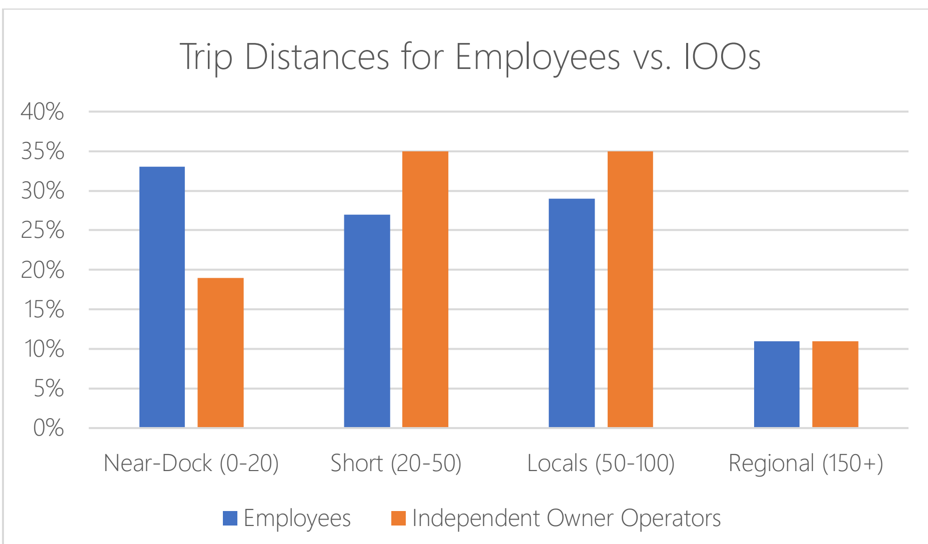

Figure 6: 2016 CALSTART survey response to the question, "What kind of port drayage service do you provide?" The numbers in the x-axis are the number of miles.

The vast majority of drayage trips are 150 miles or less. Employee drivers are more likely to be dispatched on assignments closer to the Ports than IOOs. 33% of employee driver assignments are within 20 miles of the port,

[20] Air Emissions Inventory 2019-2020 https://safety4sea.com/wp-content/uploads/2020/10/Port-of-Long-Beach-Air-Emissions-Inventory-2019-2020_10.pdf. Accessed October 2020.

compared to 19% for IOOs. IOOs are more likely to perform trips between 20 and 100 miles, totaling 70% of all IOO trips. Both employee drivers and IOOs have 11% of their trips ranging over 150 miles among the surveyed fleets. These numbers are consistent with the distances reported by the three fleets in CALSTART's 2020 interviews. While BEVs today can meet that range, number of trips per day poses more of a problem. For one fleet traveling 110-120 miles from the Inland Empire to the Port and back, their diesel trucks can make up to three trips per day. With BEVs, they can make two trips at most. All three fleets interviewed discussed the possibility of needing to purchase more than one BEV to replace a diesel truck. Zero-emission trucks are already more expensive than conventional diesel trucks, and drayage fleets are looking for alternatives to purchasing additional ZEVs in order to complete their daily routes. Fleets are hoping that fuel cell trucks, expected to have ranges of over 300 miles and quick refueling, will be a solution to issues of range.

According to the 2016 surveys, fleet employees and IOOs averaged 3.9 and 4.2 trips per day to the Ports, respectively, with a minimum of 1 and maximum of 10. The average time per round trip for employee drivers and IOOs was 3.1 hours per trip and 2.4 hours per trip, respectively, with a minimum of 30 minutes and maximum of 7 hours. CALSTART's 2016 survey also asked fleets how far from the San Pedro Bay Ports their trucks domicile when not in use. About 18% were within 6 miles, 60% were between 6-20 miles, and 12% were more than 20 miles away. The following section will explore the alternative fuel truck options available today, their pros and cons, and their current share of the market.

2.3 FUEL TYPE COMPARISON AND EMISSIONS ASSESSMENT

There are four main fuel types that are commonly discussed in the drayage industry; diesel, compressed natural gas (CNG), battery electric, and hydrogen. This section will explore the pros and cons of each and their current commercialization status.**Error! Bookmark not defined.** It should be noted that there are a few variations within the CNG category including liquified natural gas (LNG) and CNG plug-in hybrid electric. These will be discussed as well, albeit in less detail because they largely fit into the same trends as CNG. The following table describes the pros and cons of the four main fuel types in heavy-duty trucks.

Table 4: Pros and Cons of diesel, CNG, battery electric, and hydrogen fuel cell heavy-duty trucks

Pros	Cons

Diesel	• The most common fuel type for decades, so capital costs are low and fueling locations are common • Range only limited by driver's 10 hour driving limit	• Biggest polluter of particulate matter and greenhouse gases • Loud and odorous operation • Relatively high maintenance costs • Being phased out by California and port regulations
CNG	• Less emissions than diesel • Quick refill like diesel • ~ 300 mile range • Fueling infrastructure relatively common • Fuel slightly less expensive than diesel • Quieter operations	• Not zero-emission • Although highly commercialized now, gained a reputation for not being reliable when first entering the market • Emits about 75% as much CO_2 and 10% as much NO_x as diesel trucks
Battery Electric	• Zero tailpipe emissions • Ability to opportunity charge while idling • Quiet operations • Reduced maintenance costs • Torque / acceleration	• Slow charging times • Limited range currently up to 150 miles • High MSRP • Installing charging infrastructure can be expensive, time consuming, and takes up space • Heavy battery can lead to weight issues (maximum gross vehicle weight limit of 82,000 lbs)[21]
Hydrogen Fuel Cell	• Zero tailpipe emissions • Quick refueling (10 minutes) • Expected 300+ mile range • Quiet operations • Reduced maintenance costs • Possibility for extended range with 700 bar fueling • Torque / acceleration	• Least commercialized option with fewest vehicles on the road • High MSRP • High fuel cost • Fueling infrastructure not commonly available

As noted in Table 4, diesel trucks are being phased out in California by state and port regulations. In accordance with Governor Newsom's Executive Order (N-79-20), which will be discussed in Section 3.1.4, 100% of drayage truck sales must be zero-emission by 2035.[22] While CNG trucks are often viewed as a great intermediary between diesel and ZEV vehicles because they emit much lower NO_x, their long-term future in the heavy-truck market at California Ports is unclear. Still, of the 4% of terminal calls at the Ports in 2019 that were not serviced by diesel trucks, most of them were by LNG trucks.

[21] The Consolidated Appropriations Act, 2019, Truck Size and Weight Provisions. October 2019. https://ops.fhwa.dot.gov/freight/pol_plng_finance/policy/fastact/tswprovisions2019/index.htm#:~:text=Natural%20gas%20and%20electric%20battery%20vehicles.,82%2C000%20pounds)%20under%20this%20section. Accessed October 2020.

[22] Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars & Drastically Reduce Demand for Fossil Fuel in California's Fight Against Climate Change https://www.gov.ca.gov/2020/09/23/governor-newsom-announces-california-will-phase-out-gasoline-powered-cars-drastically-reduce-demand-for-fossil-fuel-in-californias-fight-against-climate-change/Accessed October 2020.

In addition, one of the fleets interviewed has had a great experience piloting the BAE Kenworth CNG plug-in hybrid electric truck. Drivers "love the vehicle" for its 350 mile range, smooth riding "like a Cadillac," and quiet, odorless operations. The fleet plans to reinvest in the technology and adopt more CNG hybrid trucks in the near future. The following table details some key metrics related to the performance of the different fuel types. In addition to those listed, sources include internal documents from leading OEMs in the hydrogen and BEV field.

Table 5: Comparison of key performance metrics for diesel, CNG, hydrogen fuel cell, and battery electric heavy-duty trucks[23]

	Diesel	CNG	Hydrogen Fuel Cell	Battery Electric
MSRP	$120,000	$202,624	$520,000	$340,000
Miles / diesel gallon equivalent (DGE)	6.3	5.7	6.0 / kg H_2	2.6 kWh / mile
$ / DGE	$3.53	$3.00	$10.90 / kg H_2	$0.10 / kWh

As detailed in Table 5, diesel truck MSRPs are the lowest, followed by CNG, battery electric, and hydrogen fuel cell, respectively. Incentive funding for ZE truck capital costs is available in California and will be discussed in the following section. Diesel, CNG, and hydrogen all get around 6 miles / DGE and offer comparable ranges to diesel with 10-15 minute refueling. Currently, CNG fuel is slightly less expensive than diesel, and hydrogen is much more expensive than both other options. Hydrogen fuel costs are expected to drop over the coming decades with fuel for heavy-duty vehicles reaching $7.26/kg or lower by 2035. Hydrogen is much more energy dense than diesel, and 1 kg of hydrogen contains about the same amount of energy as a gallon of diesel. Fuel cell vehicles are expected to get much higher miles per diesel gallon equivalent, meaning fleets can get more range out of the same cost of hydrogen fuel.[24]

Battery electric vehicles in their current state are more range limited but offer the potential for a lower total cost of ownership (TCO) because of the low cost of electricity. Tesla Semis, expected to disrupt the market upon release in late 2021, are said to have two options for battery configurations with ranges of 300 and 500 miles in fully loaded trucks. Tesla's Elon Musk has also announced that the Semi will be able to achieve an 80% charge in 30 minutes with their new solar-powered Megacharger.[25] These significant advancements in BEV technology are still to be displayed publicly and proven in real-world operations.

To achieve a lower TCO, it is critical for fleets adopting BEV technology to closely examine the rates offered by their utility (as there may be special rates for commercial EVs) and whether demand charges are part of the rate structure. The following table examines the emissions differences between the fuel types.

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[23] AFLEET Tool 2018. https://afleet-web.es.anl.gov/afleet/ Accessed November 2020.
Gas Prices. https://gasprices.aaa.com/state-gas-price-averages/. Accessed November 2020
Annual Energy Outlook 2020, January 2020. https://www.eia.gov/outlooks/aeo/. Accessed November 2020.
[24] Molloy, P. Run on Less with Hydrogen Fuel Cells, October 2019. https://rmi.org/run-on-less-with-hydrogen-fuel-cells/#:~:text=By%20contrast%2C%20hydrogen%20has%20an,12%E2%80%9314%20kWh%20per%20kg. Accessed November 2020.
[25] Della Cava, M. Tesla Semi, an electric big rig truck with 500-mile range, rolls into reality. November 2017. https://www.usatoday.com/story/tech/2017/11/16/tesla-semi-electric-big-rig-truck-rolls-into-reality/873162001/ Accessed October 2020.

Table 6: Tailpipe emissions comparison for diesel and CNG heavy-duty trucks. Units in grams per mile.[26]

	Diesel	CNG
NO_x	1.508	0.151
$PM_{2.5}$	0.007	0.007
CO_2	1,235.2	987.3

Diesel trucks produce the most NO_x, $PM_{2.5}$, and CO_{2e}. Natural gas vehicles produce the same amount of $PM_{2.5}$ emissions but only 10% of the total NO_x emissions. There can be a wide variety in these emissions values based on how the vehicle is driven, the aftertreatment process, and duty cycle. The biggest benefit of CNG vehicles are their reduced NO_x emissions as they still produce 75% as much CO_2 emissions as diesel. As zero-emission vehicles, fuel cell and battery electric trucks produce no tailpipe emissions. It is Important to note, however, that BEVs and FCBEVs are only truly zero-emission if running on renewable energy. While they do not produce any air pollution, the production of electricity to charge BEVs, and the energy required to produce hydrogen, commonly emit both GHGs and particulate matter.

As state and port regulations guide the industry towards zero-emission vehicles, it is critical to simultaneously transition the electrical grid and all forms of hydrogen production to renewable energy. The following section will review the policies, regulations, and incentives that play a role in the drayage market.

2.4 INDUSTRY INTERVIEW TAKEAWAYS

This section will discuss the takeaways from three interviews with major drayage fleets including Dependable Highway Express (DHE) and Total Transportation Services (TTSI), as well as insight from the Harbor Trucking Association (HTA). As detailed in Table 3 above, a relatively diverse group of fleets was interviewed. Two fleets had a combination of IOOs and employee drivers, and one chose to stop employing IOOs. One of the fleets with IOOs requires them to drive CNG vehicles, and the other simply requires them to abide by the Clean Truck Program regulations. Two fleets buy their vehicles new and operate them for 5 and 7 years, and one fleet leases their vehicles new for 3 years. Their views on the future of IOOs, BEVs, FCBEVs, CNG, and infrastructure all related to the drayage sector at California Ports will be discussed.

2.4.1 FUTURE OF INDEPENDENT OWNER OPERATORS

Multiple stakeholders feel that if AB5 does not outlaw the independent owner operator model outright, Advanced Clean Fleets and other California and Port regulations will be the biggest threat to IOOs over the next decade. They explained that an inability to afford the higher capital costs of ZE trucks, compounded with the issues of needing access to charging / fueling infrastructure and the limited range associated with BE trucks will all put multiple IOOs out of business. The stakeholders were concerned about the potential for tens of thousands of IOOs to lose their jobs and be stranded with "dead assets," meaning the diesel vehicles they would likely have trouble reselling. They also noted that a lack of IOOs would make it harder for drayage fleets to operate in California.

When asked about the number of IOO drivers in the California drayage market, one stakeholder estimated that there had been a shift from 90% being IOOs five years ago to 80% today. In their view, the majority of IOOs do

[26] Di Filippo, J. et al. Zero-Emission Drayage Trucks. October 2019. https://innovation.luskin.ucla.edu/wp-content/uploads/2019/10/Zero_Emission_Drayage_Trucks.pdf Accessed October 2020.

not want to be employee drivers, so they see a mass transition from IOOs to employee drivers as unlikely. They believe that many IOOs like to control their own schedules, like the financial upside of being an independent contractor, and value the notion that if they build their company the right way, IOOs can scale to a sizable business.

Still, stakeholders felt that Advanced Clean Fleets would not pose an immediate threat to IOOs. They cited the "Assurance of Asset 'Useful Life'" provision of the California State Transportation Agency.[27] It states that trucks will not be required to turnover until they have reached 13 years from the model year of the engine or 800,000 vehicles miles traveled, with a maximum limit of 18 years from the model year. The two fleets with IOOs had more than five times as many independent owner operators than employee drivers, meaning that a transition away from IOOs would be a significant shift. While CA legislation may not necessarily mean the end for IOOs, some fleets are not waiting to see things play out.

One fleet made the decision to transition all contractors who wanted to be employees to this more permanent classification. They noted that it affected operations somewhat at first and they likely had to employ more drivers, but they did not want a potential court decision from AB5 striking down the IOO model to leave them unprepared. The stakeholders agreed that utilizing IOOs is a great benefit for fleets because they can be hired and let go as necessity demands, unlike employees, and that the contractors are incentivized differently. The IOO model comes down to "the more you do, the more you make," and that leads to high productivity. Many IOOs and fleets enjoy the independent owner operator model, but whether it can coincide with California's transition towards cleaner drayage operations remains to be seen.

2.4.2 DRIVERS AND ROADBLOCKS TO BEV ADOPTION

Battery electric trucks are primed to constitute a significant percentage of the drayage market over the coming years. They are currently the most commercialized zero-emission technology option with numerous OEMs in the pilot and demonstration phase and a few, including BYD, Freightliner, Lion Electric, and Peterbilt, with Class 8 trucks ready for commercial purchase. When asked why a fleet might adopt zero-emission vehicles, the interviewed stakeholders had the following responses.

Most companies try to be good environmental stewards, and it is good PR. As a result, they believe that the slow uptake of BEV technology so far is not a result of fleets slow to adapt to the market, but rather a result of the OEMs being able to meet fleets' required duty cycles. Once the technology has been tested and proven, a steady increase in BEV adoption is expected. In addition to positive PR, regulation has a significant impact on BEV adoption. With upcoming regulations like the Advanced Clean Truck Rule and the Clean Truck Program, many fleets are exploring their options for alternative fueled vehicles. The timeline puts battery electric trucks in a great position to grow their market share as fuel cell truck technology races to catch up.

Still, there remain multiple hurdles for BE drayage trucks to overcome. First, the total cost of ownership for BE trucks must be equal to or cheaper than a diesel truck. The stakeholders noted that they are not aware of any fleet operating a BE truck right now without receiving financial incentives. The three main factors influencing TCO are capital cost, cost of infrastructure, and the cost of fuel. Capital costs for battery electric trucks are expected to drop closer to diesel truck costs as BE trucks scales and battery technology improves. Utilities will play a key role in establishing charging infrastructure and rates that are financially viable for fleets. Southern California Edison's $356 million Charge Ready Transport program budgeted millions for commercial vehicle

[27] SB1 Truck Provisions: Q&A https://calstablog.files.wordpress.com/2017/04/sb-1-truck-provisions-q-and-a.pdf. Accessed November 2020.

charging station rebates and the utility recently released their TOU-EV-9 rate option for commercial EVs with charging demands exceeding 500 kW.[28]

Second, BE truck range and charging speed is a major roadblock for fleets. While drayage trips are very often less than 150 miles roundtrip and many BE trucks today can offer this range on a full charge, diesel drayage trucks may take up to three trips per day. Multiple stakeholders stated that a 300 mile range minimum would be ideal for battery electric trucks. Otherwise, fleets may need to purchase more than one BE truck to replace a diesel truck so that when a driver's battery is running low they can stop and switch to a fully charged truck while the first truck recharges. Obviously, this option adds a lot of operational complexity, cost, and other limitations for fleets and could be avoided with a longer range. Quicker recharge times could also help solve this issue.

Third, fleets are seeking easily digestible information about BE truck operations. Many fleet managers have decades of experience with diesel technology and know, for example, the miles per gallon they can expect. With new factors influencing range like elevation gain, stop and go vs straight driving, and payload effects, easily digestible performance data for BE trucks in the field could help fleet managers make informed decisions and feel more comfortable investing in BE technology. Significant improvements in battery technology over the coming decade might increase BEV range enough to make these factors negligible.

Regulation timelines put BE trucks in a great position to penetrate the drayage market. The industry's ability to achieve lower cost, meet more demanding duty cycles, and educate fleets on their successes will influence the rate and extent of this market penetration. Hydrogen fuel cell technology is expected to be a solution to many of the duty cycle issues that BE trucks face, but the less-commercialized technology also faces several of its own roadblocks.

2.4.3 HYDROGEN'S ROLE IN THE INDUSTRY

Thoughts on the future of hydrogen in the drayage market varied from curiosity with an admitted lack of knowledge about the technology, to an expectation that the technology will be "the way to go" but currently ten years away from commercialization, to currently demoing fuel cell trucks. One fleet said they were talking to multiple hydrogen drayage truck OEMs and would likely have one or two hydrogen trucks by early 2022.

Several positives were noted about fuel cell technology. These included quick refueling, an ability to scale the infrastructure to serve many vehicles, and a much desired longer range than current BEV technology. Still, infrastructure is a highly limiting factor. Shell and Toyota are collaborating to develop the first hydrogen truck refueling station at the Port of Long Beach.[29] This is a step in the right direction, as stated by stakeholders, but more stations will be necessary to justify adoption. The fleet currently demoing the technology has hydrogen trucked in. They explained that operations with the fuel cell vehicles were running smoothly despite some reliability issues, but being forced to return to base to refuel, unlike diesel and CNG, poses limitations.

Finally, one stakeholder detailed his personal experience with the port and states' push towards cleaner drayage technology: "We're taking people like me and trying to turn them into experts in a new topic. The faster we can educate people like me, the faster we can accelerate adoption. We need collaboration where my experience with

[28] Rate Schedules TOU-EV-7, TOU-EV-8, TOU-EV-9 for Business Customers Charging Electric Vehicles https://www.sce.com/sites/default/files/inline-files/TOU-EV-7_8_9%20Rate%20Fact%20Sheet_WCAG_0.pdf Accessed November 2020.

[29] Shell and Toyota move forward with hydrogen facility at Port of Long Beach https://www.prnewswire.com/news-releases/shell-and-toyota-move-forward-with-hydrogen-facility-at-port-of-long-beach-300633259.html Accessed November 2020.

freight matches with someone who has the engineering experience." Fuel cell vehicles are often well suited for drayage duty cycles and offer multiple operational benefits. The amount fuel cell technology can penetrate the market may depend on how successfully fuel cell truck OEMs are able to engage fleets and offer them a seamless transition to zero-emission technology.

2.4.4 FUTURE OF CNG

One of the first points stakeholders made regarding CNG vehicles was the significant progress the technology has made over the past decade. When first entering the market in 2008-2010, CNG trucks gained a reputation for not being reliable or being able to compare to diesel trucks. Since then, many fleets operating newer CNG trucks have a new perspective on the low emissions technology. Many fleets now operate CNG trucks and some even prefer the technology over diesel because it can meet the required duty cycles with a quieter, cleaner, and odorless ride.

TTSI specifically has had an excellent experience piloting a BAE Kenworth plug-in hybrid electric vehicle. As noted above, operators "love the vehicle" for its 350 mile range, smooth riding, and quiet, odorless operation. They also appreciated that CNG fueling infrastructure is largely established near the Ports, providing the added benefit of allowing fleets to fuel offsite. The fleet plans to reinvest in the technology moving forward.

One stakeholder felt that although they supported the state's move to cleaner technology, natural gas should play a big role in the solution. Specifically, they noted the emissions savings that can come from renewable natural gas (RNG). Some RNG, like natural gas produced at dairy farms, can have a carbon intensity value lower than zero, meaning on a net basis it can decrease carbon in the atmosphere. The Bae Kenworth plug-in hybrid EV also has a Zero-Emission mode that allows the vehicle to operate solely off the battery, though with a more limited range than a full EV. This function allows the vehicle to operate in ZE for shorter trips, or when operating in non-attainment areas, and revert to CNG when necessary.

They went on that the infrastructure for CNG was already in place, and that it does not necessarily serve California's emissions goals if electric vehicles are charged on a grid powered by non-renewables. Especially when EV technology is currently more expensive than CNG, they believe natural gas vehicles should play a role in the solution.

2.4.5 CHARGING / FUELING INFRASTRUCTURE

Whether fleets choose to adopt battery electric, hydrogen fuel cell, or a combination of both technologies in order to meet zero emission vehicle regulations, charging / fueling infrastructure will pose a significant barrier. The primary recommendation fleets offered for those considering adopting BEV technology is to engage the utility early in the process. From stakeholders' experience, utilities are quoting 18 months to get started and added that "you're going to experience delays along the way. We pushed our timeline out probably a dozen times." Another stakeholder "just went through the trenching process and it's an immense hassle." They noted that they are "more prepared for net time, but there are so many stakeholders. Compared to buying a normal vehicle, it's tremendously more complex. The hard part is getting infrastructure in place."

Fleets explained that a knowledge gap further complicates the process. "The first question a utility is going to ask you is, 'how much power are you going to need?" Even an engineer wouldn't know because he doesn't have real world data. China and Europe have all these vehicles deployed; I'd like to see their data. Knowing if you need 1:1 charging, we need to learn from all that." Fleets' desire for information to help them make informed decisions offers an opportunity to bridge the gap between vehicle operators and zero-emission technology providers to accelerate the transition.

One fleet described their biggest hurdle with installing infrastructure was that they lease property from the Ports rather than own it. Leasing can draw out the timeline for trenching, infrastructure installation, and commissioning. Recognizing that the Port of Long Beach's 2017 Clean Air Action Plan has a goal of transitioning on-road trucks entering the port to zero-emission by 2035, one stakeholder is considering purchasing ZE trucks specifically to go into the port and bring TEUs out.[30] The TEUs would then be transferred to diesel trucks with longer range to transport them away from the port.

Another stakeholder believes installing enough infrastructure to reliably charge / fuel zero-emission vehicles will be the greatest hurdle to overcome. They noted that BE trucks draw immense amounts of energy, and while rolling blackouts on California's grid have become something of a norm in the summer months, freight simply cannot afford to rely on an unreliable grid. This led the stakeholder towards a favorable position on hydrogen technology.

Hydrogen refueling is quick, non-reliant on the energy grid, and can be provided by public stations that service numerous fleets just like a normal diesel station, but there are currently very few stations offering hydrogen fueling for heavy-duty vehicles. Some have proposed that CNG stations be converted to hydrogen stations in the future. Nevertheless, both zero-emission infrastructure types demand significant financial investment. They pointed out that Newsom's administration cut funding from the budget for infrastructure investment even before the COVID-19 pandemic.

Charging standards add complexity to the situation. One fleet operating Daimler and Volvo BE trucks must have different chargers for each OEM because there are no unified charging standards. Tesla has also been known to use their own charger configurations as well. While this practice may keep fleets loyal to one OEM after installing their charging infrastructure, unifying charging standards may help accelerate BE adoption since fleets could install infrastructure with more confidence that the investment will be usable for years to come even if they choose to operate different OEMs' trucks.

Fleets are searching for creative solutions for ZE infrastructure hurdles. With the Ports often leading the push, stakeholders are curious to see how port activity will adjust to make it better suited for ZE trucks. Some are hoping for staging areas where trucks can charge as they wait in line to enter the port. Others are hoping inductive charging technology allows for wireless charging at different waiting areas. As more fleets begin to adopt ZE technology, the focus on quick installation and reliable service from charging / fueling infrastructure for commercial heavy-duty technology may soon become a critical aspect of the path towards cleaner vehicles.

3. REGULATIONS AND INCENTIVES

3.1 REGULATIONS

California and the San Pedro Bay Ports have instituted a variety of ambitious regulations to reduce emissions from drayage trucks. The following table summarizes the regulations that will be discussed in this section.

[30] Our Zero Emissions Future. https://www.polb.com/environment/our-zero-emissions-future/#program-details. Accessed November 2020.

Table 7: Summary of all regulations that affect drayage trucks included in this report and the timeline of their implementation

Year of Implementation	Regulation	Mandate
2018	Clean Truck Program	Only MY14 trucks will be allowed to register in the San Pedro Bay Port's PDTR.
2020	Truck and Bus Regulation	California's Department of Motor Vehicles (DMV) will no longer register vehicles older than model year 2010.
2021	Clean Truck Program	A $10-per-TEU surcharge will take effect at the San Pedro Bay Ports for trucks that are not zero or near-zero emission vehicles.
2023	Truck and Bus Regulation	Nearly all trucks and buses in CA must have a model year of 2010 or newer.
2023 (Expected)	Advanced Clean Fleets	In coordination with CARB's Advanced Clean Trucks Rule, fleets will be required to purchase zero-emission vehicles. The framework for this program is still be determined.
2024	Advanced Clean Truck Rule	OEMs will be required to sell an increasing percentage of ZEVs in California starting in 2024.
2024 (Tentative)	Heavy-Duty Omnibus Regulation	If passed, NO_x emissions standards will be cut by 75% starting 2024 and 90% by 2027.
2035	Executive Order N-79-20	All drayage trucks sold in California must be zero-emission.

3.1.1 CLEAN TRUCK PROGRAM

Part of the San Pedro Bay Ports' Clean Air Action Plan, the Clean Truck Program has significantly reduced air pollution from harbor trucks by instituting bans on older, higher polluting trucks. The terminals also worked to optimize their gate systems to rapidly identify trucks with Clean Truck Program compliance to reduce idling time. At the Port of Long Beach, for example, they were able to reduce idling time by 26% between 2005 and 2019.

Studies have found that between 2005 and 2012, the Clean Trucks Program successfully reduced heavy-duty vehicle emissions of NO_x and particulate matter by 80% and 90%, respectively. This resulted in an estimated net savings of $13 million in cardiovascular and respiratory related impacts.[31] The following table outlines the timeline of standards put in place by the program.

[31] Kuo, T and Saphores, J. AO6 San Pedro Bay Ports Clean Air Analysis, June 2015. https://www.sciencedirect.com/science/article/abs/pii/S2214140515005472#:~:text=Results,been%20reduced%20by%20over%2090%25. Accessed November 2020.

Table 8: Timeline of standards put in place by the San Pedro Bay Port's Clean Truck Program

Year of Implementation	Standard
2008	Banned pre-1989 trucks from entering the port
2012	Banned trucks that did not meet 2007 emissions standards
2018	Only model year 2014 or newer trucks can register for the Port Drayage Truck Registry (PDTR). All trucks entering the port must be registered in the PDTR.
2021 (Likely)	Originally set for Fall 2020 and potentially postponed due to the pandemic, a $10-per-TEU surcharge will be applied. Near-zero and zero-emission trucks will be exempt.

Since 2008, the Ports have sent clear signals to fleets that the future of drayage will be with near-zero and zero-emission trucks. The $10-per-TEU surcharge noted in Table 8 will generate an estimated $90 million annually to provide incentive funding for clean trucks. The Ports have a goal of 17,000 ZE drayage trucks operating at the port by 2035.[32]

3.1.2 ADVANCED CLEAN TRUCK RULE

Signed into law June 2020, the California Air Resources Board's Advanced Clean Truck Rule (ACT) is the world's first zero-emission commercial truck requirement. It requires truck manufacturers to increase the percent of their sales for zero-emission trucks over the next fifteen years. It also states that fleet owners with 50 or more trucks will be required to report data about their existing fleet operations to help identify future strategies to ensure fleets purchase zero-emission trucks and place them in service. CARB held multiple workshops in 2020 to hear public feedback about the data reporting requirement. Affected vehicle owners must submit the one-time reporting requirement by April 1, 2021. The required timeline for truck manufacturer ZE sales increases is outlined in Table 10.

Table 9: OEM timeline for mandated sale of ZE Class 7-8 Tractors [33]

Model Year (MY)	Class 7-8 Tractors
2024	5%
2025	7%
2026	10%
2027	15%
2028	20%
2029	25%
2030	30%
2031	35%
2032	40%
2033	40%
2034	40%
2035 and beyond	40%

[32] Coalition for Clean Air, Ports Release Faulty Clean Truck Program Economic Study, December 2019. https://www.ccair.org/ports-release-faulty-clean-truck-program-economic-study/ Accessed November 2020.
[33] Advanced Clean Trucks Fact Sheet, June 2020. https://ww2.arb.ca.gov/resources/fact-sheets/advanced-clean-trucks-fact-sheet. Accessed October 2020.

An extremely ambitious regulation, the ACT Rule is also expected to create substantial statewide benefits. According to the NRDC, by 2040 these will include 7,442 new jobs, $1.7 billion in avoided CO_2 emissions, $5.9 billion in industry savings, $282 million added to state GPD, and $8.9 billion in health savings.[34]

There are two key reasons why the ACT Rule is so ambitious. First, the technology to achieve the mandated levels of market penetration is not yet fully commercialized. As of the writing of this report, BYD, Freightliner (Daimler), Kenworth, Mack, Navistar Inc., Peterbilt, and Volvo are all working to develop and demonstrate commercialized battery electric Class 8 tractor trucks.[35] Kenworth and Toyota are also collaborating on a Class 8 fuel cell truck that is being demonstrated at the Port of Los Angeles.[36] Drayage trucks will be the first to transition to zero-emission, but transitioning regional and long-haul trucks that regularly drive over 500 miles per day will be more challenging.

Second, charging and fueling infrastructure may pose a major barrier to ZE truck market penetration. According to a 2019 white paper by the ICCT, charging infrastructure can cost between $28,000 and $58,000 per battery electric drayage truck.[37] In addition to cost, trenching, installing, and commissioning charging infrastructure can take more than 1.5 years of planning. The process is further complicated for fleets located at the port and for those leasing their land. Even with proactive planning and enough funding, the energy required to electrify thousands of drayage trucks at the Ports is immense. As one of the stakeholders CALSTART interviewed put it, "I think the battery technology will get there, but it's all about the infrastructure."

3.1.3 ADVANCED CLEAN FLEETS

In coordination with the Advanced Clean Truck Rule which mandates OEMs to sell an increasing percentage of zero-emission vehicles starting in 2024, CARB is developing Advanced Clean Fleets to mandate that fleets purchase zero-emission vehicles. Advanced Clean Fleets creates the demand to meet the supply provided by the Advanced Clean Truck Rule. Affected fleets include organizations with more than $50 million in revenues, fleets that own or dispatch 50 or more vehicles with a GVWR greater than 8,500 lbs, and government agencies at all levels with at least one vehicle with a GVWR over 8,500 lbs. CARB is currently considering an appropriate framework for a phase-in of mandated zero-emission fleet purchases. The requirement will likely go into effect in 2023.[38]

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[34] Portillo, P. California Makes History with Clean Trucks Rule, June 2020. https://www.nrdc.org/experts/patricio-portillo/california-makes-history-clean-trucks-rule#:~:text=In%20a%20groundbreaking%20win%2C%20the,the%20Advanced%20Clean%20Trucks%20rule.&text=Beginning%20in%202024%2C%20manufacturers%20must,40%2D75%20percent%20by%202035. Accessed October 2020.

[35] San Pedro Bay Ports Clean Air Action Plan 2018 Feasibility Assessment for Drayage Trucks, May 2020 https://kentico.portoflosangeles.org/getmedia/0c341695-2dec-430a-b2d9-f828d4b2df1a/final-drayage-truck-feasibility-assessment-w-addendum. Accessed October 2020.

[36] Gilroy, R. Kenworth, Toyota Partner on Hydrogen Fuel Cell Class 8 Trucks, October 2019. https://www.ttnews.com/articles/kenworth-toyota-partner-hydrogen-fuel-cell-class-8-trucks. Accessed October 2020.

[37] Hall, D. and Lutsey, N. Estimating the Infrastructure Needs and Costs for the Launch of Zero-Emission Trucks. August 2019. https://theicct.org/sites/default/files/publications/ICCT_EV_HDVs_Infrastructure_20190809.pdf Accessed November 2020.

[38] Advanced Clean Fleets https://ww2.arb.ca.gov/our-work/programs/advanced-clean-fleets Accessed November 2020.

3.1.4 GOVERNOR NEWSOM'S EXECUTIVE ORDER (N-79-20)

In September 2020, California's Governor Newsom signed Executive Order N-70-20 mandating that by 2035, all new cars and passenger trucks sold in California be zero-emission vehicles. This will include drayage trucks. Before this rule went into effect, the Advanced Clean Truck Rule mandated that 40% of drayage trucks sold be zero-emission by 2035. This executive drastically increases the necessary rate of zero-emission drayage adoption and sends a very clear signal to industry that diesel and even CNG trucks' days are numbered in the California drayage industry. It is yet to be seen if additional provisions will be made for near-zero emission vehicles like renewable natural gas vehicles.[39] CARB is currently creating a framework to achieve this goal.

3.1.5 TRUCK AND BUS REGULATION

The Truck and Bus Regulation, another CARB regulation, aims to reduce NO_x and $PM_{2.5}$ emissions from heavy-duty on-road vehicles in order to meet federal attainment standards. It states that by 2023, nearly all trucks and buses in California will be required to have a model year of 2010 or newer. In working towards this goal, starting January 1, 2020, the Department of Motor Vehicles (DMV) will only allow vehicles compliant with this regulation to get registered.[40]

3.1.6 HEAVY-DUTY OMNIBUS REGULATION

The California Air Resources Board's Heavy-Duty Omnibus Regulation supplements the Truck and Bus Regulation in working to reduce NO_x emissions standards by 90% compared to today's diesel engine standards. This measure is specifically geared towards achieving federal health-based air quality ozone standards in the South Coast and San Joaquin Valley air basins by 2031. CARB previously established optional low-NO_x standards in 2013 with 0.02 g/bhp-hr to encourage manufacturers to develop and certify low NO_x engines.

The Heavy-Duty Omnibus Regulation is currently under review by the California Air Resources Board. If it were to pass, the regulation would cut NO_x standards about 75% below current standards by 2024 and 90% below current standards by 2027. It would also revamp the heavy-duty in-use testing program, strengthen the heavy-duty durability demonstration program, create emissions averaging, banking, and trading program improvements, and create powertrain certification test procedures for heavy-duty hybrid vehicles.[41]

3.2 INCENTIVES

[39] Governor Newsom Announces California Will Phase Out Gasoline-Powered Cars & Drastically Reduce Demand for Fossil Fuel in California's Fight Against Climate Change, September 2020. https://www.gov.ca.gov/2020/09/23/governor-newsom-announces-california-will-phase-out-gasoline-powered-cars-drastically-reduce-demand-for-fossil-fuel-in-californias-fight-against-climate-change/ Accessed November 2020.

[40] Truck and Bus Regulation https://ww2.arb.ca.gov/our-work/programs/truck-and-bus-regulation/about. Accessed October 2020.

[41] Facts about the Low NO_x Heavy-Duty Omnibus Regulation https://ww2.arb.ca.gov/sites/default/files/classic//msprog/hdlownox/files/HD_NOx_Omnibus_Fact_Sheet.pdf Accessed October 2020.

There are a variety of different incentives available to drayage fleets to help reduce costs of alternative fuel drayage trucks, charging infrastructure, and the cost of fuel / electricity. The following table summarizes each of the incentive programs covered in this report and includes where those interested in applying should go to get involved.

Table 10: Summary of incentives and how to get involved with incentives related to drayage trucks, infrastructure and fuel

Incentive	Summary	How to Get Involved
HVIP	Point-of-sale, first-come first-served, no scrappage vouchers for zero and near-zero emission equipment.	Interested applicants should review the Eligible Vehicle Catalog at californiahvip.org/how-to-participate/#eligible-vehicle-catalog and contact the affiliated vendor.
VW Mitigation Trust	$90M for zero-emission class 8 freight and port drayage trucks. The program is first-come first-served and does require scrappage.	Interested applicants should visit vw.gms.aqmd.gov
Carl Moyer	Case-by-case applications reviewed by air districts on the project's cost-effectiveness of reducing NO_x, PM_{10}, and ROG.	Sign up for South Coast AQMD's updates at http://www.aqmd.gov/sign-up.
CEC Block Grant	$50M in incentives for refueling infrastructure.	This program does not yet have an administrator and is not yet accepting applications.
Charge Ready Transport	Southern California Edison offers low-to no-cost charging infrastructure, both on the customer and utility-side of the meter, for heavy-duty trucks and other vehicles.	Email chargereadytrasnport@sce.com or visit sce.com/CRT for more information.
Low Carbon Fuel Standard	Allows owners of charging / fueling equipment to generate credits depending on the carbon intensity of the fuel.	For more information, visit https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/resources.

3.2.1 HVIP

The Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP) is a CARB-funded and CALSTART-administered project that provides point-of-sale incentives for eligible zero and near-zero emission vehicles. This innovative project has administered hundreds of millions of dollars to accelerate the adoption of alternative fuel medium and heavy-duty vehicles. HVIP is a first-come first-served project, meaning that if funds are available, little more than a purchase order is required to receive a voucher. It also has no scrappage requirement.

Purchasers that receive HVIP funding never have to pay for the total cost of the vehicle. Rather, trained HVIP-dealers front the incremental cost of the voucher and receive a reimbursement from CALSTART after the equipment has been deployed. As new equipment becomes commercialized, OEMs may apply for it to be eligible for HVIP funding. HVIP anticipates accepting new voucher requested beginning in early 2021. The table below includes all the Class 8 tractor trailers included in HVIP.

Table 11: Class 8 tractors available for incentive funding through HVIP as of October 2020 [42]

OEM	Vehicle Name	Technology Type	Vehicle Incentive
BYD	BYD 8TT Tandem-Axle Tractor	Battery Electric	$150,000
Freightliner	eCascadia	Battery Electric	$150,000
Lion Electric	Lion8	Battery Electric	$150,000
Peterbilt	579EV	Battery Electric	$150,000
Freightliner	114SD with Cummins-Westport Engine	Low-NO_x CNG	$45,000
Freightliner	Cascadia Day Cab with Cummins-Westport Engine	Low-NO_x CNG	$45,000
Kenworth	T680 with Cummins Engine	Low-NO_x CNG	$45,000
Mack	Mack Trucks Anthem with Cummins-Westport ISX12N Engine	Low-NO_x CNG	$45,000
Peterbilt	Model 579 with Cummins-Westport ISX12N	Low-NO_x CNG	$45,000
Volvo	VNL 300 with 12L Engine	Low-NO_x CNG	$45,000

3.2.2 VW MITIGATION TRUST FUNDING

As part of the VW Settlement, CARB allocated $90 million in first-come, first-served funds to support the expansion of zero-emission Class 8 trucks, including drayage trucks, for both public and private entities. The first installment of these funds includes $27 million and applications opened August 18, 2020. The program quickly oversubscribed and interested applicants should remain vigilant for future announcements on when the next installment will begin accepting applications. This is a scrap and replace program with a maximum cap per entity of $2.7 million. Applicants granted an award must submit annual usage reports for the term of the contract.[43]

3.2.2 CARL MOYER PROGRAM

The Carl Moyer Program has a goal of obtaining emissions reductions of NO_x, PM_{10}, and Reactive Organic Gases (ROG) from heavy-duty vehicles operating in California as quickly and cost-effectively as possible. The program has approximately $61 million per year in statewide funding that is distributed to the state's numerous air districts. Air districts consider each application on a case-by-case basis and rate projects by how impactful they will be on achieving the program's goal. For the South Coast Air Quality Management District region, the solicitation period closed August 4th, 2020 and updates on the next solicitation period will be announced in March 2021.[44]

3.2.2 CEC BLOCK GRANT

[42] HVIP Eligible Vehicle Catalog https://www.californiahvip.org/how-to-participate/#Eligible-Vehicle-Catalog Accessed November 2020.

[43] Zero-Emission Class 8 Freight and Port Drayage Trucks Category. https://xappprod.aqmd.gov/vw/zero-emission.html Accessed November 2020.

[44] On-Road Vehicles, South Coast AQMD. http://www.aqmd.gov/home/programs/business/carl-moyer-memorial-air-quality-standards-attainment-(carl-moyer)-program/on-road-vehicles Accessed November 2020.

The CEC's Block Grant for Medium-Duty and Heavy-Duty Zero-Emission Vehicle Refueling Infrastructure Incentive Projects will provide $50 million in incentive funds for refueling infrastructure for various California projects. This project has not yet been implemented and, as of October 2020, solicitations to become the project's administrator have been submitted and are under review by the CEC.[45]

3.2.2 CHARGE READY TRANSPORT PROGRAM

Southern California Edison's Charge Ready Transport (CRT) Program offers low-to no-cost electrical system upgrades to support the installation of charging equipment for EVs including drayage trucks. Once a customer is approved, SCE will design, construct, and install the necessary infrastructure on both the utility-side and customer-side of the electric meter. If a customer prefers, they can perform the customer-side of the meter electrical work and receive a rebate. Additional rebates are available for eligible companies operating within disadvantaged communities. To qualify, customers must lease or purchase at least two medium or heavy-duty battery powered EVs and keep the charging infrastructure operational for at least ten years.[46]

3.2.2 LOW CARBON FUEL STANDARD

CARB's Low Carbon Fuel Standard (LCFS) is designed to encourage the production and use of low-carbon transportation fuels in California. The program assigns a Carbon Intensity (CI) value for fuels based on a life-cycle assessment of their emissions. Based on a fuel's CI value, it can earn credits or deficits depending on whether the fuel's CI value is above or below the CI benchmark for that year. Similar to a cap and trade system, fuel providers with deficits must purchase credits from eligible fuel providers. Generally, the entity that owns the fueling or charging supply equipment is eligible to generate credits. Fleets using alternative fuel vehicles can generate credits if they opt into the program and own their own equipment.[47]

4. DRAYAGE TRUCK MARKET ASSESSMENT

This chapter discusses forecasts for future sales of drayage truck technologies in Los Angeles County and Orange County, representing the areas surrounding the Ports of Los Angeles and Long Beach. Developing forecasted scenarios for the future adoption of drayage trucks is crucial for commercial fleets' strategic operations, policy assessments, OEM market evaluation, and planning the deployment of charging infrastructure. Projections of future market behavior are speculative and will depend on the data used as inputs. Looking toward the future of this market based on conditions today provides one set of estimates for how the market may adopt these technologies. However, it is important to remember that this is a dynamic, emerging market. The spread of technology, as modeled for this project, is not deterministic, but rather subject to the influence of many evolving factors.

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[45] GFO-20-603 – Block Grant for Medium-Duty and Heavy-Duty Zero-Emission Vehicle Refueling Infrastructure Incentive Projects. https://www.energy.ca.gov/solicitations/2020-07/gfo-20-603-block-grant-medium-duty-and-heavy-duty-zero-emission-vehicle. Accessed November 2020.

[46] Charge Ready Transport Program. http://crt-sce.com/program-details?ecid=none Accessed November 2020.

[47] Low Carbon Fuel Standard https://ww2.arb.ca.gov/our-work/programs/low-carbon-fuel-standard/about Accessed November 2020.

4.1 METHODOLOGY

The goal of these projections is to simulate the demand-side behavior of the drayage truck market between 2020 and 2035 as segmented by fuel type. Fleet owners' decision-making process for acquiring drayage trucks was approximated quantitatively and, where required, qualitatively. The demand response was modeled to include a variety of factors, with adjustments toward more or less aggressive adoption outcomes to produce a range of forecasted scenarios. The model quantified fleet owners' behavior using probability curves to represent their attitudes toward each technology parameters and market condition.

For example, a lower total cost of ownership (TCO), including fuel, maintenance, and purchase price, would increase the probability of a given fleet adopting. However, a lower TCO does not guarantee adoption of an electric truck because purchase decisions are more complicated than a single equation. Despite a lower TCO, an electric drayage truck might only be available at a high upfront cost that falls outside the fleet's budget, preventing a purchase. Financing to invest in this technology will also vary from fleet to fleet.

The likelihood of adoption was adjusted based on the range of acceptable payback periods as calculated using the vehicle manufacturer suggested retail price, fuel costs, and any available incentives. The modeling effort also incorporated drayage truck technology suitability for a fleet's operations. This stage integrated technology readiness levels and the ability to meet the operational demands of fleets. The figure below summarizes the factors considered by the tool and the following subsections will describe how each of these were taken into account.

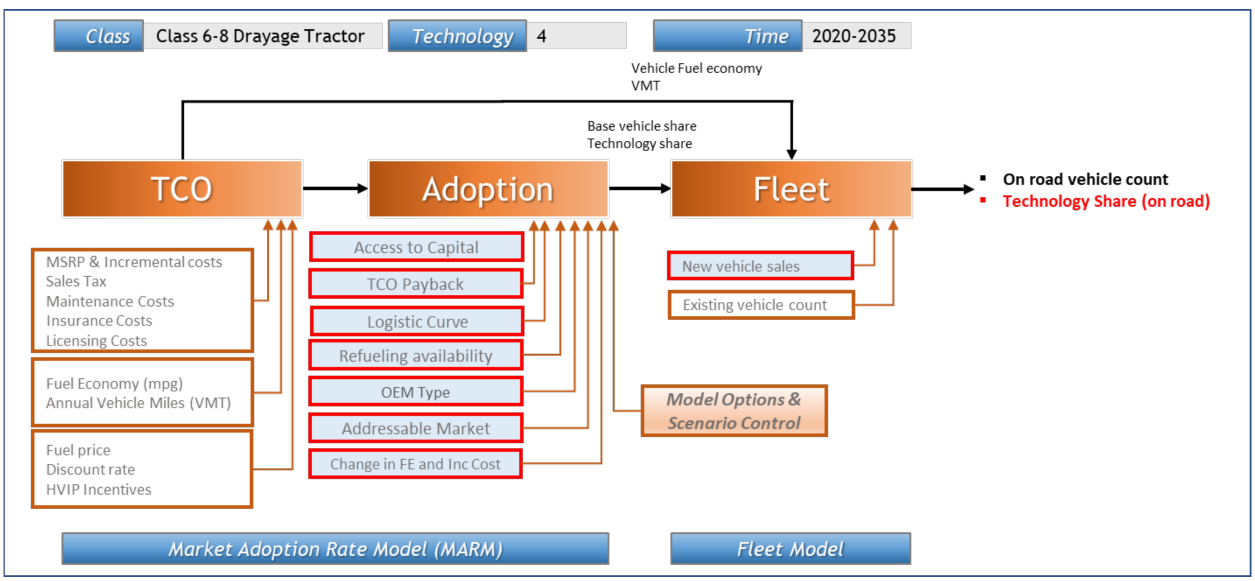

Figure 7: Schematic diagram of major factors affecting the model's results

As shown in Figure 7, the model focuses on Class 6-8 drayage tractors between 2020 and 2035. It first calculates a vehicle's TCO to ensure that it is cost-competitive with baseline vehicles. It then accounts for multiple factors, like capital cost, to ensure that adoption is possible. Finally, it projects these assumptions onto the size of the vehicle market under consideration, namely Los Angeles County and Orange County. The model outputs the technology share of each fuel type and also explores the emissions produced by each scenario outcome.

4.1.1 TOTAL COST OF OWNERSHIP

The following inputs are included in the TCO calculations to determine the benefits and payback period.

Table 12: Definitions of inputs that affect the tool's total cost of ownership analysis

Inputs	Definition
MSRP & Incremental costs	Vehicle manufacturer suggested retail price (MSRP) for drayage truck technology (diesel, CNG, battery electric and hydrogen fuel cell)
Sales Tax	Average new vehicle purchase sales tax in California
Maintenance Costs	Estimated $/mile maintenance costs for each drayage truck technology
Insurance Costs	Estimated insurance costs of drayage truck
Licensing Costs	Estimated licensing cost of drayage truck
Fuel Economy (mpg)	Fuel economy for each drayage truck technology.
Annual Vehicle Miles (VMT)	Average drayage truck annual miles driven
Fuel Price	Current and projected California fuel prices for diesel, natural gas, electricity, and hydrogen fuels
Discount Rate	Discount rate to account for inflation and dollar value
HVIP Incentives	California state electric vehicle purchase incentive

With these inputs, the TCO produces two results. One shows an estimated payback period for purchasing and operating a CNG, BE, or FC drayage truck compared to a fleet's baseline vehicle. The other result shows a breakdown of costs associated with operating both the alternative fuel truck and the fleet's baseline vehicle, including the following costs: vehicle capital expense, fuel cost, incentive funding, maintenance cost, insurance cost, and a total cost.[48]

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[48] Gas Prices https://gasprices.aaa.com/state-gas-price-averages/ Accessed November 2020.

Annual Energy Outlook 2020 https://www.eia.gov/outlooks/aeo/data/browser/#/?id=7-AEO2020&region=0-0&cases=ref2020~highmacro~lowmacro~highprice~lowprice~highogs~lowogs~hirencst~lorencst~aeo2019ref&sourcekey=0 November 2020.

4.1.2 ADOPTION

The model simulates different types of consumer actions. These inputs and options are used to generate a variety of market scenarios that estimates the expected adoption rate of vehicle technologies under different conditions. The following inputs are included in determining the likelihood of adopting drayage trucks of each fuel type.

Table 13: Inputs and definitions that approximate consumer adoption choices in the model

Inputs	Definition
Access to Capital	Fleet owner's behavior to an increased incremental cost over base vehicle MSRP. This is associated with fleet owner purchase power and innovation type.
Payback Period	Consumer willingness to adopt a technology by payback period in years
Logistic Curve	Applies a logistic curve to estimate the time it takes fleet owners to feel comfortable purchasing the technology. This is a preference factor associated with technology risk, reliability, and experience.
Refueling Availability	Estimates fuel and fuel station availability based on station counts and regulations
OEM Type	Brand, size (global, national, emerging, or startup) and capacity to scale
Addressable Market	This calculates the addressable market of each vehicle type over time based on location and what year the technology is available.
Changes in FE and Inc Cost	Accounts for changes over time in fuel economy and incremental cost of each vehicle type over the baseline cost.

4.1.3 SCENARIOS

Three possible scenarios for how the drayage market may look between 2020 and 2035 were reviewed. Summarized in the table below, these are meant to represent three possible outcomes that align with California regulatory goals.

Table 14: Description of the three scenarios analyzed by the model

	Zero-Emission Sales By 2035	Scenario Basis
Scenario 1	100%	Governor Newsom's Executive Order (N-79-20) mandating 100% of zero-emission drayage trucks by 2035.
Scenario 2	75%	An intermediary outcome between Scenario 1 and Scenario 3 where 75% of sales of zero-emission drayage trucks are realized by 2035.
Scenario 3	40%	The Advanced Clean Truck Rule's mandate of 40% sale of zero-emission Class 7-8 Tractors by 2035.

Scenario 1 models the fastest transition to zero-emission vehicles, driven by massive investments in battery electric charging and hydrogen fueling infrastructure, reductions in the incremental costs of ZEVs, and the rapid scaling of ZEV drayage trucks by OEMs. The ACT Rule's 40% ZEV sales requirement is this model's lower limit explored in Scenario 3, with Scenario 2 analyzing an intermediary 75% ZEV sales requirement. It is important to remember that before Governor Newsom's Executive Order was announced in September 2020, the Advanced Clean Truck Rule's zero-emission sales targets (including the 40% drayage sales target by 2035 used in Scenario 3) were considered extremely ambitious. The outcomes modeled by each of these three scenarios would, without being driven by regulation, likely take until late into the 21st century, if ever, to materialize.

4.2 RESULTS

The three scenarios described in Section 4.1.3 were investigated as to how the drayage market in Los Angeles County and Orange County would look if each scenario was realized by 2035. This section will detail the results of the model described in Section 4.1 in terms of new and cumulative drayage sales by fuel type. It will also estimate the avoided gallons of diesel and CO_2 and NO_x emissions under each Scenario between 2020 and 2035.

4.2.1 DRAYAGE TRUCK NEW AND CUMULATIVE SALES

The figure below describes drayage truck sales between 2020 and 2035 for each fuel type under Scenario 1.

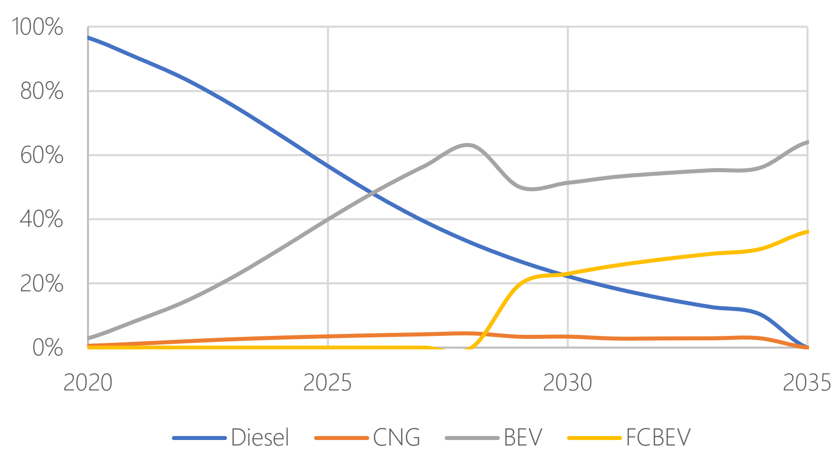

Figure 8: Drayage truck new sales by fuel type under Scenario 1

Under Scenario 1, diesel drayage sales drop from about 98% in 2020 to 0% by 2035. The 2% of sales that were non-diesel in 2020 were CNG. Because Scenario 1 calls for 100% zero-emission sales by 2035, CNG sales reach 3% by 2030 and then drop to 0% by 2030. BEV sales see strong growth through 2028 when fuel cell battery electric vehicles (FCBEVs) begin to penetrate the market. Total ZEV sales (including both BEVs and FCBEVs) are estimated to reach 50% of drayage sales by 2030 and 100% by 2035. BEVs and FCBEVs would then make up approximately 60% and 40% of sales, respectively. The following figure describes the cumulative number of alternative fuel drayage trucks sold in Los Angeles and Orange County under Scenario 1.

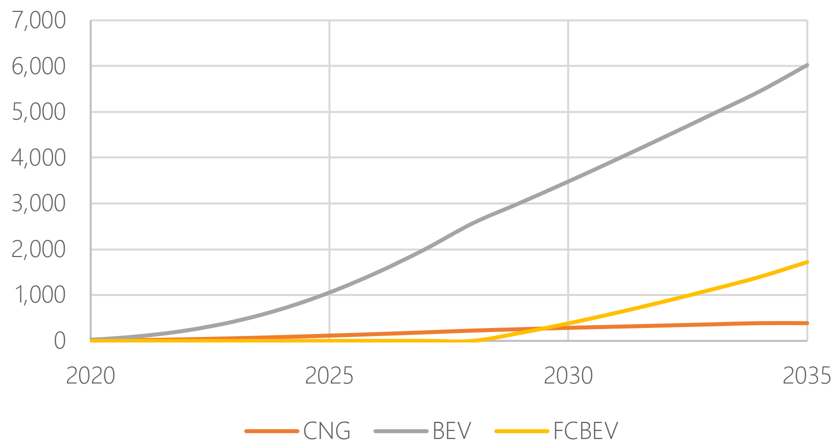

Figure 9: Cumulative alternative fuel drayage sales by fuel type under Scenario 1

According to Figure 9, about 6,000 BEVs would be sold between 2020 and 2035 in Los Angeles and Orange Counties, followed by slightly less than 2,000 FCBEVs and nearly 400 CNG trucks. The model predicts that by 2035, annual BEV and FCBEV sales in these markets will be around 550 and 330, respectively, and growing. As noted, CNG and diesel sales would drop to zero under Scenario 1, bringing up two major trains of thought. First, technology readiness and necessary investment comes into question. For Scenario 1 to succeed, ZEVs must be able to complete the duty cycle requirements to fully replace conventional drayage trucks. This means that major ZEV roadblocks like truck range, BE charging speed, and infrastructure reliability must all be overcome in the 2030s.

Second, with Governor Newsom's EO only being announced a few months before the writing of this report, it is still unclear how the diesel and CNG industries will respond. CNG trucks, when operating on RNG, can be zero or even negative-emission vehicles. The Governor's EO sets out goals and asks CARB to find methods to achieve them. CARB may incorporate opportunities for CNG trucks to be sold if they are running on fuel with a low enough carbon intensity value. Figure 10 describes the sales outcome of Scenario 2 where the 100% ZEV sales by 2035 was presumably too challenging, but 75% ZEV sales were achieved.

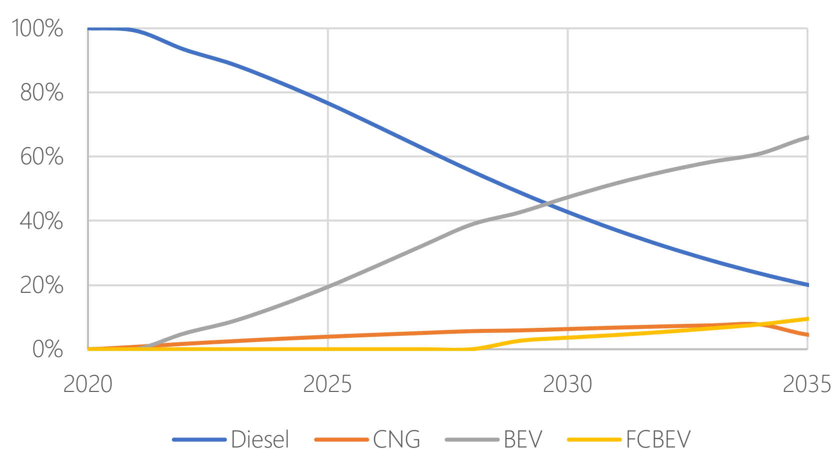

Figure 10: Drayage truck new sales by fuel type under Scenario 2

Under Scenario 2, 25% of sales by 2035 are non-ZEVs. Diesel is expected to consume 21% of this and CNG will make up the remaining 4%. BEVs grow steadily between 2022 through 2035 and reach slightly over 60% of new sales. FCBEVs do not have significant sales until 2028 and by 2035 achieve only 10% of new sales. The following figure shows cumulative alternative fuel drayage sales under Scenario 2.

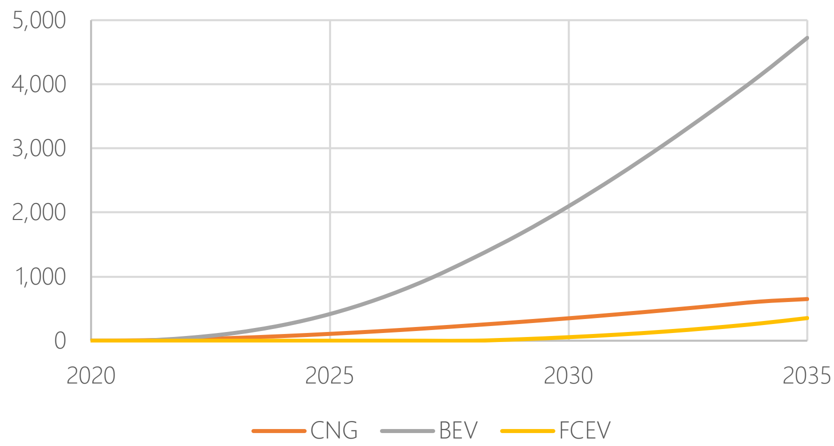

Figure 11: Cumulative alternative fuel drayage sales by fuel type under Scenario 2

Scenario 2 predicts that by 2035, about 4,800 BEVs, 650 CNGs, and 350 FCBEVs will be sold in Los Angeles and Orange Counties. This amounts to 1,000 fewer BEVs and 1,650 fewer FCBEVs sold compared to Scenario 1. A weak market penetration of FCBEVs, as shown in Figures 10 and 11, may be one reason why 100% of sales by 2035 are not zero-emission. If fuel cells trucks are not able to prove technology readiness by the mid-to-late 2020's, their market penetration may be delayed. Similarly, if the necessary investment for heavy-duty hydrogen fueling is not made, the deployment of FCBEVs will be stifled.

A slow FCBEV uptake is only one reason why the goals set out by the Governor's EO may not be achieved. Significant incentive funding must be made available to account for higher capital costs, charging and fueling infrastructure costs, and electricity and fuel costs. Additionally, 100% of drayage sales may be zero-emission by 2035, but the number of ZE vehicles in operation can vary greatly. Fleets may put off purchasing new ZE technology until the late 2030's or after. The Ports and CARB must play a very active role in maintaining dialogue between fleets, OEMs, utilities, and other drayage stakeholders over the coming decades to quickly identify and address barriers to ZEV adoption.

The figure below explores Scenario 3 where ZE drayage sales are even more delayed. Scenario 3 projects the outcome of the Advanced Clean Truck Rule where 40% of Class 7-8 tractor truck sales must be ZE by 2035. Because the percent of all tractor truck sales are combined in this regulation, drayage trucks are likely to be sold at rates above 40% to account for difficulties in electrifying regional and long-haul trucks.

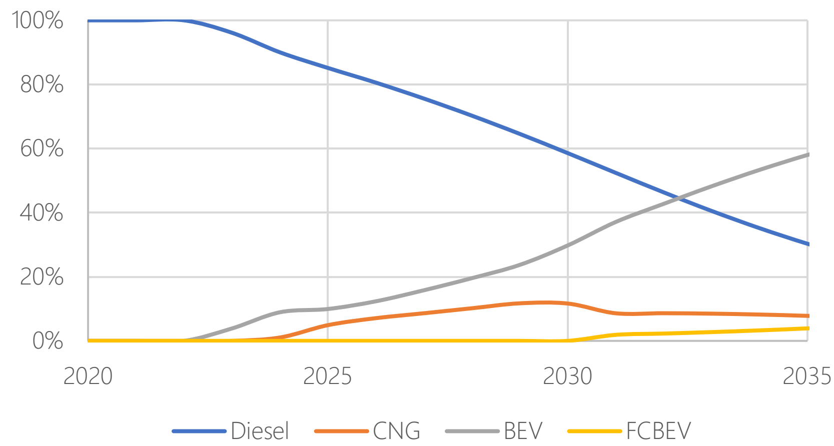

Figure 12: Drayage truck new sales by fuel type under Scenario 3

Under Scenario 3, 40% of sales are ZE by 2035. Again, before the Governor's EO, 40% was regarded as very ambitious. In Figure 13, BE sales nearly reach 60% by 2035, followed by about 30% diesel sales, 8% CNG sales, and below 5% FCBEV sales. Notably, diesel sales remain dominant at nearly 100% through 2023 while BEV sales do not achieve greater than 10% penetration until about 2026 and FCBEV sales do not begin to grow until the 2030s. The following figure displays cumulative sales under Scenario 3.

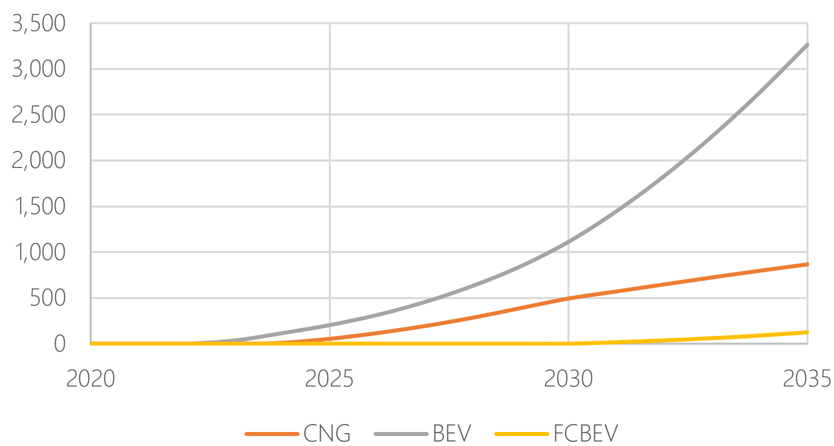

Figure 13: Cumulative alternative fuel drayage sales by fuel type under Scenario 3

Figure 13 predicts nearly 3,300 BEVs, 870 CNGs, and 130 FCBEVs sold in Los Angeles and Orange Counties by 2035. This is about 2,700 fewer BEVs and 1,900 fewer FCBEVs than Scenario 1. In Scenarios 2 and 3, CNG sales rose. This would likely open happen if the Governor's EO was revised to either allow CNG sales past 2035 or if the 100% ZEV sales deadline was pushed out further than 2035. However, if ZEV technology readiness proves slower than expected, or if sufficient investments in infrastructure or capital cost incentives have not been met, CNG might remain a transitionary technology between diesel and ZEVs. Finally, because market penetration takes time, the uptakes of BEVs and FCBEVs in Figure 10 and Figure 12 can be compared with drayage sales numbers as they come out in the 2020's to update predictions and evaluate progress.

4.2.2 DIESEL, CO_2, AND NO_X EMISSIONS REDUCTIONS

The following figure displays the gallons of diesel that would be avoided under each Scenario.

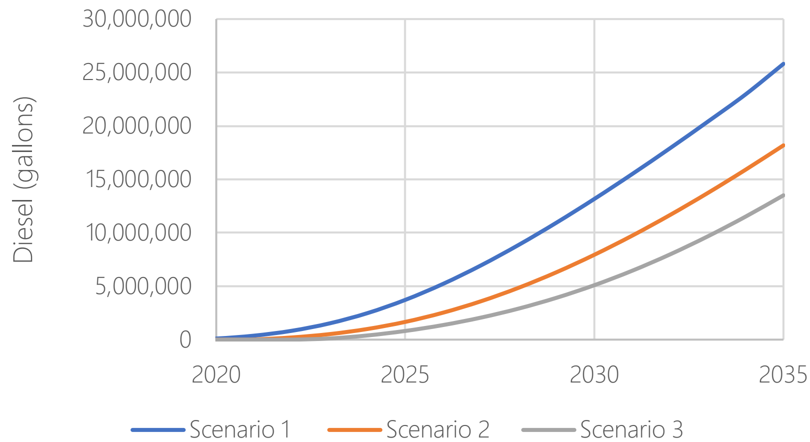

Figure 14: Avoided gallons of diesel used by drayage trucks in Los Angeles and Orange Counties under each Scenario

Under Scenario 1 with 100% ZEV sales by 2035, the use of 25.8 million gallons of diesel would be avoided through 2035. At 75% ZEV sales by 2035, Scenario 2 would avoid an estimate 18.2 million gallons of diesel, and at 40% ZEV sales, Scenario 3 would avoid about 13.5 million gallons of diesel. The figure below translates these into CO_2 emissions reductions.

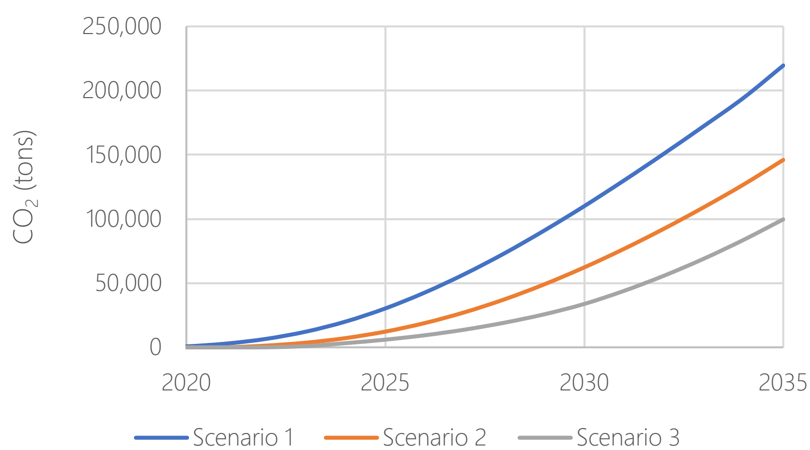

Figure 15: Avoided tailpipe CO_2 emissions by drayage trucks in Los Angeles and Orange Counties under each Scenario

Figure 15 calculates the CO_2 emissions avoided from diesel vehicles while accounting for cumulative emissions produced by CNG vehicles. By 2035, Scenarios 1, 2, and 3 would reduce CO_2 emissions by 220,000 tons, 146,000 tons, and nearly 100,000 tons, respectively. These are equivalent to taking nearly 48,000, 32,000, and 22,000 light-duty vehicles off the road. Similarly, this is equivalent to planting approximately 31,000, 21,000, and 14,000 trees to offset CO_2 emissions. These values assume 0.00885 and 0.00653 tons of CO_2 produced per gallon of diesel and CNG, respectively.[49] When accounting for greenhouse gas emissions in total, these values would be slightly higher. In 2019, heavy-duty trucks at both Ports produced nearly 700,000 tons of CO_{2e}.

With Governor Newsom's EO enforcing the sale of ZE drayage trucks in combination with the Clean Truck Program requiring trucks entering the port to have recent model years, significant emissions reductions can be expected by 2035. The faster fleets take diesel trucks out of operations, the faster greenhouse gas reductions will be achieved. The following figure shows the NO_x emissions reductions under each scenario.

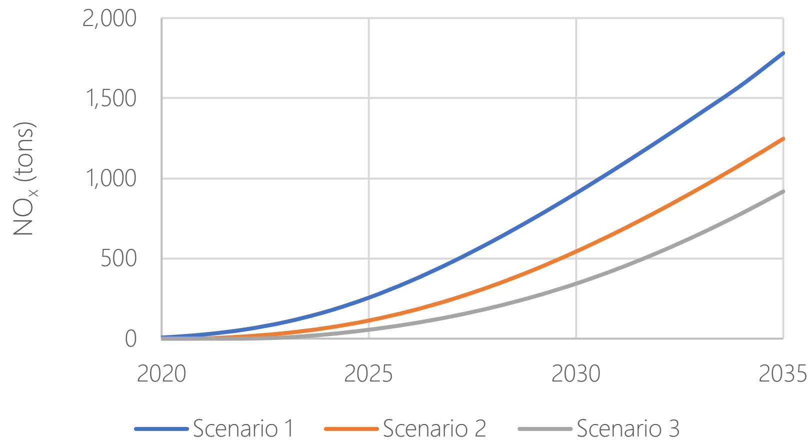

Figure 16: Avoided NO_x emissions by drayage trucks in Los Angeles and Orange Counties under each Scenario

By 2035, Scenarios 1, 2, and 3 would offset about 1,800, 1,200, and 900 tons of NO_x, respectively.

5. MAJOR FINDINGS

Overall, the drayage industry at the Ports of Los Angeles and Long Beach will be very dynamic over the coming decades fueled by port and California regulations pushing for zero-emission drayage. The Clean Truck Program has been highly successful at reducing air pollution like NO_x from the Ports. Despite the major progress that has been made since 2005, the regions near the Ports are still not in federal attainment and significant improvement is required to benefit the pollution overburdened communities nearby. Greenhouse gas emissions have not reduced significantly since 2005, and heavy-duty trucks remain the leading source at the Ports. Alternative fuel drayage trucks directly benefit this cause.

The future of the independent owner operator business model is unclear. Many IOOs prefer the current model over being employee drivers because they can control their own hours and it offers them a path towards scaling up their small business. AB5 and regulations that increasingly mandate the operation of new, alternative fuel vehicles will make it hard for IOOs to continue to operate due to increased capital costs, access to BEV charging infrastructure, and the challenges of limited range. Although most drayage trips are less than 100 miles, most

[49] Argonne National Laboratory GREET Model https://greet.es.anl.gov/ Accessed November 2020.

drayage trucks take 2-4 trips per day. Fleet managers are seeking creative solutions to avoid having to increase their fleet size in order to complete the same number of trips each day.

Port and California regulations indicate a clear shift towards zero-emission drayage. Specifically, Governor Newsom's executive order that all drayage sales must be zero-emission 2035 will significantly accelerate this transition. This leaves a dubious long-term role for CNG in the market. Renewable natural gas and plug-in hybrid electric CNG vehicles have the potential to emit less carbon than battery electric vehicles charging off the grid right now. However, it is still to be determined if low-carbon CNG vehicles will be allowed to compete in California.

Multiple incentives are available to fleets in California to help reduce costs associated with the initial purchase price, charging and fueling infrastructure, and fuel costs for zero-emission vehicles. Still, many fleet stakeholders say that additional incentive funding is necessary to abide by the ambitious timelines set out by regulation. They specifically target infrastructure as a weak point in the industry noting that in addition to high costs and slow timelines to install charging and fueling infrastructure, the heavy-duty trucking industry cannot be reliant on a grid as unstable as the current one for freight to be transported successfully. They also note that even with incentives, aggressive policies may drive IOOs out of business, potentially leaving thousands unemployed and with old diesel trucks as dead assets.

CALSTART's model estimated drayage adoption by fuel type under three different Scenarios. Scenario 1 assumes that the San Pedro Bay Ports can meet Governor Newsom's Executive Order (N-79-20) and reach 100% ZE drayage sales by 2035. Under this Scenario, BEVs make up about 60% of sales and FCBEVs make up about 40% by 2035. This amounts to roughly 6,000 BEVs and 2,000 FCBEVs in operation by 2035 in Los Angeles and Orange Counties. This aggressive transition would prevent 25.8 million gallons of diesel from being combusted, preventing the release of about 220,000 tons of CO_2 emissions and 1,800 tons of NO_x between 2020 and 2035.

While Scenario 1 offers the highest emissions savings, it leaves room for two major unknowns. First, it leaves the unknown of whether CNG will be completely phased out of the market. With RNG able to make the vehicles zero or below-zero emission, CARB may still include the option for CNG vehicles that meet certain carbon intensity values. Second, it assumes that ZEVs will be able to completely replace conventional drayage truck duty cycles by the late 2030s. One of the most critical areas of investment needed to facilitate this replacement may be for charging and fueling infrastructure, since heavy-duty hydrogen fueling is currently in a nascent stage and grid stability must be guaranteed for the freight sector to be able to rely on BEVs. The rapid transition timeline would likely also upend IOOs at the fastest rate.

Scenario 2 investigates the case where 75% of drayage sales are zero-emission by 2035. The model calculated that 21% of sales would be diesel, 4% CNG, 65% BEV, and 10% FCBEV. These amount to an estimated 4,800 BEVs and 350 FCBEVs in operation in Los Angeles and Orange Counties. Scenario 2 would prevent the use of 18.2 million gallons of diesel and the release of 146,000 tons of CO_2 and 1,200 tons of NO_x.

The results of Scenario 2 indicate a weak market penetration of FCBEVs that leave the Ports unable to meet the Governor's goal of 100% ZE adoption by 2035. A slow FCBEV uptake could be the result of numerous causes including insufficient access to capital for fleets, a lack of investment in heavy-duty hydrogen fueling, and delayed technology readiness in addition to delayed fleet exposure and understanding of the technology. Still, weak FCBEV market penetration is only one potential reason why the Governor's 100% ZE sales goal by 2035 might not be met. It will be critical for the Ports and CARB to play a very active role in maintaining dialogue between fleets, OEMs, utilities, and other drayage stakeholders over the coming decades to quickly identify and address barriers to ZEV adoption.

Scenario 3 examines the case where, as mandated by the Advanced Clean Truck Rule, 40% of Class 7-8 tractor sales are zero-emission by 2035. Before the Governor's Executive Order pushed the goal to 100%, this was viewed as highly ambitious. That being said, drayage trucks would likely make up more than 40% to account for slower ZE penetration into regional and long-haul trucking. Regardless, Scenario 3 achieves 40% ZE drayage sales by 2035 and acts as the lower limit included in this report.

Under Scenario 3, BEVs sales nearly reach 60%, followed by 30% diesel, 8% CNG, and below 5% FCBEV sales. Notably, diesel remains dominant at nearly 100% sales through 2023 while BEV sales do not achieve 10% market penetration until about 2024 and FCBEVs do not grow until 2030. This equates to 3,300 BEVs, 870 CNGs, and 130 FCBEVs sold in LA and Orange Counties by 2035. Scenario 3 results in 13.5 million gallons of diesel not used, 100,000 tons of CO_2 emissions avoided, and 900 tons of NO_x emissions avoided.

CNG vehicles play a larger role in this scenario because now that the Governor's Executive Order was announced, it would likely take major delays in ZE adoption for only 40% of the market to be ZE by 2035. If this occurred, CNG might be used as an intermediary between diesel and ZEVs. Significant delays might be the result of ZEV technology readiness taking longer than expected or if sufficient investments in infrastructure or capital cost incentives are not made.

Overall, a few major trends in the drayage industry can already be predicted. Battery electric and fuel cell trucks are likely to grow their market shares significantly over the next decade. The reduced number of diesel trucks on the road will be to the benefit of pollution overburdened communities near the Ports as well as the global population where everyone benefits when greenhouse gas emissions are reduced. While major fleet companies will likely be able to make a successful transition towards lower emissions vehicles, many independent owner operators will likely struggle to remain in business.

The drayage industry may be a beachhead sector for both electrifying the heavy-duty sector and for testing how successfully California can grow its economy while advancing sustainability measures in the freight sector. Some drayage stakeholders worry that the Ports of Long Beach and Los Angeles themselves may suffer financial losses and lose business to other Ports with fewer regulations and green initiatives. Still, all fleets interviewed expect to grow their business and hire new drivers in the coming years. They also point to the Gerald Desmond Bridge Replacement Project at the Port of Long Beach, which will allow larger international container ships to enter the port, as a positive sign of the Ports' future business.[50] If the Ports of Los Angeles and Long Beach can successfully guide the drayage industry towards cleaner operations while preserving financial growth and jobs, they will be a model for other Ports around the world to emulate.

[50] Completion of Iconic New Bridge Celebrated in Long Beach, October 2020. https://www.polb.com/port-info/news-and-press/completion-of-iconic-new-bridge-celebrated-in-long-beach-10-02-2020/ Accessed November 2020.

SCAQMD Contract #16022 **Date of Publication (January 2021)**

ZERO EMISSION CARGO TRANSPORTATION II

Contractor

Gas Technology Institute (GTI)
Kenworth Trucks
BAE Systems
CALSTART

Cosponsors

Southern California Gas

Project Officer

Seungbum Ha

Background

Despite major advances in air pollutant emissions performance, heavy-duty diesel trucks operating in dense urban areas continue to face pressure to achieve lower emission operation.

An area of significant focus is the Los Angeles Goods Movement and Industrial Corridor adjacent to the Ports of Long Beach and Los Angeles, the busiest port complex in North America. The area is in an industrial setting with diesel truck activity mingled with a variety of uses including residences, schools, daycares and senior centers.

An opportunity exists in integrating mature technologies such as battery-electric powertrain with a near-zero natural gas engine into a CNG-hybrid drayage truck, with a limited zero-emission capability.

Project Objective

The primary objective for this project was to reduce criteria pollutants in the South Coast Air Basin by reducing diesel emissions from the transportation and movement of goods from the ports to intermodal and warehousing facilities throughout Southern California. The technical objective was to accelerate the introduction and penetration of hybrid technologies into the cargo transport sector which will help in achieving the primary objective of substantial reduction of criteria pollutants, and as an additional benefit reduce petroleum consumption and greenhouse gases (GHG's).

Technology Description

The technical concept combines all-electric and CNG-based operation to provide a zero emissions (all-electric) mode and a conventional hybrid-electric mode. The system architecture is built around a battery-electric drivetrain that can provide a propulsion power output of 320 kW integrated into a Kenworth T680 tractor. The 100kWh / 650Vbattery electric powertrain is supplemented by Near-Zero Emission natural gas engine operating as a range-extender, with 50 diesel-gallon equivalent (DGE) CNG storage onboard.

Status

The project started in June 2016 and concluded in November 2020 with an accumulation of 8,835 miles of revenue service at the Port of LA without major incidents, operating from October 2019 through November 2020. Prior to commercial service, the truck accumulated 3,700 miles over 15 months in a field test performed by Kenworth in Washington state. The test, although not in a commercial service, was performed at full load and on representative duty cycles. The testing enabled the team to discover address multiple Infant Mortality (IM) failures. Thanks to the extensive testing, the vehicle delivered to the fleet offered competitive performance and good uptime.

The design and build of the truck proceeded without major issues and were completed in Q1 2018. One notable change in the project scope was removal of catenary interface. The interface was expected to provide extended zero-emission range and en-route charging capability, however the technology was not available in time to support the project schedule. The team added plug-in charging to address the loss of catenary power capability.

Results

The vehicle performance met or exceeded all of the targets.

Attribute	Target	Result
Range	150 miles	284 miles
Top Speed	62 mph	65 mph
Grade-ability	6.5% @ 20mph 5% @ 30mph	8.5% @ 20 mph* 5.5% @ 30 mph* *(simulation results)
All-Electric Range	20 miles or 1 hour	26 miles
Startability	30% (stretch goal)	20%

Detailed acceleration tests performed on the test track demonstrated acceleration exceeding conventional diesel powertrains, and was supported by anecdotal reports from the drivers.

Portable Emissions Measurement System (PEMS) emissions testing proved difficult to perform while in commercial service and offered unexpected and inconclusive results. While the CO_2 emissions where lower than conventional CNG and diesel trucks, the calculated fuel consumption was highest for the CNG hybrid. NO_X and CH_4 emissions unexpectedly were higher than conventional CNG, suggesting an operational issue or an opportunity for optimization.

	CNG Hybrid	CNG	Diesel
kNOx (g/bhp-hr)	0.23	0.08	1.95
CH4 (g/bhp-hr)	0.17	0.13	NA
Calculated FE (mpdge)	5.8	6	7.3
CO2 (g/bhp-hr)	458.7	559	506.1

The inconclusive emission results warrant further investigation into the root cause and additional testing under controlled test conditions.

Benefits

The near-zero emissions technology offers a significant advantages in criteria pollutant emissions over the diesel engines. It is expected that a hybrid application offers a further improvement criteria pollutant emission, due to improved fuel efficiency. While the test results do not demonstrate a NO_x improvement over the conventional CNG engine, it is not clear whether this is a result of the testing protocol, emissions/engine issue or indicating a need for further optimization of the range-extender utilization. It is expected that the CNG-hybrid technology, operating correctly and optimized, will offer significant reduction of criterial pollutant emissions and potentially negative greenhouse gas emissions when operating on Renewable Natural Gas (RNG).

Project Costs

The overall project cost was $5,466,016.92 and the project was completed within the originally budgeted amount of $5,627,319.

Commercialization and Applications

Port and California regulations indicate a clear shift towards zero-emission drayage. Specifically, Governor Newsom's executive order that all drayage sales must be zero-emission 2035 will significantly accelerate this transition. This leaves a dubious long-term role for CNG in the market. Renewable natural gas and plug-in hybrid electric CNG vehicles have the potential to emit less carbon than battery electric vehicles charging off the grid right now.

The CNG-hybrid technology has potential to be brought to the market in similar timeframe as battery-electric vehicles, while offering an extended range, existing fueling infrastructure and negative carbon emissions with RNG. The remaining effort is required in optimization of the emissions and fuel economy, and improving the reliability to a commercial level, however no major technological barriers are expected. The incremental cost is expected to be a major barrier, especially for the independent owner operators, although this barrier will be common for all zero-emission technologies and will require a systemic approach by the state.

Zero-Emission Cargo Transport (ZECT) - II

Fuel Cell Range-Extended Electric Trucks

Draft Final Report

For SCAQMD Contract 16023

January 21, 2021

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Executive Summary

The overall goal of the ZECT II Fuel Cell Range Extender (FCRE) project has been to design and demonstrate a zero emission fuel cell version of TransPower's Class 8 battery-electric drive system to augment battery energy and thus extend the vehicle operating range. This addresses the SCAQMD - DOE goals of zero-emission (ZE) cargo transport and ZE drayage for the ports.

The two trucks have been used in demonstrating ZEV cargo movement starting in 2017. The critical success factors demonstrated include:

- Successful packaging of fuel cell and battery subsystems on trucks;
- Achievement of a high level of systems integration as required for safe and reliable operation of the ZECT trucks in real-world drayage operations; and
- Demonstration of the attributes of use of small fuel cells for this application.
- Continuing development of the batteries and drivetrain integrations needed for powering such hybrid electric high power vehicles.

Driver response has been largely complementary, with appreciation of the smooth and quiet operation and power responsiveness, and with understandable annoyance when reliability was not meeting the needs of the task.

New Understanding: The small fuel cell range extender concept serves well for localized deliveries to several recipients, but is not so appropriate for long distance freeway deliveries to remote warehouses. Data on deliveries to locations as remote as the inland empire as presented herein show the possibilities and the limitations.

Technical Effectiveness, Economic Benefit: It was inevitable that the use of novel new technologies would lead to delays as well as development of improved components. Notably:

- Significant delays were occasioned by the use of a newly developed tank solenoid valve, which develop systemic leakage of hydrogen within a year. The manufacturer replaced all valves with an improved design which has worked without flaw.
- The fuel cells were repeatedly down for component failures, this continues to be the prime reliability issue as the needed improvements are still in process.
- Energy storage system battery issues were a major issue with the prototype truck leading to use of an improved newly developed battery on the second truck. This new design was retrofitted to the prototype, at TransPower's cost, making a much improved more reliable tractor.

Public Benefit: Zero Emission goods transport has been demonstrated, even though the demonstration has revealed multiple issues. Experience with these tractors has shown the need for continued component improvement and the importance of matching the truck to the task. Further, it suggests the need of larger fuel cells for long range delivery trucks and of active cooling of the battery for trucks working more than single shift per day.
Finally, it is clear that ZE goods transport has become the new standard, for the ports and world. Major truck OEMs prepare commercial E-products, and fuel cell firm stocks are suddenly dear.

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Prologue: Intent of the ZECT Contract

The ZECT award was to use the TransPower developed unique and capable heavy duty battery electric drive technologies for demonstration of port drayage, with intent of extending range capabilities from the battery only limitations. Previous experience of TransPower staff with fuel cell busses suggested the application of fuel cells to cargo transport.

In the ensuing half decade there have been striking developments leading to developing enthusiasm for fuel cell trucks, far outrunning expectations at the time of planning this program. The early surprise of a 2017 Economist cover reporting the internal combustion engine as "Roadkill" has given way to E-truck development programs by all major truck OEMs and recent announcements of major investments and orders for fuel cell trucks in Europe and China. Hyundai has taken the lead, with recent double page advertisements touting its development program and sales to Switzerland. Stock pricing of fuel cell firms, Ballard and Plug Power as examples, have run way beyond any expectations.

In contrast to this amazing swing to ZE trucking, the intent of the ZECT II contract .. signed over 5 yearss ago … was quite limited and simple: To demonstrate the use of a 30kW fuel cell, and then a pair for a total of 60kW, as range extenders for battery electric trucks. To do this would involve:

1. Choice and acquisition of fuel cells and hydrogen storage.
2. Design and integration of a fuel storage and fuel cell APU, which would necessarily include tanks, pressure regulation and valves to supply fuel to a power unit which would not only generate power from the hydrogen but step up the voltage to supply current to charge the battery based energy storage system.
3. Software development to allow the APU to support the operation of the electric truck over a period of several hours of drayage deliveries.
4. Integration on the electric truck, which was chosen as the Navistar "ProStar", along with the electric drive train and energy storage system (ESS).
5. Commissioning, assuring the interoperability of the APU, the ESS and the electric drive system.
6. Demonstration of completed trucks in actual drayage service

1. Development of the ZECT II Fuel Cell Truck Design

The TransPower electric trucks are built onto a chassis designed for diesel power, with the fuel tankage and engine replaced by all electric components, which include:

- The MDS, Motor-Drive System, 300kW of electric motor power coupled through an Eaton truck transmission which is automated to shift with motor speed matched to vehicle speed,
- The PCAS Power Control and Accessory Systems, including the contactors for control of high amperage 400 volt power, the vehicle computer, and electric hydraulic and air supply.
- High voltage batteries, capable of 300KW drive power

To this we now add hydrogen fuel storage and a fuel cell APU Auxiliary Power Unit, sized to trickle charge to the batteries to maintain battery charge over the day.

The above components are under microprocessor control, including:

1. The SCM (System Control Module), which acts as the vehicle controller,
2. The PCM (Powertrain Control Module), which provides for the coordinated shifting of the transmission with motor speed synchronized to the drive shaft speed, and
3. Unique to the hybrid electric vehicles, the GCM (Generator Control Module) which provides for fuel cell management including circulating cooling fluid through the components, cooling fans, temperature and power management, ground fault protection and power conversion.

Although TransPower management had experience with fuel cell power for transit buses, the company and staff were new to gaseous fuels and to fuel cells. Hence a simple fuel cell

Figure 1-The benchtop fuel cell system was used to gain early experience with the HD30 fuel cell and with the required control processes. Batteries are on the skid in foreground, fuel cell at left under the tent, DC-DC highest at center. The large radiator for fuel cell cooling is largely obscured by the batteries.

bench top system was set up using a single Hydrogenics HD30 fuel cell to provide initial experience with the hardware and the software requirements. A DC-DC converter, of the type to be used in the truck, was included to allow the fuel cell output – in the vicinity of 100 volts with currents of hundreds of amperes – to charge a battery. Cooling systems – one for the fuel cell and one for the DC-DC converter, were strapped on the side of the bench.

As the benchtop system was being developed, TransPower engineering did a comprehensive CAD design of the fuel cell based APU system to be installed in the trucks, in which two of the Hydrogenics HD-30 fuel cells were linked to a single large cooling system and to a DC-DC conversion electronic system to boost the lower DC voltage from two fuel cells in series to the battery operating voltage of a nominal 400 volts. A second DC-DC converter operates from the high battery voltage to provide the nominal 24 volts required to power the APU electronics and cooling systems.

Two distinct cooling systems are used, one high power system with a coolant pump for each fuel cell and a single large radiator suitable for cooling the reject heat from 60kW fuel cell power at the low temperatures fuel cells operate at (in this case typically 60°C), and a smaller one with a single additional pump and coolant passing through the two power converters as well as inductors necessary for the DC-DC conversion. The need for distinct cooling systems was driven by necessity, with a low conductivity (distilled water) coolant required by the fuel cell system, compounded with the incompatible materials used in the design of the DC-DC converters and inductors. Copper, commonly used in cooling systems, cannot be used in the fuel cell system as the copper ions poison the fuel cell catalysts.

Fuel Cell System design was a key focus in 2016, resulting in a power package CAD model as shown:

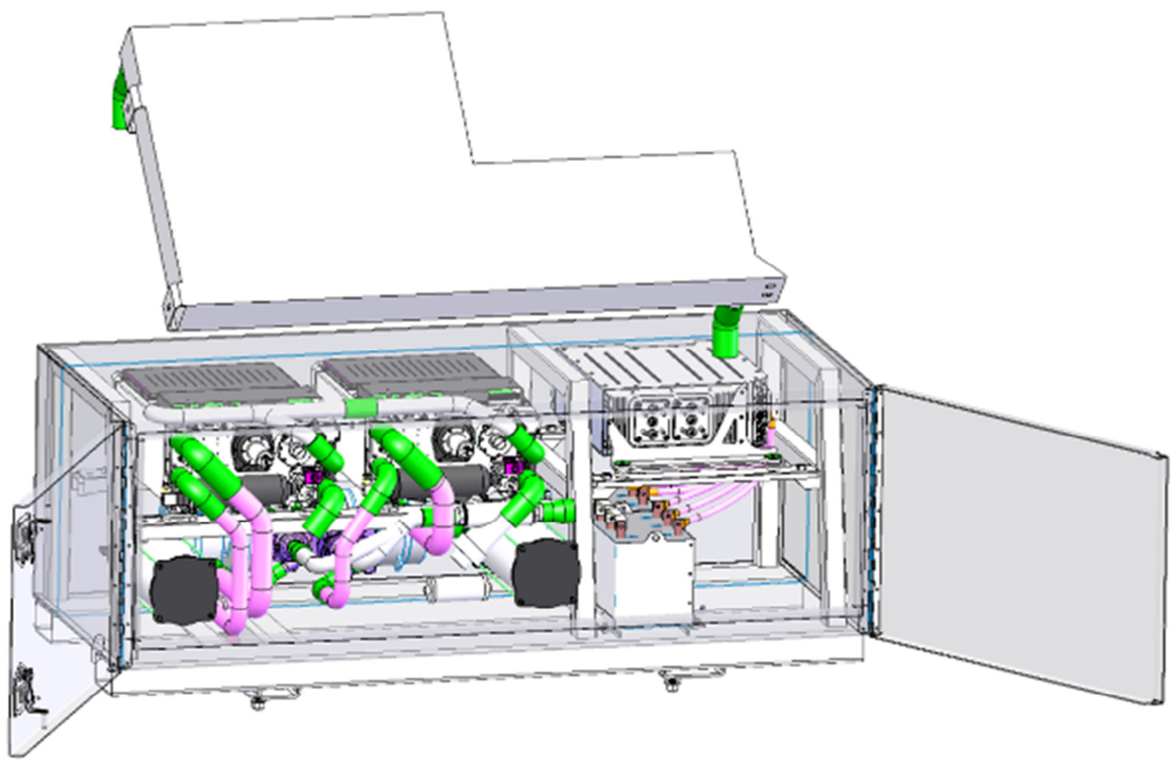

Figure 2- Fuel Cell APU design, with inverter and cooling package

From top to bottom:

- A large L shaped radiator package sits atop the Energy Conversion Pack, upper right in the open part of the L will be the inverter heat exchanger. The aluminum radiator is of the same design which was used in fuel cell buses operating in London, these are of special construction suitable for the low temperature and highly corrosive coolant (distilled water) used for fuel cells.
- The dual fuel cells are located lower left, complete with air circulation blowers and the air filters. At the right is the DC-DC converter at top and inductors at bottom.

Fuel storage is done using four hydrogen storage cylinders of nominal 16" diameter, stacked in a frame between the truck cab and the fuel cell APU. A1 Alternative Fuel Systems, based in Fresno Ca, was chosen as the integrator and SCI Worthington as the supplier of the Type 3 (aluminum liner) cylinders. The fuel system stores a nominal 19 kg of hydrogen at a nominal 350 bar (5000 psi) It is expected that this would provide fuel for a nominal 6 hours of operation at 45kW average, or 9 hours at 30kW average. Range was expected to be above 120 miles, dependent on load and driving conditions.

The truck is a conversion of a Navistar Prostar, the standard wheelbase was stretched by adding a section so as to allow for the fuel and APU mounted behind the cab. The PCAS (Power Conversion and Accessory Subsystem) including air supply for brakes, hydraulic power for steering, power conversion - including battery charger - and control module) is under the hood, the batteries under the cab sides. The standard TransPower MDS (Motor Drive System) converts the power from the PCAS to driveshaft torque, with an upper limit of approximately 300kW. The Eaton transmission driven by the dual drive motors provides the needed multiple gears for torque and power over the entire speed range.

Figure 3-KAM cell battery modules in test with the TransPower AV900

For the prototype truck the battery design incorporated the high power density Lithium Iron Phosphate KAM cells of cylindrical form, as shown in test in Fig. 3. This design was coupled with a BMS of TransPower design, which featured charge shuffling balancing powered from the batteries.

2. Early Experience with the Prototype

The completed prototype truck, "FC1", drove first as a battery electric in June 2017, then drove for its first fill of hydrogen in mid-July and thus entered the commissioning phase. It was not without difficulty, both fuel cells were replaced during the first month of operation. The development of the software (which we now refer to as the Generator Control Module (GCM) software) to control the fuel cells was much more difficult than envisioned, as the fuel cell controller (Hydrogenics access only) quickly shuts down operation at the least provocation.

Figure 4-The prototype truck about to enter commissioning. Shown here without the port side cover for the hydrogen storage, showing the four tank valves which would all be replaced the following summer. The KAM cell batteries are under each door, the fuel cell APU is aft supporting the radiators.

Regrettably, Hydrogenics did not easily share its software or rules for fuel cell operation. However Hydrogenics staff members shared their time and counsel accelerating the trial and error process of getting reliable fuel cell operation, but not without considerable delay and cost. Each failure needed to be diagnosed by a sequence of observations, e-mails, phone calls, documentation with Hydrogenics proprietary software, and often repeated e-mails and calls. We were all learning. A bench top single fuel cell system (Figure 1) was the first learning tool, followed by bringing to life the dual fuel cell system on the truck. The following table recollects some of these experiences:

Fuel Cell Purgatory		
Date	Experience	Interpretation and Results
20 July'17	E-Stop fault	Related to internal over-pressure switch, low cell voltages. Hydrogenics shared their HyPMView diagnostic software
21 July	FC will not start	User load exceeded Current Draw Allowed, damaged fuel cells… replaced both fuel cells and returned damaged units to factory. [later reported damaged circuit boards, replaced along with 3 cells]
24 July	Low hydrogen pressure report	Replaced pressure sensors with new model
6 Sept. .	Unable to restart FCA	Fuel cell returned, rebuilt
20 Sept., 26Sept.'17	FC inop., Intermittent issues with FC, then FC running	Kash sent data, repeatedly inquired, Paul Forte responded 12 Oct with suggestions.
13 Ap.'19	FC2 one fuel cell leaking, other having abnormal operation	Removed and replaced both fuel cells.
15 Ap.'19	FC2 - Fuel cell FCB has dropping H pressure	Removed and replaced HRP (Hydrogen Recirculation Pump)
5 July '19	FC1 – FCA leaking water	Removed and replaced, returned for rebuild
5 Feb. '20	FC2 showing anode pump fault	Removed and replaced HRP (Hydrogen Recirculation Pump)
22Oct. '20	FC1 FCB showing low H pressure	Removed and replaced HRP (Hydrogen Recirculation Pump)

Among the better remembrances was a first extended trip with the prototype truck, in which we drove on battery only to a shopping mall in Orange County, where the fuel cell was used to recharge the batteries with our watchful eyes on the laptop monitoring the operation. By such recharge procedure the truck proceeded to Long Beach for its first AQMD appearance, and returned, again on its own power.

In only weeks following the difficult first months of fuel cell control coding development the fuel cell truck was operational to the point of extended trips under full GCM control. Progress was fast with a working fuel cell system. The bigger challenge was to bring the fuel cell operation to near full power, which was only partly completed during the tenure of the contract.

Even so, it became evident through the repeated failures that there are fuel cell quality issues which made it difficult to keep a fleet of trucks in operation, or even just one or two trucks.[1] Largely these are component issues, evidence of a weakly developed supply chain. The delays at times were substantial, we were generally unsuccessful in convincing Hydrogenics to maintain west coast supply or to allow us to stock parts on consignment.

In periods with working fuel cells notable progress ensued. Matt Vito, a TransPower lead technicians (now heading up our manufacturing operations), took the lead in 2017 by personally

[1] Appendix A is a terse record, by serial number, of our experiences with the Hydrogenics HD30 fuel cells. Rob Del Core, the Hydrogenics west coast representative urged at one point that we use their more integrated version of these fuel cells, but at that point the budget had been fixed and the dual HD30 was used.

driving, finding and enumerating issues and resolving them one by one. The early work, driving bobtail, quickly established that the truck had a range without trailer of well over 200 miles, but it also demonstrated some of the limitations of the range extender implementation with a small fuel cell: The fuel cell power was fine for stop and go, such as delivery and drayage service, but inadequate for long freeway drives, even without trailer. Thus Mr. Vito – having been encouraged to get as many miles as possible accumulated, would drive a few hours and then take lunch while the fuel cells recharged the battery, then continue.

The KAM cell battery pack served well during commissioning, but after delivery the truck was used only irregularly, in part inasmuch as the TTSI hydrogen fueling facility was not yet operational. There were soon failures due to the BMS and the cell integration design.

This active BMS, used only for the prototype, draws power and thus discharges the battery in the process of active balancing. Unless the truck was plugged in every few days the battery is soon discharged, resulting in cell damage. The battery would then have to be rebuilt, replacing failed BMS boards as well as cells that had been damaged by discharge.

Figure 5-In its first commercial haul, FC1 delivered steel from San Diego Harbor to Otay Mesa – 1 Nov. 2017

Trailer tows were included in over a thousand miles of commissioning preceding the first commercial tow, from the Port of San Diego to deliver steel to Otay Mesa, the first day of November 2017– Figure 5.

The prototype was exhibited at the 2017 Fuel Cell Seminar, it was also shown at a CHBC (California Hydrogen Business Council) meeting early December and then delivered to TTSI on 18 December, 2017, ready for use – although the hydrogen fueling was not yet operational at TTSI.

3. Commissioning and Design Improvement

Each tractor is equipped for telemetry, with selected parameters read from the CAN bus communication lines and recorded for transmission. Initially we used the commercial FleetCarma system, then as that firm was acquired and the changes in the firm dictated change TransPower replaced all the telemetry units with Viriciti modules. Presently Viriciti tracks all the trucks, we can go to the Viriciti website and see present use as well as summaries and vehicle tracks. Thus we have not only Mr. Vito's commentary on the trips, but logged data showing operational parameters and even location and elevation.

Figure 6-FC2, shown here with trailer during commissioning, entered TTSI drayage service in 2019.

Figures 7 and 8 provide a preview of the level of information that is available as records of these trips, here jumping forward to some of the most demanding excursions which were done at 80,000 pound GVW with FC2 after the prototype had been delivered to TTSI. (See in Fig. 5 FC1 doing commercial service a year before the tractor trailer combination of Fig. 6 was used for these evaluations). The GPS information displayed includes altitude reported with severe resolution limitations, the Rainbow Valley exit turnaround[2] at the center of Fig. 8 is at about 350 meter altitude with the southbound grade dropping to about 80 meters to a river valley, with then

[2] This exit is just south of the ridge that bounds the Temecula valley in the north and the County of San Diego.

another major grade before dropping to Escondido, TransPower's home base. Note also in this data:

- With 80,000 lb gross, the vehicle slows severely on the grades, this is common with this series of e-trucks.
- Although the fuel cell genset is steadily developing about 34kW, the battery SoC drops notably, to below 40%. This is a severe limitation, an expected result of the limited power capability of the fuel cell power package compounded by the difficulty of getting full power from the fuel cells.
- With discharge currents occasionally exceeding 800 amperes (not shown), the traction batteries are heated and the battery temperature rose to 46C due to ohmic resistance and due to power dissipation in the BMS system. (The KAM cell batteries used on the prototype (FC1) were notably smaller at 140 KWh capacity, and hence discharge rates as a % of cell capacities were higher.) The discharge heating is proportional to the square of the current. To the extent that the battery pack is counted on to provide a large portion of the drive power for these severe duty cases, the heating is thus expected to be more of an issue than on the battery electric vehicles which have more battery storage.

Figure 7-Vehicle track on I15 north from Escondido to Rainbow Valley

To reduce high operating temperatures a forced air cooling system of the KAM cell packs was contemplated, designed, but never implemented, in large part because of other issues – notably the repeated failure of the packs once the truck moved from daily use in commissioning to occasional use after delivery to TTSI. Further the forced air cooling system, using cabin air to cool the batteries, had somewhat complex entry and exhaust to and from the battery boxes that promised sealing issues in wet weather.[3]

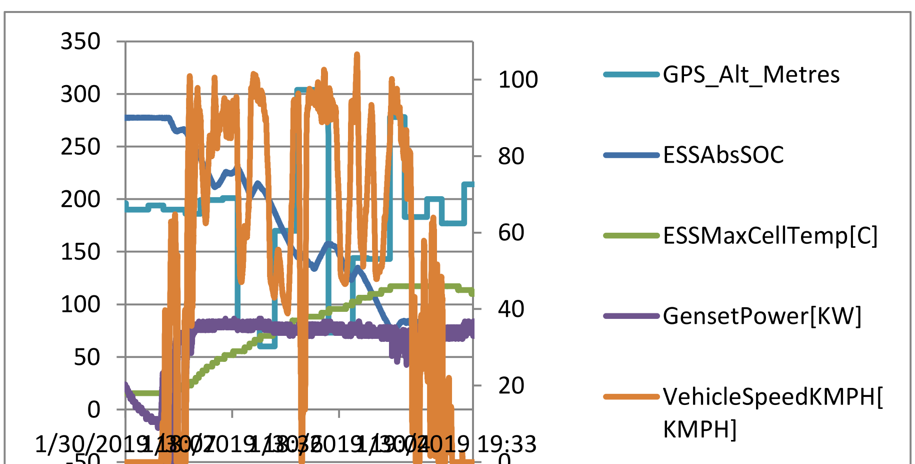

Figure 8-FC2 climbing from Escondido to Rainbow Valley Turnabout, with return.

[3] The author had developed a liquid cooling system for a battery with Kokam cells years earlier, the complexities of such a liquid system design were thought too much for the resources of this program.

Commissioning entailed numerous events:

Notable Experience Commissioning, Testing, Demonstration		
4 Aug. '17 Matt Vito	153 miles bobtail	Instrument cluster drop out, battery temperature started at 30, rose to 55C
7Aug.'17 Matt Vito	198 miles bobtail	had to stop 3 times for recharge, Tbatt to 58C
1 Nov. '17 Joshua	44 miles full load	Towing steel – SD Port to Otay Mesa (pic Fig. 6)
Nov. '17 Joshua	Drove to LB	Shown at Fuel Cell Seminar – Long Beach
Feb. 21, 2018	At TTSI	First Responder training (Mike Mendenhall)
March 2018	At TTSI	Had to rebuild battery due to not being charged
April 2018	At TTSI	Can't enter drayage service due to lack of RFID, tech. Mike Mendenhall "it is a great truck"
April-May 2018	At Long Beach	Shown at ACT Expo, sealed water leak in power control relay box which caused ground fault.
June 2018	TTSI	Entering drayage service - 2023 miles on odometer
26 June 2018	TTSI	Faulted during charging, replaced BMS board
27 June 2018	TTSI	Taken from service due to small hydrogen tank valve leak, replaced one, then all 4 valves
19 July2018	TTSI Tony inquires about the	range of the truck, stating "we did not have any issues with power of the truck"
17 July 2018	FC2 development	Fuel cell issues with flow sensor, current sensor
4 Sept. 2018	FC1 - TTSI	Being used for the night shift…
13 Sept. 2018	FC1 - TTSI	"truck suddenly lost all power", MM unable to replicate, fault never duplicated, put back in service.
21 Sept. 2018	FC2 – at TP	All four tank valves replaced, after earlier replacement on FC1.
3 Oct. 2018	FC1 – at TTSI	Different temperatures reported, likely air in the coolant loop, due to leakage, lack of coolant.
10 Oct. 2018	FC1 – at TTSI	GCM-SCM communication issue, cured next day with software update – but truck stayed out of service
2 Mar. 2019	FC1 returned	To TransPower due to battery issues
12 Apr. 2019	FC2 – at TP	Replaced both fuel cells, one had leakage, delivered following week to TTSI.
23 May 2019	FC2 – at TTSI	Entered service at TTSI

Figure 9-FC1 refueling with solar hydrogen at the CalStateLA fueling station.

FC1 was used for first responder training in February of 2018, then was neglected and not put on charge… the truck was designed to be used and charged daily, and if not daily, at least every few days. Neglect led to the BMS drawing down the battery charge to the point of failure. This damaged cells and a time-consuming rebuild was required by a skilled technician. This recurred several times. It became clear that a more self-sufficient battery was needed.

FC1 was shown at the ACT Expo in Long Beach late spring of 2018, as was the second truck, FC2, the following year at the follow-on event.

4. Commercial Service and Continuing Improvement

Total Transportation Services Inc., TTSI, is TransPower's partner for demonstration and use of the fuel cell range extender trucks in drayage service. Readying the truck for commercial service in the LA Ports requires a number of certifications and permits, such that FC1 was delivered in 2017 it did not enter commercial service with TTSI until early summer 2018.

Among the documents and devices required are:

- Manufacturers Certificate of Origin
- Title
- Registration, with license plate
- Experimental Permit, required by the Air Resources Board for alternative fueled vehicles
- USEPA Testing Exemption
- Lease agreement between TransPower and TTSI
- Automotive Insurance ID Card

- VIN sticker
- TTSI recorder installed
- RFID installation
- Safety Card (for first responders) and PID
- Decals on truck with US DOT#, MC#, CA#
- Drayage Truck Registry Exempt sticker with bar code
- DMV Non-Expiring Motor Carrier Permit
- CHP Hazardous Materials Transportation License
- ARB Drayage Equipment Registration

Until one reviews this list of requirements it is surprising that it can take months from the delivery of a vehicle to actually connecting a load and doing a commercial haul.

And add to the above… making fuel available. For the ZECT program fuel was made conveniently available by a CEC contract to Air Products to put fuel on site, but that did not become operational until early 2018.

Once all that had been completed and the prototype was in service:

We were pleased by initial favorable reports "they love our truck". However… in due time reliability issues developed, as noted in the table above. Key issues were:

- Battery BMS, one failed during charging (in June), subsequently if the truck was not used and charged every few days a massive battery failure would be caused by the active BMS system depleting the battery due to the constant discharge in balancing.
- Fuel cell component failures would ground the truck, it did not help that there were dual fuel cells on board, if either failed the truck was sidelined.
- A hydrogen sensor failed.
- Hydrogen tank valves developed leaks. This component issue led to the replacement of all the tank valves, at supplier cost.
- By September 2018 TTSI was regularly using the fuel cell truck for the night shift. On Sept. 13, there was a power failure which stranded the driver and truck. Our technician was not able, in subsequent driving, to replicate this failure or hence to isolate the cause. The failure diminished confidence, the truck thereafter was intermittently used. That occasional use

Figure 10 - One of four battery enclosures mounted to truck FC2, later retrofitted to FC1 as well, shown in test with front cover off.

and limited service attention resulted in a fuel cell issue, then another battery failure. Some months later FC1 was returned to factory for further testing and upgrades.

- Not until summer of 2019 was it noted, on FC2, that fuses used for the coolant pump power were discoloring. Changes were made to take some of the high current fuses out of the fusebox and hence reduce the heating. This was done before there was any failure
- The radiator cooling fans draw 7 amperes each in operation, but have a starting transient of more than double that. As improved engine control software was implemented, it was noted that there was a correlation between fan starting and sudden shutdown of the fuel cells, apparently due to the transient on the 24 volt bus that supplies the fuel cell controller. High current thermistors were added to the fan circuit, slowing the start, and the issue vanished.

Figure 11- FC1, the prototype of the ZECT2 trucks, has been upgraded with NiMC storage batteries and the step structure shown below the cab.

As noted above, quality issues experienced with the cylindrical "YHKAM" batteries built into FC1, the prototype truck, led to the adoption of the nickel manganese cobalt (NMC) batteries manufactured by Nissan for the second truck. While the KAM battery performance in the first truck was excellent during the prototype deployment, the delays in deployment following delivery resulted in lack of use and hence damage to the battery system. TransPower elected to switch to the NMC batteries for the second truck because, after several months of testing and consultations with supplier Nissan, these batteries appeared to offer a significant improvement in quality of cells and BMS as well as allowing more energy onboard. Figure 10 is a photo of the interior of

the outer battery enclosure TransPower designed to house the Nissan batteries. Visible inside the module are the endplates of three stacks of Nissan battery modules. Each stack consists of nine Nissan modules and stores about 14.4 kWh of electricity. Therefore, the enclosure shown has a total storage capacity of 44 kWh. Four such enclosures, each a 44kWh battery string with integrated BMS, were installed on the second fuel cell truck, and a similar battery system has now been retrofitted on prototype FC1. This upgrade provided notable improvement in reliability, durability, water ingress
protection, and increased the rated battery capacity from 140kWh to 176kWh.

Figure 11 shows the installation of the Nissan cells completed on the prototype truck early 2020, making this truck identical in configuration to FC2. TransPower made the battery upgrade in both of these fuel cell trucks at its own expense.

In the midst of this program – September 2019 -- Cummins purchased Hydrogenics, with consequence of change in some personnel and changes in procedures. The new staff support structure has in some ways improved response to the issues as they occur, with new and competent persons learning as they proceed to address some of these issues.

5. Learning from the Extensive Test Data

It is also of note that the change from the KAM cell installation to the improved battery had one negative aspect, diminished performance at low state of charge. The change was from a LFP (lithium iron phosphate) chemistry to the NMC (Nickel-Manganese-Cobalt) formulation, still a lithium based battery but with a softer voltage curve. Softer in the sense that the LFP voltage

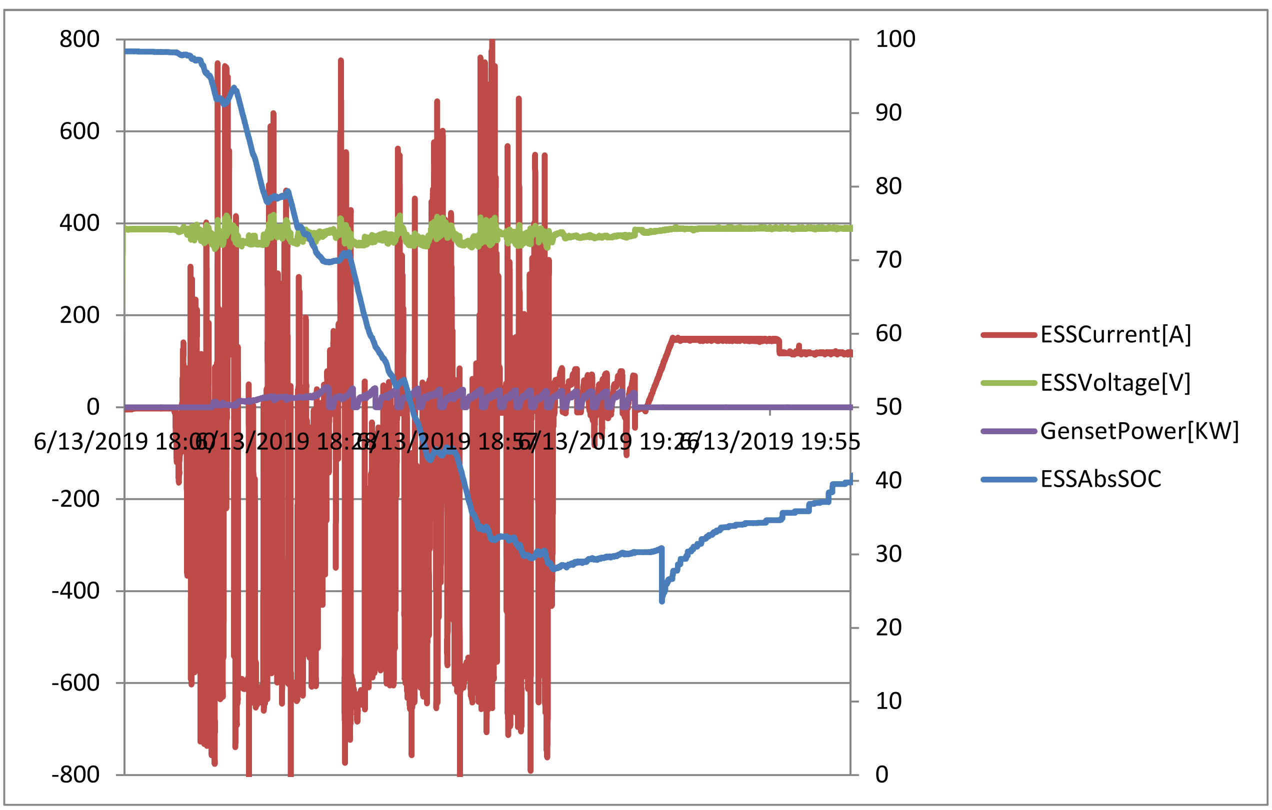

Figure 12-FC1 49 miles 13 June 2019, discharge of KAM cell battery with minor reduction of ESS voltage.

varies little during discharge, but the NMC cell voltage droops notably, the discharge starts from higher voltages and goes to markedly lower voltages at low SoC.

The “stiff” curve of LFP is illustrated in Fig. 12 by the record from a test drive with trailer done at an average speed of 44mph, current drawn from the battery is represented as negative excursion from zero of the red trace, oft to 800 amperes or approximately 280kW (375 HP) to the wheels. The positive excursions are mostly regenerative braking, added to by an oscillating fuel cell system averaging about 15KW output, totally inadequate for maintaining battery charge level. Hence the data shows the battery energy depleted to near 30% SoC within an hour, but it is notable that the battery voltage is more affected by the deep current draws, in excess of 600A, than by the battery state of charge. Note that when demanded, the battery could put out 800A even with low SoC.

This very flat discharge curve is a notable advantage of the LFP cells, as compared to the NMC formulation in which case discharge from full charge to 30% results in a 14% drop in voltage. As a consequence, the vehicle performance with the new batteries depends critically on maintaining a relatively high state of charge. We have had drivers complaining of performance, and checking the log it is clear that they have left without first charging the batteries. With the NMC batteries it is important that the vehicle be plugged in to recharge before departing, unless the service is sufficiently light that the APU will maintain the cell voltages.

Fortunately, for practical purposes this oft is not an issue. Much of the time the drayage truck is at a stop or at low speed, with the generator adding charge to the battery as needed.

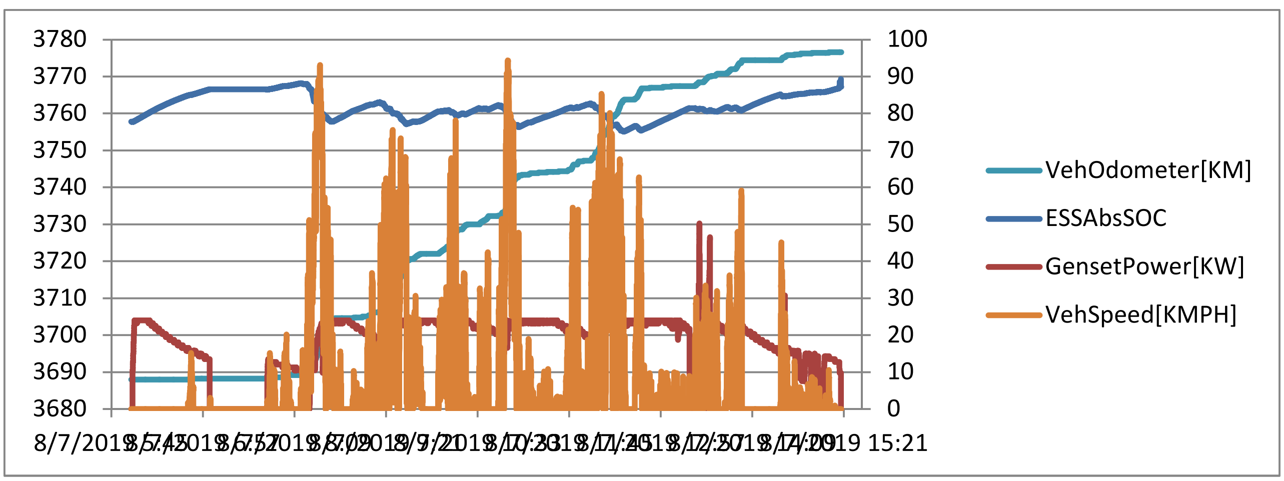

Figure 13-FC2 service of 7 August '19 55 miles starting at 6 am. Note average speed is under ten mph, with repeated small trips of approximately 10 miles. This is typical of drayage service, oft adding an evening shift.

The Figure 13 record is of FC2 in actual drayage service, showing intermittent use and the battery being maintained with SoC at 75% and above. This relatively light use is more the rule than the exception.

However the following Figure 14 record is representative of a day of demonstraed freeway use and long distance service, with SoC being a prevailing issue. Here the intermediate state of the fuel cell control software and the resulting operation at about 40% of rated performance slowed the truck. Even so, the 167 mile day, likely the longest of the period of drayage service, is especially notable.

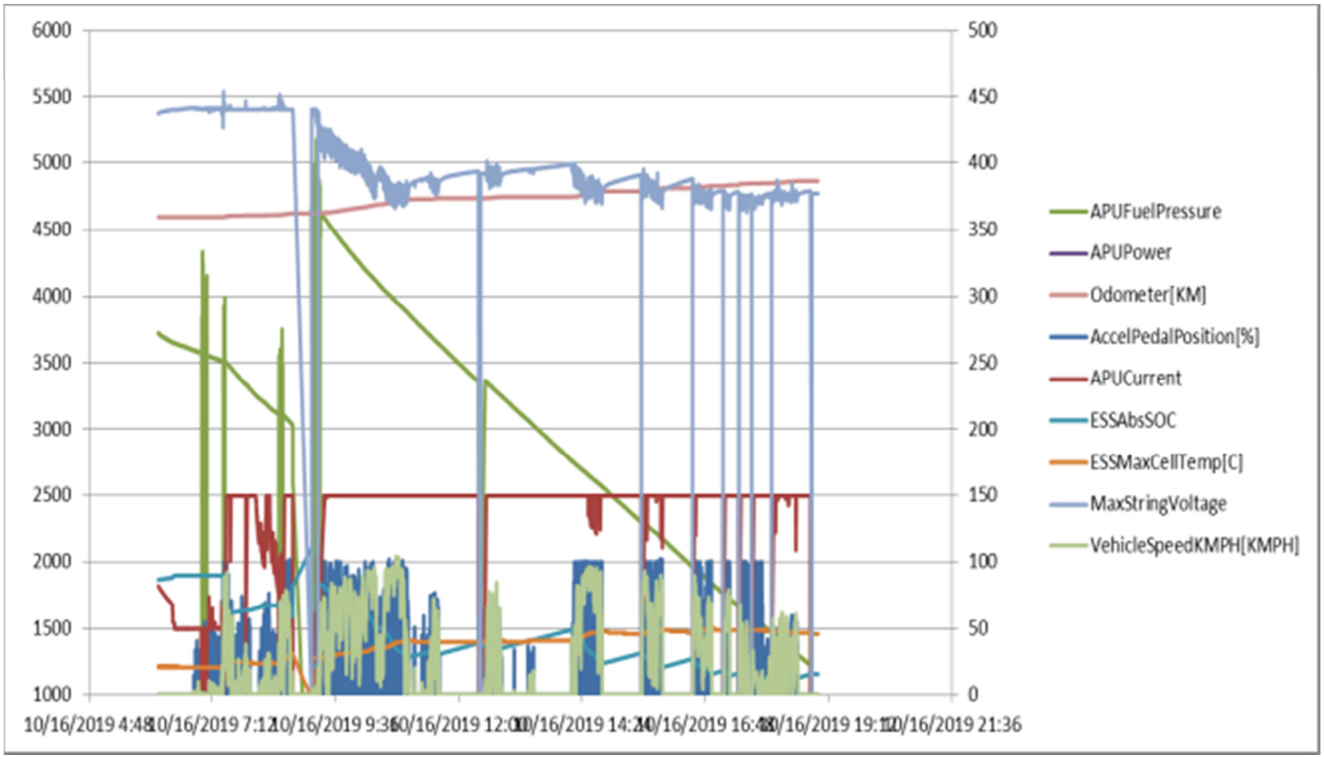

Figure 14-A long (12 hr) day, FC2 16 Oct. 2019 first delivery starting 6 am, refueling, then a delivery to Fontana. Total of 167 miles, max speed 65mph, peak APU current of 150A, power of 25KW adversely affected performance, with SOC dropping to below 20%. Energy use of 2.16 KWh/mi suggests light load. MaxCellTemp=49C.

This fuel cell limitation of the performance of FC2, illustrated by figures 13 and 14 in records of TTSI drayage service, results from the difficulty of controlling the Hydrogenics fuel cell engines. Brian Moran, our AVL consultant and Stephan Hodges, our Ricardo consultant, revisited the control software in late 2019-early 2020, revising some ground rules and improving performance. This is

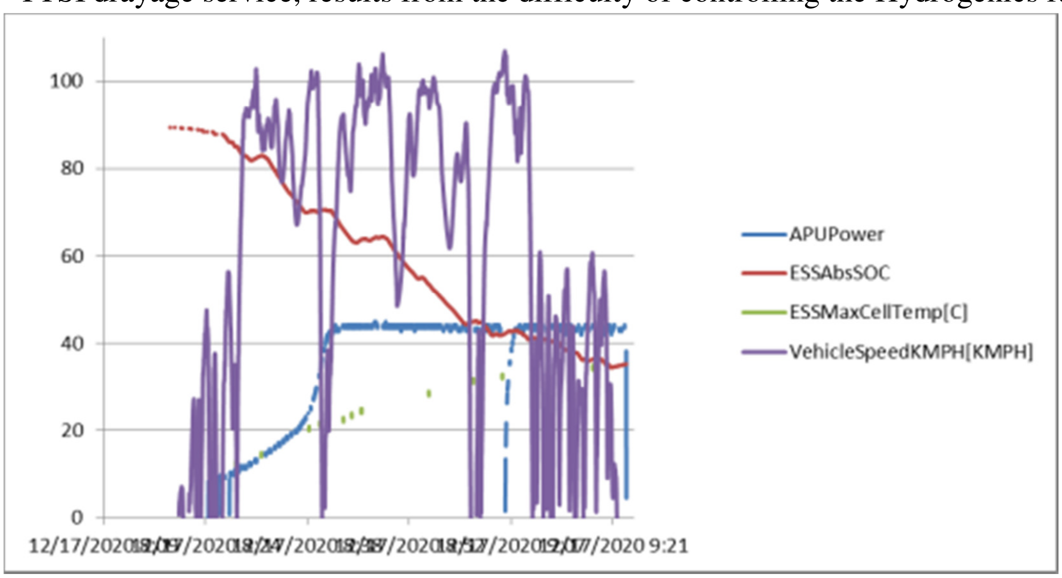

Figure 15-FC1 80,000 lb GVW, showing how fuel cell power now steadily builds with depleting SoC to 43KW. Speeds to 66mph, battery temperature increases from 12 to 35C.

reflected in Figure 15, showing FC1 with the new batteries and software, a 39 mile fast tour by the freeways of the major hills of interstate 15 south and north of Escondido. Note that the APU power, starting from low due to the high state of charge SoC, increases steadily to approximately 43KW generation rate, which seems to be the practical limit as compared to 60kW, twice the Hydrogenics rated 30KW for the FC30 fuel cell.[4]

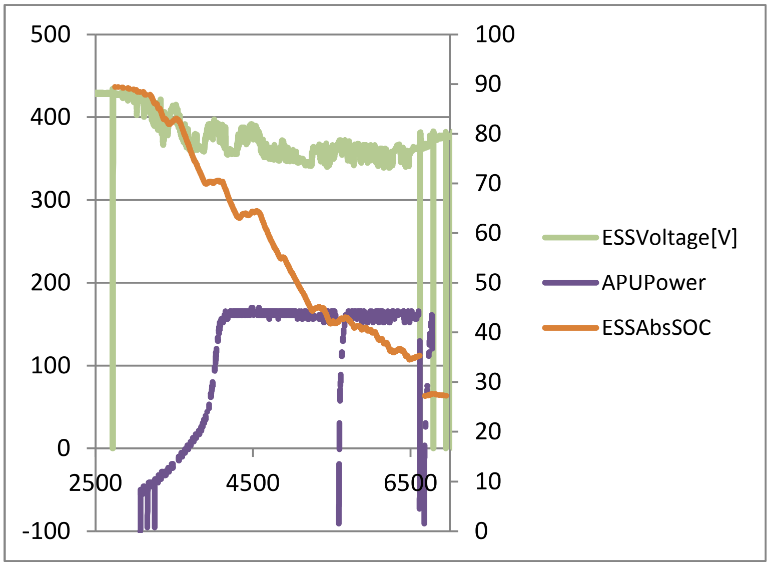

Figure 16-Same data as Fig. 13, of 17 Dec. 2020, but showing as well the battery voltage decay with battery discharge. The short term dips in battery voltage are due to high current drain as needed for hill climbs, while the higher segments relate to downhill portions, also seen as flat parts of the SoC curve .

In Figure 16 the battery (ESS, Energy Storage System) voltage decay is shown with the SoC depletion and APUPower curves. Again, this severe high speed, high power use is well beyond the design criteria for this application. Certainly the truck can do this, but for limited time "sprints", then one can recharge either by use of the fuel cells, or in somewhat shorter time by the plug-in capability of the vehicle.

The commissioning drives of FC2 of early 2019 included several challenging drives with full load over the route from Escondido to the Rainbow exit on the ridge at the northern end of San Diego County, just below Temecula, touched on earlier Figures 7 and 8.

There are hundreds of such graphic data records of the drives of these two trucks, with additional focused on individual fuel cell or converter issues. The Prototype truck was driven in excess of 3790 miles, the second truck, FC2, had 7215 miles logged by the end of 2020. Building on the ZECTII data base, three more similar design trucks have been built under successor funding, the biggest difference being additional fuel storage. Based on the near 4 year history the trucks have an improving availability record.

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[4] FC2 with the same upgrades also showed improvement, but only to about 34KW in a static test. This is still substantial improvement, about a 40% increase in power from earlier performance such as shown in Figs. 12 and 13, but it leaves open as to why the differences and perhaps more important, what further improvement is possible.

6. Conclusions and Reflections on Lessons Learned

A decade ago TransPower set out to provide a commercially attractive class 8 electric truck, resulting in the novel and powerful MDS (motor drive system) and batteries chosen for this program. These best innovations of five years ago are already outclassed by new product development that will be available at OEM outlets at commercially attractive prices in the coming year. The fuel cells, chosen for this ZECT II program as the most likely to be commercially competitive are not what we would chose today, with more powerful, compact and convenient alternatives available. Clearly, the pace of investment into electric drive goods movement has accelerated beyond most persons' expectations, and what we would plan today may be well beyond what has been realized in this program.

Even so, the two trucks developed under this program meet the performance needs of most of drayage work, do it quietly and with no emissions other than water. The drivers assigned are proud to be in the program and accept the limitations of restricted fuel cell power and range. There have been no complaints that the truck will not get over the bridge or tow a load, generally the lack of assured reliability is the greatest disappointment. And… there have been periods of months of steady service, only to come up to a new issue. Bobtail range in excess of 200 miles and of 120-150 miles with load are satisfactory, however the power limitation restricts convenient application to short range tows with moderate average speed. The trucks are freeway capable but trips of as much as an hour need be followed by a period during delivery or lunch during which the fuel cells can recharge the battery.

The trucks do have limitations:

1. As noted, a truck with more fuel cell output power would have more general application to drayage and to deliveries. As illustrated by figures 14 and 15, with average speed of 10 mph, possibly to 20 mph, the APU average power is not an issue, whereas for freeway trips, this limitation of steady use to an hour or such, depending in part on terrain, may cause inconvenience and limit productivity. However if the day is split into several freeway deliveries, or repeated 25 mile round trips with cargo load/offload and breaks at the ends, the truck is well suited for even multi-shift use. The truck could be very well suited to city delivery service with daily use of approximately 100 miles over an 8 hour day, this was not tested as the design was focused on drayage use.
2. Electric trucks are heavy, and even heavier with fuel cells and hydrogen storage. In successor programs appropriate attention to weight control, use of aluminum and plastics, will allow needed weight reduction.
3. Component reliability – or lack thereof – is more than an inconvenience, it is thought to have severely limited the use of the vehicles in demonstration. Following being stranded a driver is reluctant to choose that truck again. Lack of clear and sufficient incentives to drivers and the demonstrating entity is evident from the low number of miles… FC2 was at the ready for months during 2020 without use.

Aside from these limitations, the trucks clearly showed the capability of ZEV cargo transport for the Los Angles basin. Demonstrated capability for any range of towed loads within legal limits, and the possibility of day after day usage with 100-200 mile range have been demonstrated.

7. Financial Review

Appendix A - HD30 Experience, Fuel Cell by Fuel Cell Serial Number

151121-01	May have been benchtop; 22Jul’17 installed as FC1 FCA replacing -03
	• 5 Jul. ’19 leaking water - returned; rebuilt and reinstalled Oct.’19 as FC1FCB*
	• 22 Oct. replaced HRP (hydrogen recirculation pump)
151121-02	May have been benchtop; 22 Jul.’17 installed as FC1 FCB replacing -04
	6 Sept. ‘17 not starting, returned; rebuilt and shipped to TP 23Oct. ‘17
	April ’19 water leak in one, abnormal op removed both FC, rebuilt - now in FTFC3
151121-03	Original with prototype, returned, rebuilt with circuit board replaced,
	Removed from FC2 April ’19, rebuilt. * Now in FTFC3
151121-04	Original with prototype, returned, rebuilt with circuit board replaced, to FC1 FCA
180905-01	17 Apr.’19 anode pump fault, replaced HRP
	5 Feb. ’20 Bryson reported Anode Pump Fault… replaced HRP
180905-02	no e-mail reference to this FC -- in FC2 or Blue???
180905-03	no e-mail reference to this FC -- in FC2 or Blue???
180905-04	FCA In Red, replaced HRP Dec. ‘20
180905-05	FCB in Blue
180905-06	FCB in Red, 190628 pbs replaced HRP, Luis replaced again 3 Feb. 2020
180802-02	Installed in FC2 13 Ap.’19 as FCB, files from Morgan 190415 with failed HRP, Reported on FC2 by Aslam Sulthan, 191125

*TransPower paid over $30,000 to Hydrogenics to rebuild two fuel cells summer 2019

Development & Demonstration of Two Class 8 Fuel Cell Range Extended Electric Trucks (ZECT II)

FINAL REPORT

Prepared by:

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Executive Summary

On-road heavy-duty Diesel trucks are a significant source of Diesel particulate matter and NOx emissions with adverse health effects in the South Coast Air Basin. The impact on public health is more pronounced in the surrounding communities along the goods movement corridors near the Ports of Los Angeles and Long Beach, and next to major freeways in Southern California that are disproportionately impacted by heavy diesel traffic and the associated air pollutions. Recognizing the significant impact Diesel trucks have on air quality and public health, the SCAQMD has been working with other regional stakeholders, including the Ports of Los Angeles and Long Beach, to promote and support the development and deployment of advanced zero emission capable cargo transport technologies in the South Coast Air Basin. This project was one of four zero emission drayage truck technologies SCAQMD received a grant for under DOE's Zero Emission Cargo Transport Demonstration program.

US Hybrid developed two zero emission Class 8 fuel cell hybrid electric drayage trucks for demonstration in real world drayage operation with participating fleet operators at the Ports of Los Angeles and Long Beach. The demonstration vehicles were built on International ProStar vehicles with 80,000 lbs. Gross Combined Weight Rating (GCWR). The detailed system architecture was designed in the early stages of the project, and the concept used US Hybrid's EDU320 powertrain rated at 320 kW which is powered by a lithium Ion batter with an 80 kW fuel cell generator to provide continuous charge sustaining operation. Each truck has approximately 20 kg of hydrogen storage on board to provide an estimated range of 150 to 200 miles in drayage operations. US Hybrid used its own vehicle control unit (VCU), which uses the J1939 CAN Bus protocol, to govern the drivetrain, battery management system, fuel cells, and overall performance of the vehicles.

Actual Accomplishments with Goals and Objectives

Goals and Objectives

The objective of this project was to develop and build two Class 8 fuel cell hybrid electric drayage trucks for demonstration in real world drayage service to promote and accelerate the use of fuel cell hybrid electric transportation technologies in cargo transport operations.

Upon completion, the vehicles were to be demonstrated with the following characteristics in real world drayage service for two years in partnership with a SCAQMD-approved fleet in Basin.

Operating Parameter	Target Value	Project Achieved
Operating Range	150 miles drayage duty	√
Maximum Speed	55mph, on level ground	√
Maximum Speed at Grade	30 mph at 6% grade, GVW 65,000 lbs. 25 mph at 6% grade, GVW 80,000 lbs.	√
Energy Efficiency	< 3 kWh per mile	√
Refuel time	10-15 min for H_2	√

Project Activities

The following is a summary of tasks that were accomplished throughout the entirety of this project:

2015:

- US Hybrid finalized the subsystem design and general vehicle layout. US Hybrid also ordered two 60-80kW fuel cells to be delivered from the US FuelCell facility in South Windsor, CT.
- Started the design and sizing of the cooling system for the fuel cell engine. The traction system cooling will be similar to the battery electric system, however it will have its own custom cooling independent of the fuel cell. We are planning to use the stock radiator for the fuel cell engine.
- The Electric powertrain for the fuel cell truck is a gear less direct drive high torque motor, which will reduce cost and maintenance.
- Designed and Identified the Hydrogen storage and fill system and has identified suppliers and negotiated pricing and lead time.
- Preliminary Design the battery housing and BMS system and has generated the Preliminary drawings to be sent for fabrication quote and feedback.
- Designed the Vehicle electric driven auxiliary system and started the vehicle packaging of the auxiliaries.

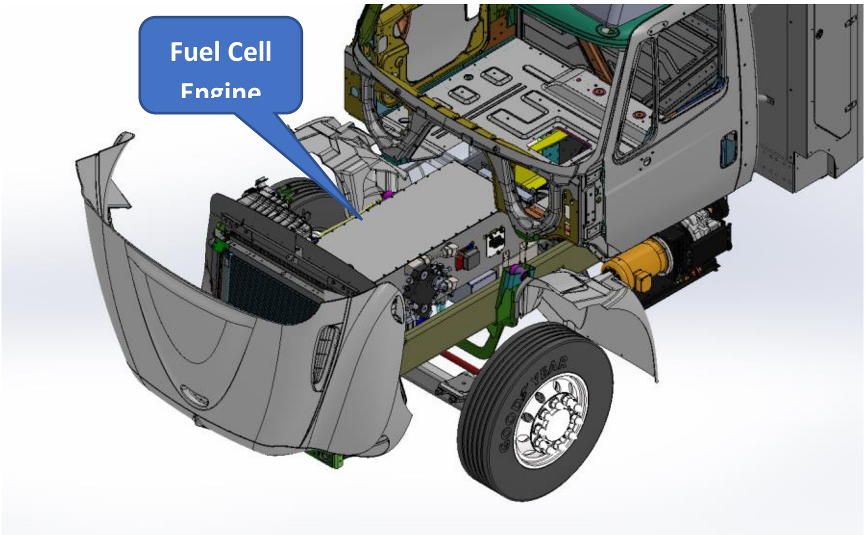


Figure 1: Fuel Cell engine truck packaging (note upadated design)

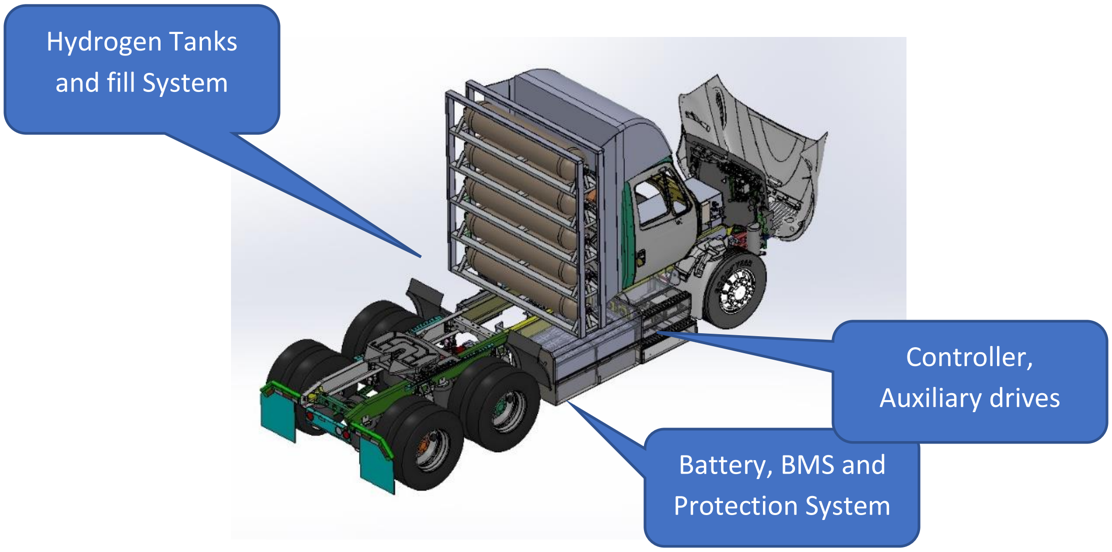


Figure 2: Fuel Cell truck battery and powertrain component packaging

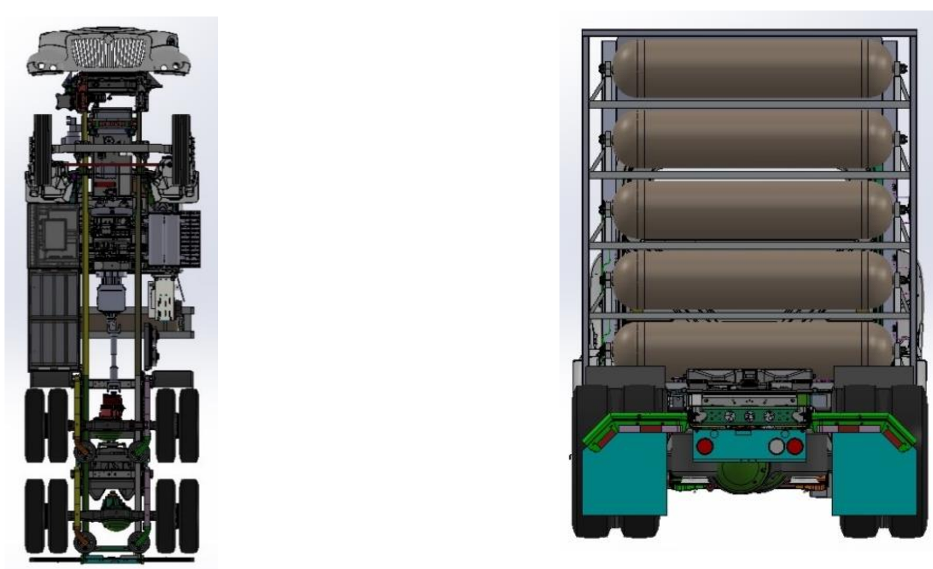
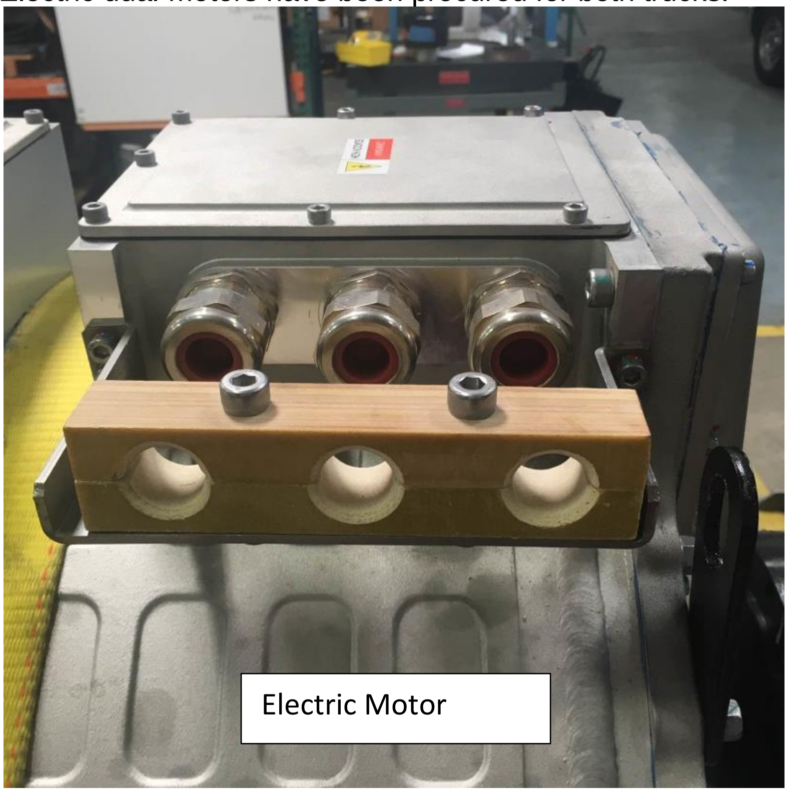


Figure 3: Fuel Cell truck major powertrain and hydrogen storage packaging concept.

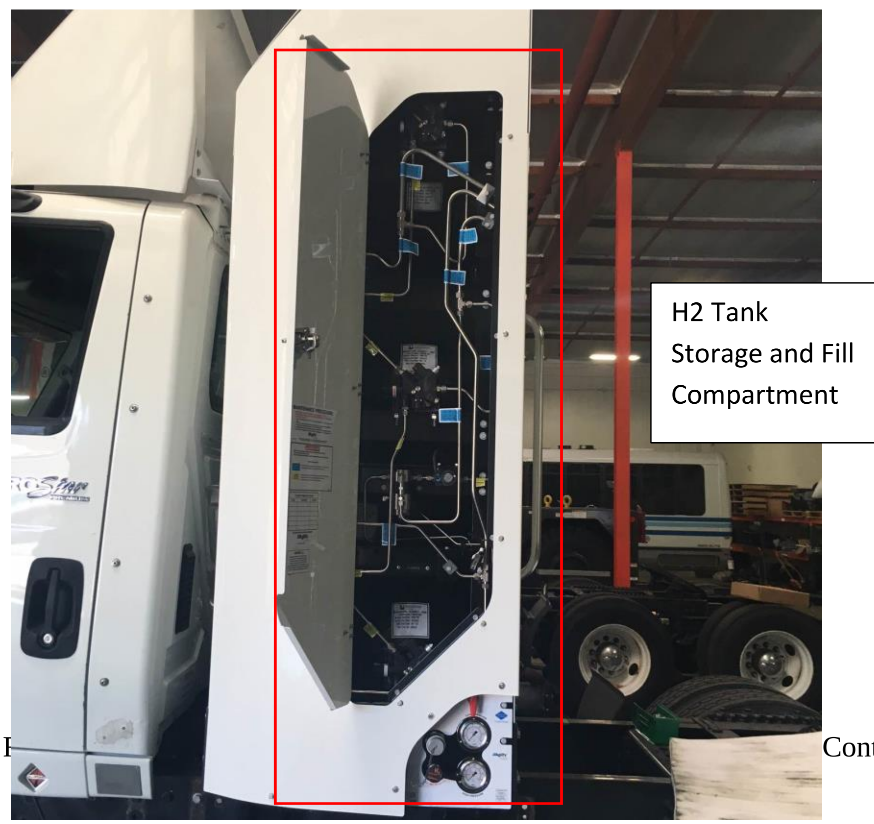
US Hybrid team in Torrance, CA and the US FuelCell team in South Windsor, CT continued design work, material and component procurement, as well as continued vehicle integration work. Vehicle level design has been confirmed and validated, and engineers have now moved on to sub-system fabrication and testing for Truck 1.

Along with integration work, testing of dc-dc power converter has been ongoing at US Hybrid's Torrance facilities, while the US FuelCell team in South Windsor, CT is undergoing fuel cell stack testing.

- Electric dual-motors have been procured for both trucks.



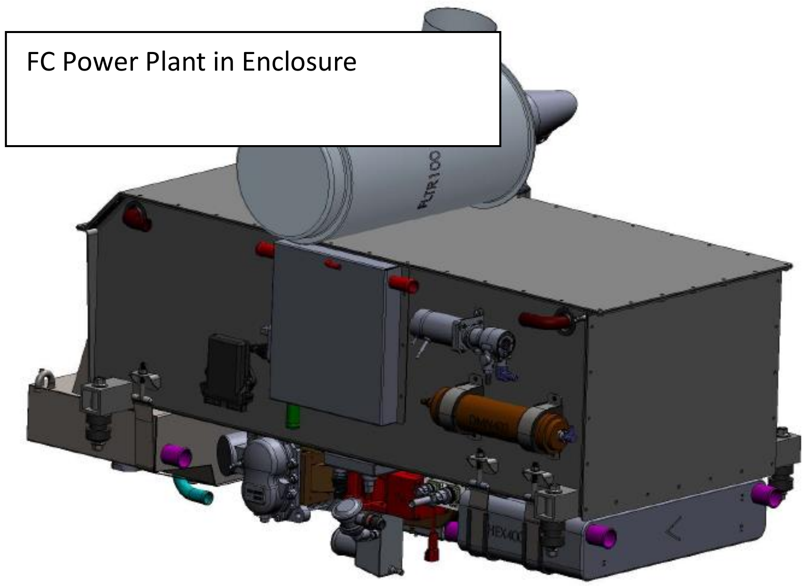
US Hybrid engineers also accepted delivery of Hydrogen tanks and completed integration of the Hydrogen storage and fill subsystem for Truck 1.



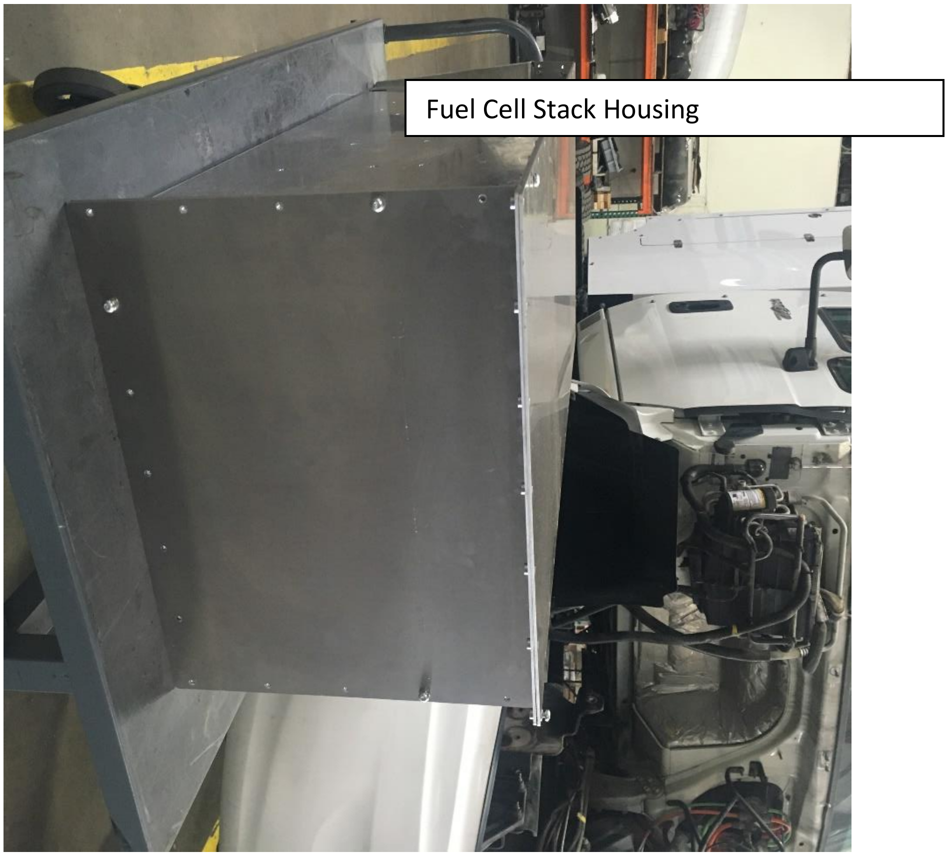
H2 Fill Interface

The US Hybrid team in Torrance, CA and the US FuelCell team in South Windsor, CT continued design work, material and component procurement, as well as sub-system component fabrication and vehicle mounting/bracketry fabrication.

Both trucks have been stripped down, with tank assembly installed on Truck 1 and tanks for Truck 2 in-house. The battery box and electronics enclosure final design is near-completion pending finalization of connector/cable pass through. US Hybrid received fuel cell stack from US FuelCell for fit into housing and motor mounts. Motor mounting design is complete and undergoing fabrication. Testing of dc-dc converter is ongoing


FC Power Plant in Enclosure


Fuel Cell Stack Housing

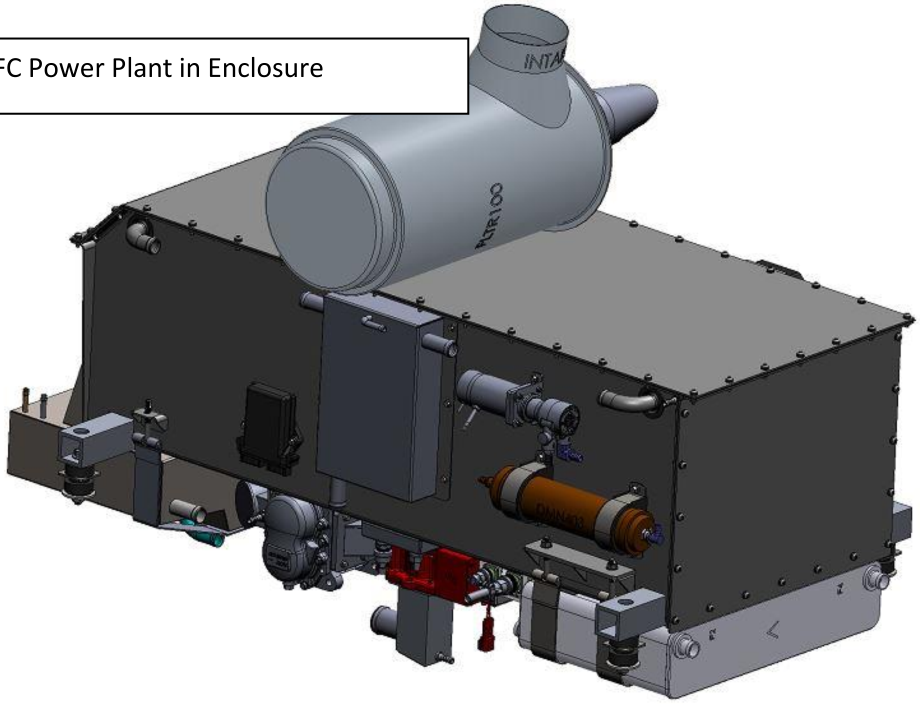


During Q4 2016, the US Hybrid team in Torrance, CA completed the Cell Stack placement location in the Stack Enclosure (SE) and the SE placement location in the vehicle. The load study report was generated for the SE, in collaboration with stress analysis personnel, as well as completion of the design/fabrication/integration of the frame mount brackets. Also, the unit cross beams design was revised, fabricated, and welded to the SE. The redesign of the external brackets and air inlet/outlet ducts for the SE was completed, fabricated, and welded, followed by a fit-check performance with the components received from the Connecticut office.

The design for two stainless DI water tanks (SEP & ACC) was finalized, as well as the sheets fabrication (no welds) with additional attached fittings. US Hybrid received the following items:

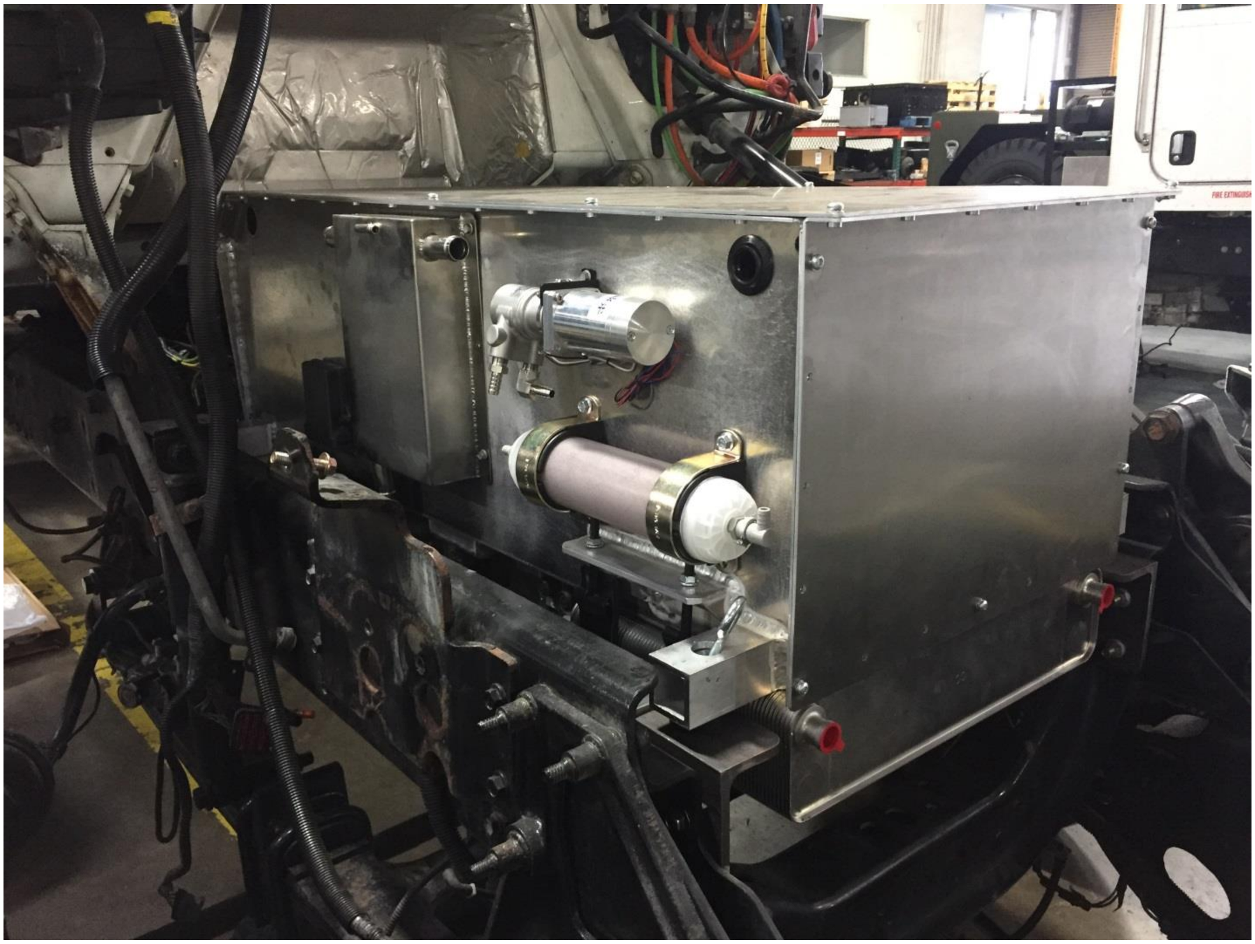
- DI Cartridge was selected and ordered. USH received one (1) unit
- Heat Exchanger (HEX) fabricator was selected and ordered. USH received two (2) units
- Strap design for HEX unit was completed and the fabricator was selected and ordered. USH received four (4) units

An order was placed for the stack “U” and tanks elbow tubes. Continuous work was also put into updating the Bill of Material.



Updated FC Power Plant in Enclosure


HELE-ON



2017

Design Work and Material Procurement

The engineering department completing the Fuel Cell enclosure components design, including the Fuel Processing System (FPS) flow path mounts blocks. The fabrication of the mentioned blocks was completed, as well as the final fit-check of assembled fabricated parts. All components related to FC power plant enclosure were then packaged and shipped to US FuelCell facilities to be reassembled for system testing.

The battery and auxiliary box design was finalized and fabricated. The battery system of 7 modules and BMS in series (total 36kWhr rating) was strung together with high voltage wiring, fuses and relays added in preparation for final enclosure and fit onto the chassis. DC20 and DA08 power converter components were assembled and prepared for fit into auxiliary box.

US Hybrid also received and began software enhancement of computer for truck dashboard including

During Q1 2017, the US Hybrid team in Torrance, CA completed the following tasks:

- Designed and fabricated motor mounts
- Designed and fabricated Fuel Cell mounts
- Finalized drawings for, and received CV38 enclosure & brackets
- Assembled and tested CV38
- ASD100 blower assembled and tested
- Received heater rods and mounts
- Selected location for batteries and fuses/relays
- Verified tire tread depth

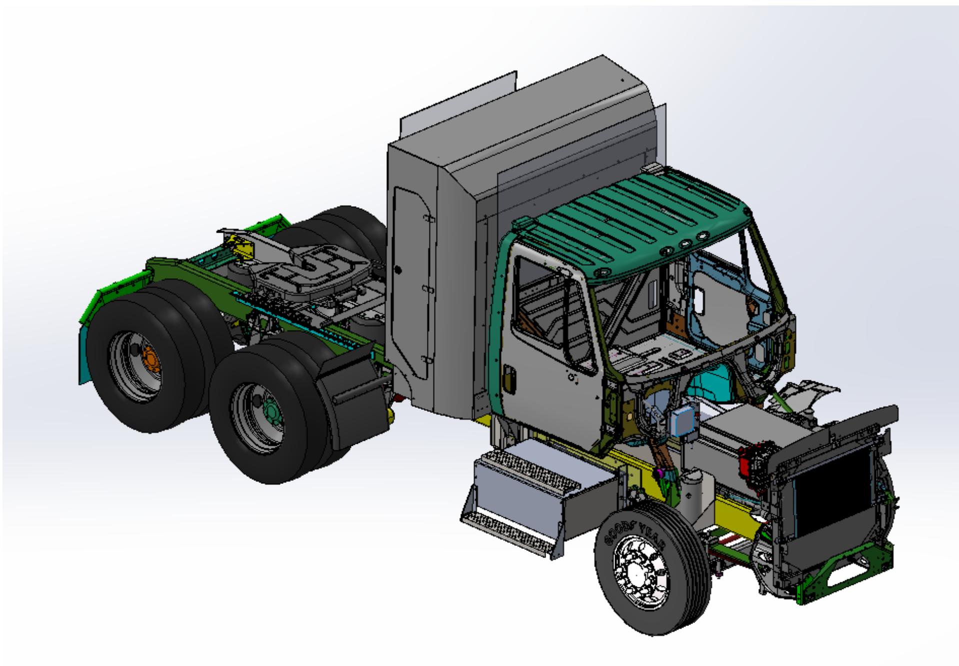


Figure 1: H2 Truck 3/4 View with FCe80 Shown

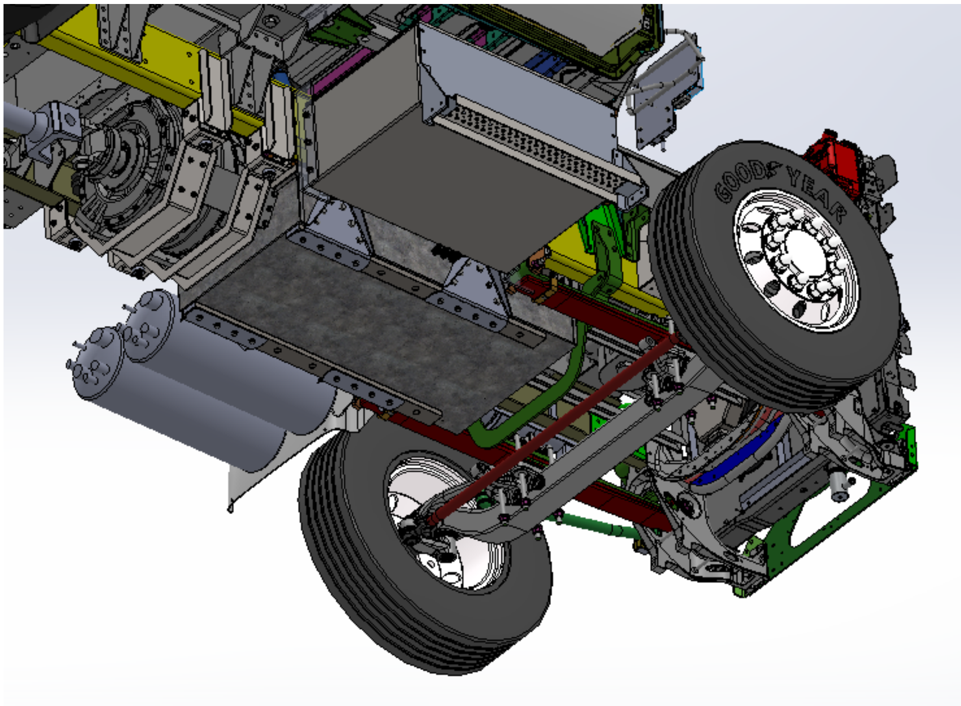


Figure 2: Bottom close-up showing battery and aux boxes

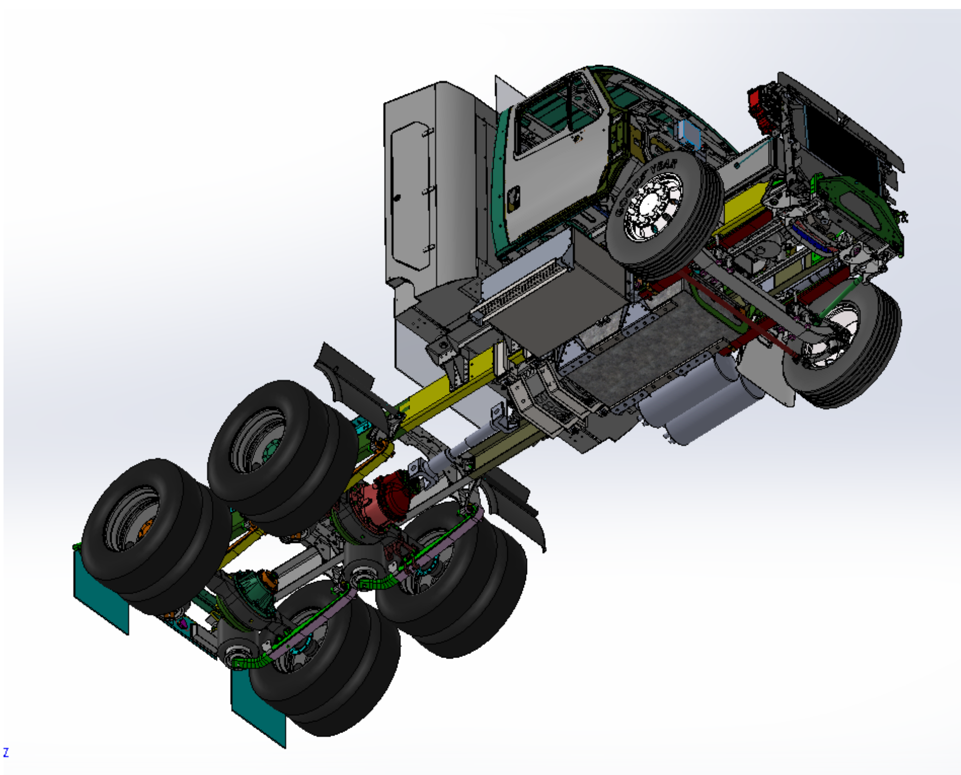


Figure 3: Bottom 3/4 View

Design Work and Material Procurement

In May, US Hybrid successfully unveiled the first H2 Truck at the 2017 Advanced Clean Transportation (ACT) Expo in Long Beach, California. This display represented the beginning of the path ahead toward commercialization.

Figure 4: H2 Truck, ACT Expo

Figure 2: H2 Truck Unveil

In preparation for the ACT Expo, the Connecticut team shipped the FCe80 fuel cell power plant to US Hybrid's Torrance integration facility for installation. The engineering team fit checked and installed the motor mounts, fuel cell enclosure mounts, and air compressor mounts. Further work included the completion of the battery and auxiliary boxes, mounting, and wiring.

Following the ACT Expo, during Q2 2017, the US Hybrid team in Torrance, CA completed the following tasks:

- Validation of all auxiliary components
- Validation of Fuel Cell power plant cooling system
- Updated the vehicle and Fuel Cell control strategy after further modeling and optimization

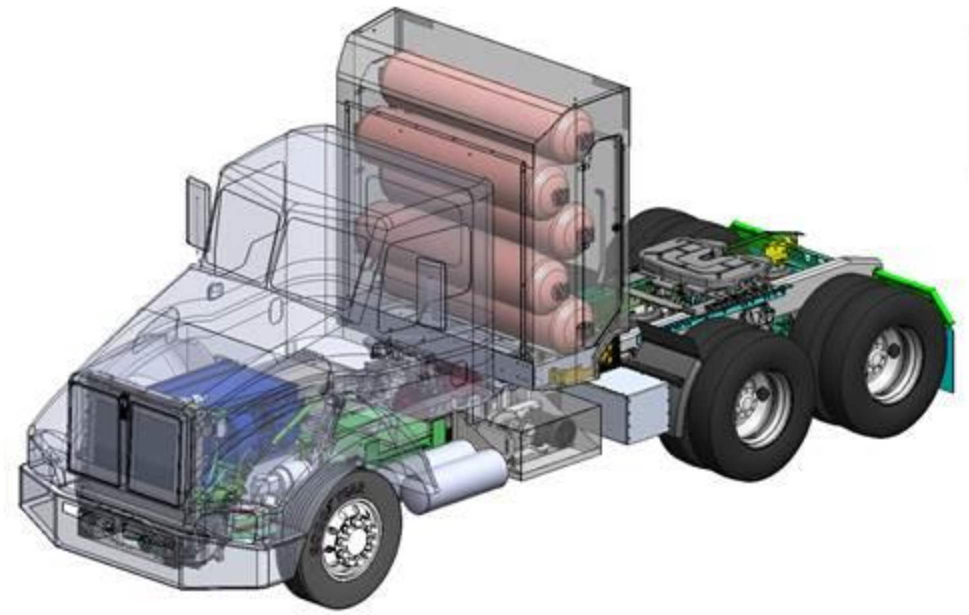


Figure 3: Updated Drawing

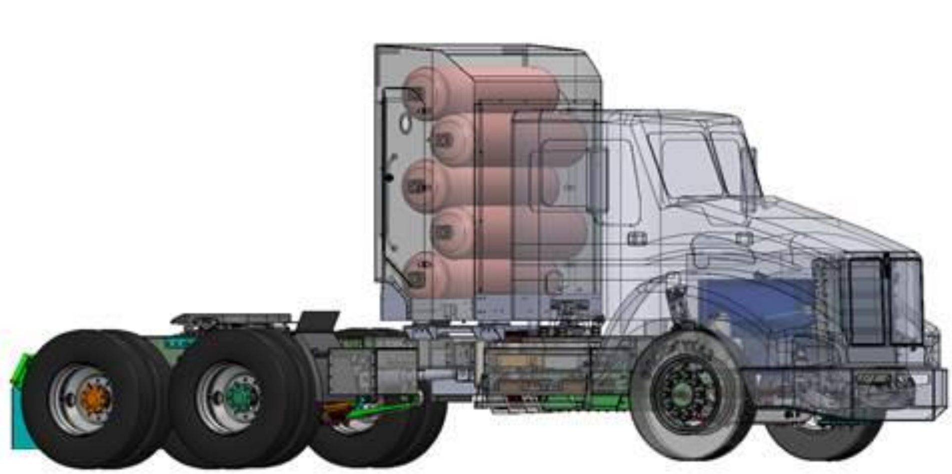


Figure 4: Updated Drawing

FCe™80 Testing and Validation

In this quarter, The FCe™80 underwent some performance and duty cycle testing. Figure 1, shows the integrated fuel cell engine performance (Hydrogen in, regulated dc voltage/current/power from the isolated dc-dc out). The performance data is provided in engine efficiency and Kwh/kg of hydrogen. At such performance one kg of hydrogen is equivalent energy of 180kg (396 lbs.) of battery weight. The stack performance and at the end of life, we can see this value reduce by 15%.

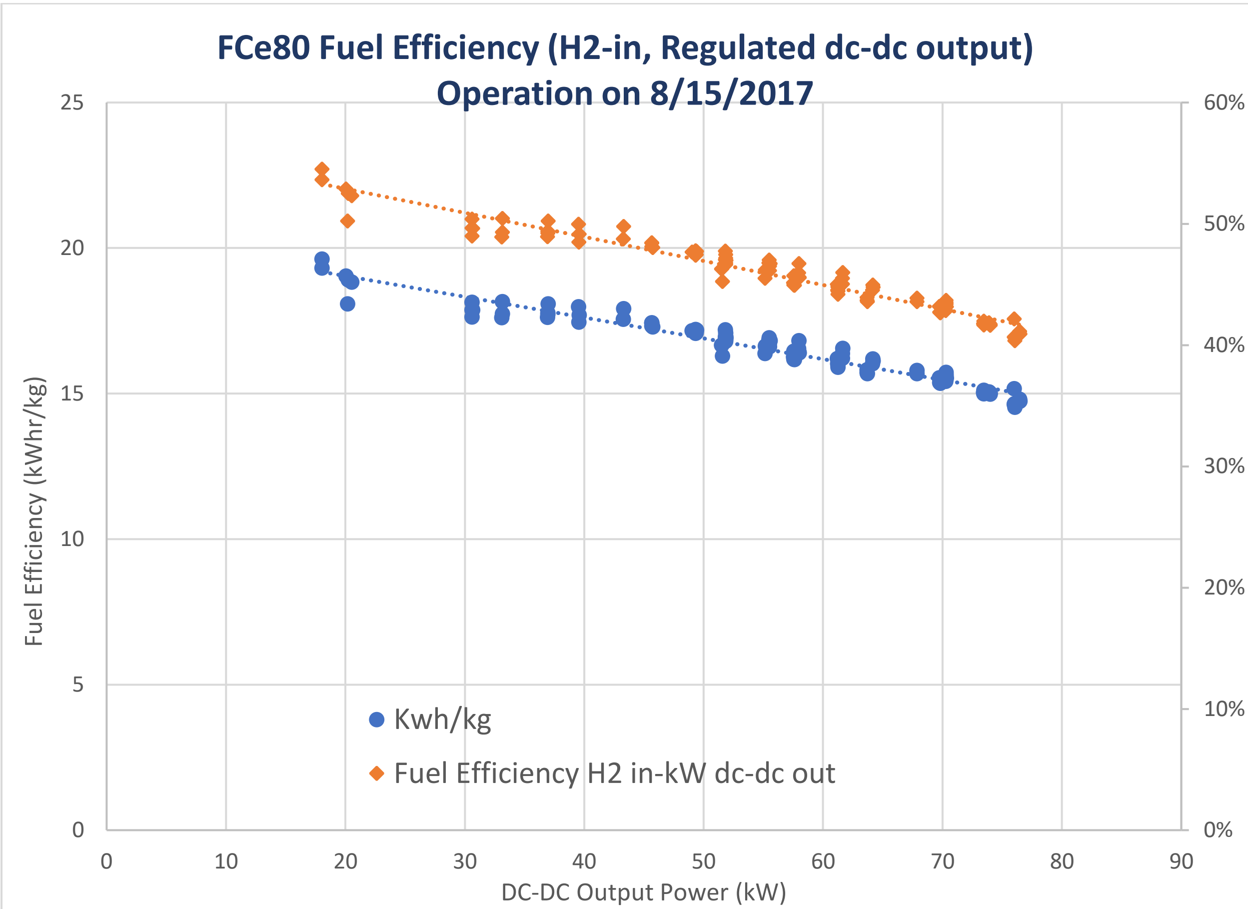


Figure 1

The data shows that the FCe™80, fuel cell engine running on ambient pressure and using the high efficiency isolated dc-dc converter, is the best in its class. We are still expecting further optimization of the fuel cell engine.

The next graph shows partial Burn-in test results of the FCe™80. Here, the output power remains at 80kW with isolated dc-dc remaining at high efficiency.

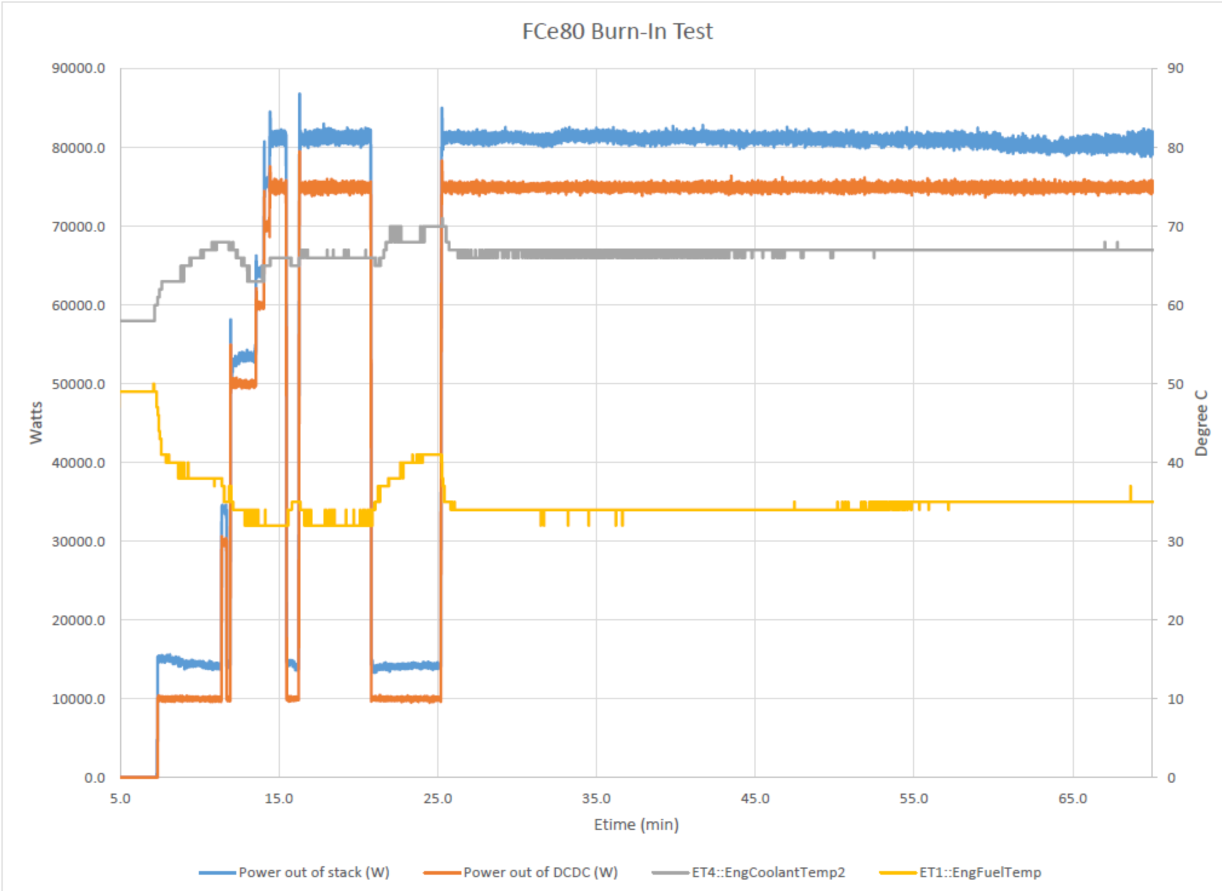

FCe80 Burn-In Test
90000.0
80000.0
70000.0
60000.0
50000.0
40000.0
30000.0
20000.0
10000.0
0.0
Watts
90
80
70
60
50
40
30
20
10
0
Degree C
5.0
15.0
25.0
35.0
45.0
55.0
65.0
Etime (min)
Power out of stack (W)
Power out of DCDC (W)
ET4::EngCoolantTemp2
ET1::EngFuelTemp

Figure 2

Continue FCe™80 Testing and Validation

In this quarter, The FCe™80 underwent more performance and duty cycle testing.

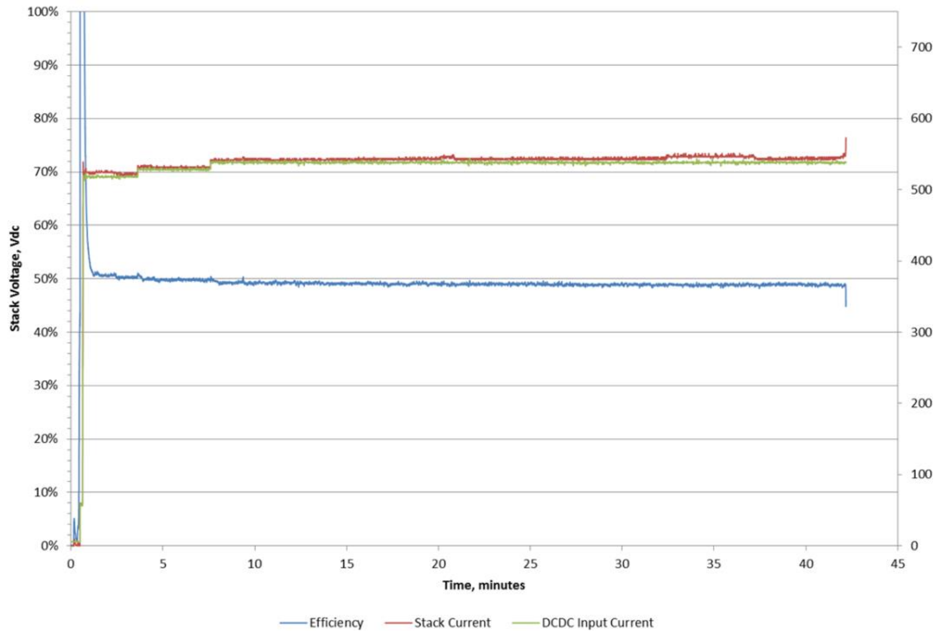


Figure 1. 80kW full power performance after one hour of continuous testing

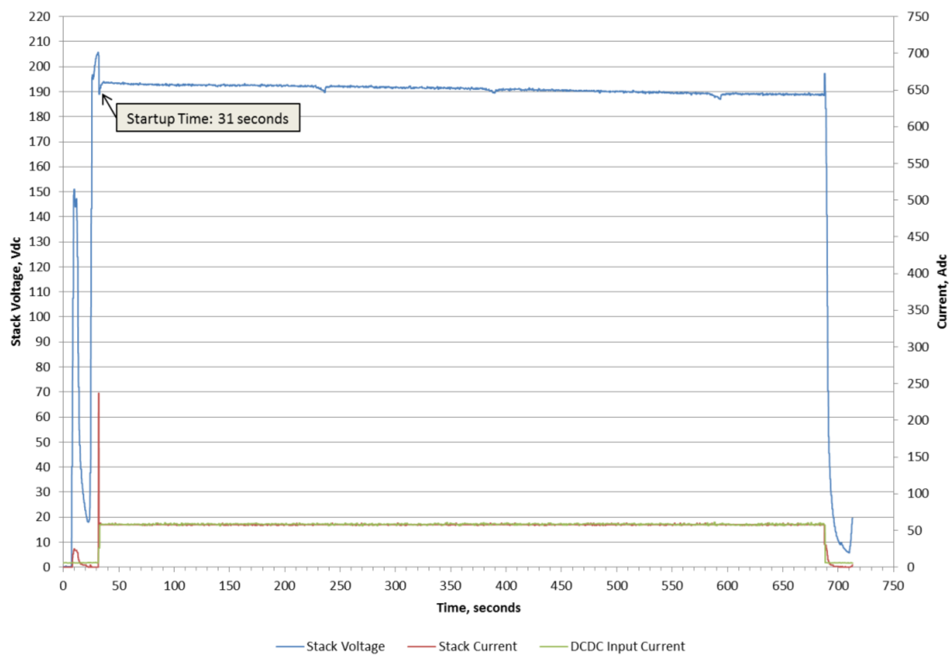


Figure 2. Cold Start 31 Seconds

The data shows that the FCe™80, fuel cell engine running on ambient pressure and using the high efficiency isolated dc-dc converter, is the best in its class. We are still expecting further optimization of the fuel cell engine.

This quarter performance on truck assembly was slow due to US Hybrid relocating its vehicle integration facility from Torrance, CA to Carson, CA, a bigger facility with better integration and yard for customer demonstration, service, and maintenance.

2018

Continue FCe™80 Testing and Validation

In this quarter, The FCe™80 underwent more performance and duty cycle testing.

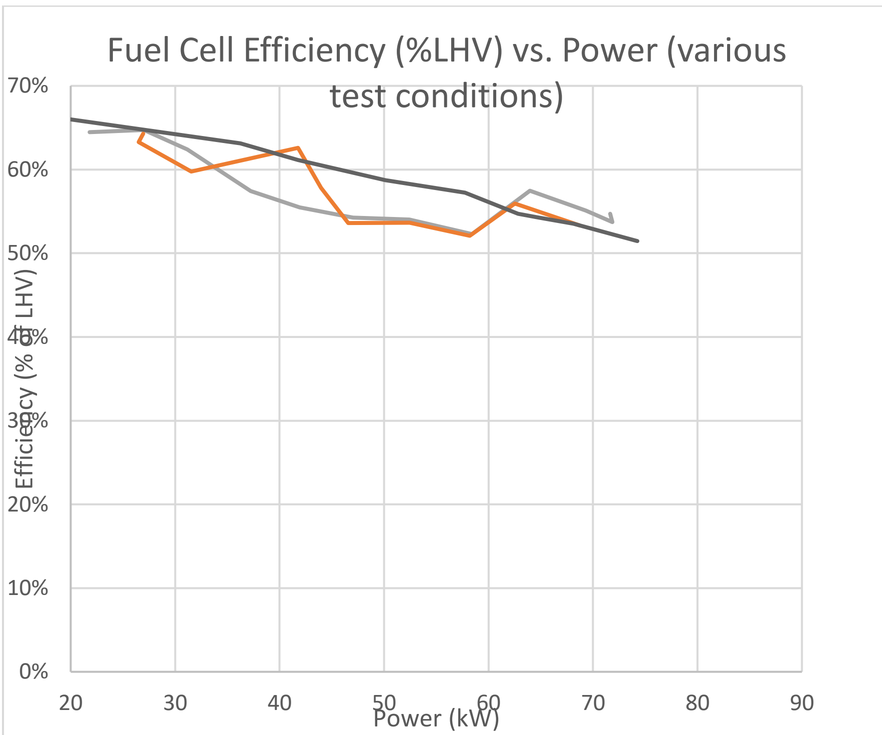


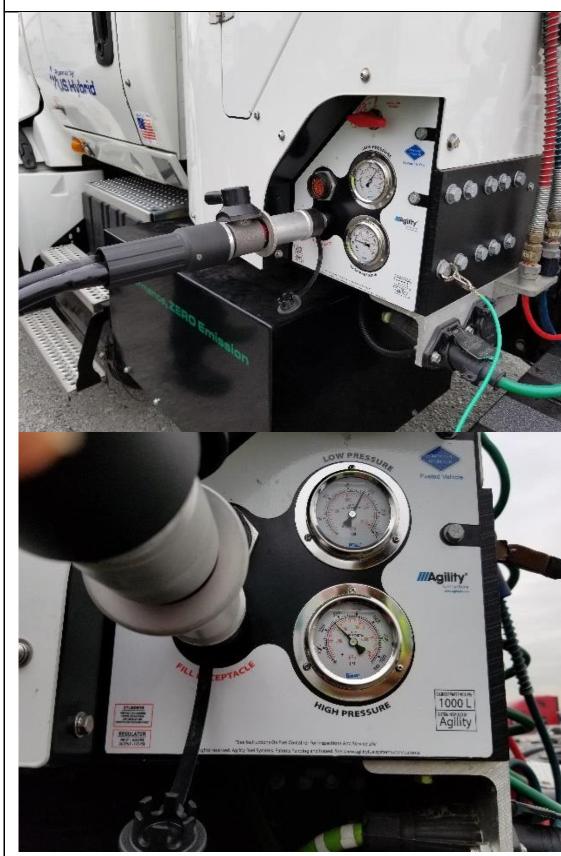
Figure 1

Figure 1, The data shows that the FCe™80, fuel cell engine running on ambient pressure and using the high efficiency isolated dc-dc converter, has the best/highest efficiency in its class globally for mobile applications, while we are still expecting further optimization of the fuel cell engine.

This quarter performance on truck assembly was slow due to US Hybrid relocating its vehicle integration facility from Torrance, CA to Carson, CA, a bigger facility with better integration and yard for customer demonstration, service, and maintenance.

Delivered the truck to TTSI/Customer for initial drive and testing

Validated the fueling interface with customer station, by doing a fueling from TTSI/Customer fueling station.



Displayed the H2Truck at the SC-AQMD, DOE meeting.

- H2Truck #1 has been deployed and operating at TTSI.
- Fuel use of 0.17kg/mile (Loaded, 80,000 lbs. GVWR) and 0.1 kg/mile unloaded (19,000 lbs. Curb).
- In late June, there was a problem with the truck body computer, not allowing the A/C operation. The truck was taken to Westrux (dealer) and by the date of this report the truck is fixed and back on service. See pictures below. Figures 1 & 2 display various plots for H_2Truck #1 with and without the trailer.
- H_2Truck #1 was operated with 54,000 lbs and 80,000 lbs load and confirm that we can sustain battery charge for operation around the port and constant speed of 55 mph, with 80kW FCe80 fuel cell engine.
- Energy efficiency and fuel consumption was quantified for the operation and is continued to determine a correct range estimation and reporting to driver.
- Various critical operation temperature and water balance was confirmed.
- H2Truck #2, Assembly status;

    Hydrogen tank assembly integrated and tested.

    Fueling interface integrated.

    Electric Powertrain (Motor and controller) installed, needing some completion of wiring harness and commissioning.

    Auxiliary systems (compressor, eHydrulic and dc-dc converter) integrated and tested.

A comparison of actual accomplishments with the goals and objectives established for the period and reasons why any established goals were not met.

- UCR dyno testing was supposed to be completed in Q2-2018 and now it is planned for Q3-2018, mainly to work with UCR on the testing time.
- Operator Manual was supposed to be release Q2-2018. Initial Preliminary version has been released and it has gone through some revisions to include fueling and it will be released Q3-2018.

Fig 1a. H2Truck at TTSI Facility Front view

Fig 1b. H2Truck at TTSI Facility Curb side

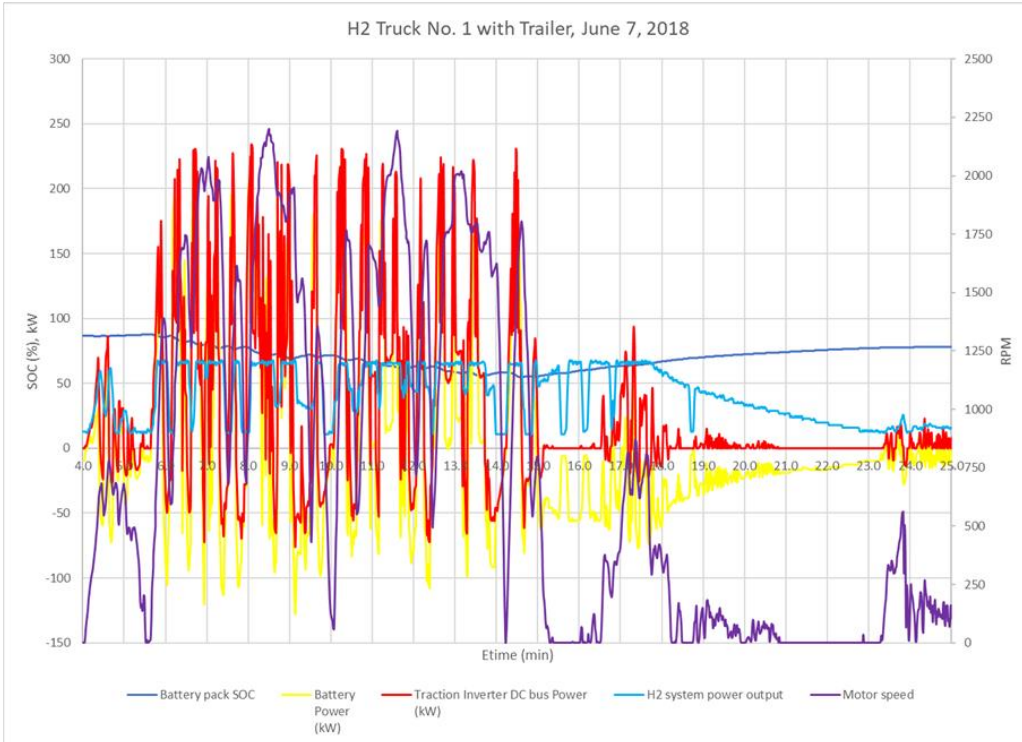


Figure 2: H_2Truck operation data (Battery SOC, Power, FC power and speed) with Trailer weighing at 80,000 lbs.

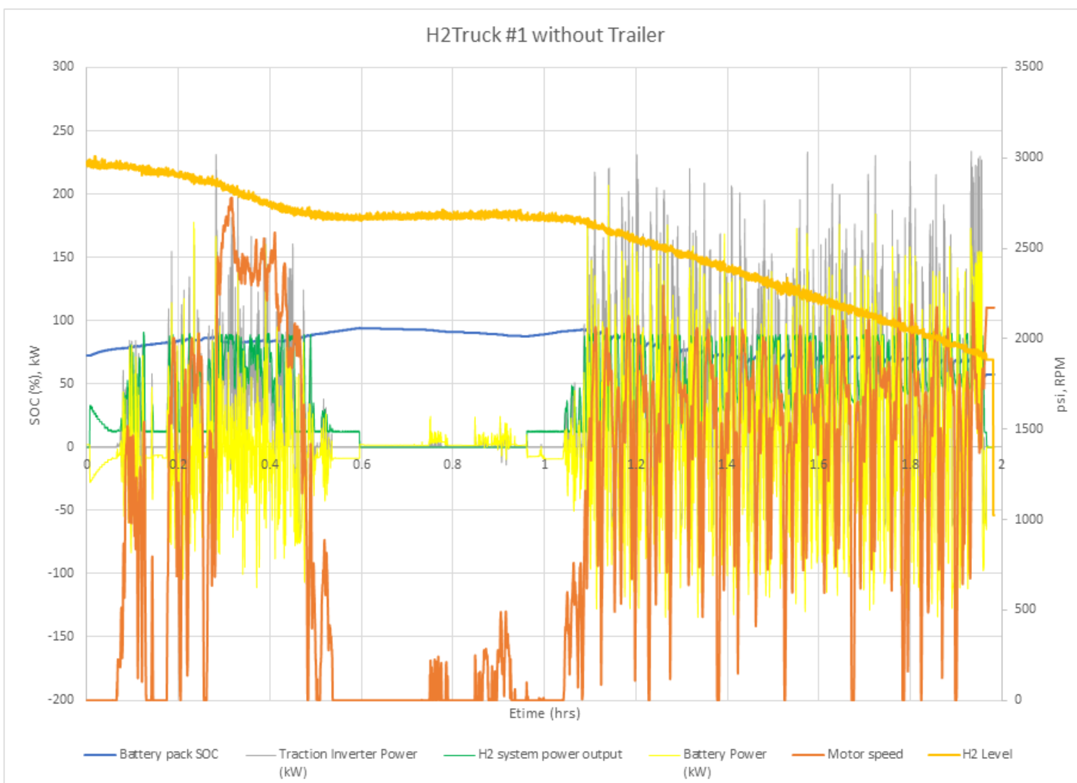


Figure 3: H2Truck operation data (Battery SOC, Power, FC power and speed), No trailer, Curb weight 19,000 lbs.

Q3-2018

During Q3-2018, US Hybrid deployed vehicle H_2Truck #1 and began operation at TTSI. Along with deployment, the vehicle's Operator's Manual and Service Maintenance Manual were provided.

Following deployment of the first vehicle, a problem was encountered. During our in-house life testing, US Hybrid detected that the vehicle's manifolds showed evidence of corrosion that penetrated the coating, which was due to the supplier's Q/A. In order to solve this issue as quickly as possible, the FCe80 power plant was sent to our South Windsor, Connecticut facility, where it is currently going through manifold upgrades. This caused our high value of conductivity.

Threaded Connections – Coating Q/A Failed to Penetrate Thread

Also, during the FC engine removal, we noticed that the WEG cooling system has evidence of rust and debris particulates. These debris may be due to not fully flushing or aging of the old radiator (this is a repower from 2012 truck). We are changing the cooling lines and re-flushing the system to ensure that there are no debris/containment in WEG.

H_2Truck #1 is scheduled to complete the upgrade and be re-released back into operation at TTSI in December 2018.

H_2Truck #2 assembly was completed and is only awaiting the upgrade of the FCe80 manifolds. Once the upgraded manifolds are integrated into the vehicle, H_2Truck #2 will be released into operation at TTSI which is currently scheduled to occur in February 2019.

Debris from back-flushed condenser (sand and some rust)

We are also adding liquid cooling to the battery box (requires battery box re-design). The design has been completed and is in procumbent for Q4-2018 integration.

Based on test data from operation at TTSI, they like to be able to maintain 60mph speed for the H2 truck and the present FC engine has been sized 80kW for the Drayage truck drive cycle duty. We are upgrading the battery cooling and recommending increasing the battery storage to 40kWhr and increasing the FC engine power to 100kW to meet the truck demand of 60 mph continuous drive.

In Q-4 2018, US Hybrid completed the manifold upgrades of the FCe80 powerplant and integrated it back into H_2Truck #1, where the vehicle was then re-released back into TTSI operation. Below is a summary of daily report of the vehicle. With the truck mileage, we can also calculate and plot fuel efficient of Miles/kg-H2, etc. Please note that 17.2kWh/kg of H2 makes our Fuel Cell engine the most efficient engine in the world.

Operation hours – 3.3
kW-hr – 116.0 (CSA) / 108.8 (Engine)
Amp-hr – 590

H_2 flow in – 6.31 kg
H_2 consumed based on Amp-hr – 5.99 kg
CSA kWhr/kg – 18.4
FC Engine kWhr/kg – 17.2

US Hybrid also continued with the manifold upgrades of the FCe80 powerplant for H_2Truck #2 and will then complete build and testing of the vehicle.

Additionally, US Hybrid worked on designing a new batter box for liquid cooling. This was done in order to re-build the truck cooling system with complete flushing and change of cooling lines. It was recommended to increase the FC engine power to 100kW based on TTSI/ operator demand for higher highway speed at 80,000 GVWR.

A comparison of actual accomplishments with the goals and objectives established for the period and reasons why any established goals were not met.

- US Hybrid accomplished the goals set for this period by completing manifold upgrades of the FCe80 powerplant and integrating it back in to H_2Truck #1 and re-releasing the vehicle back into TTSI operation. Furthermore, US Hybrid continued designing a new battery box for the liquid cooling, as well as upgrading the FCe80 manifolds for H_2Truck #2.
- UCR dyno testing was supposed to be completed in Q4-2018 and is now planned to be completed by end of Q1-2019, mainly to work with UCR on the testing time.

<u>Q1-2019</u>

In Q-1 2019, US Hybrid completed the following tasks:

Procurement of the liquid cooling cold plate and fabricated the new liquid cooled battery boxes:

Received the motor mount bracket and drilled holes for the controller and motor mount brackets:

Completed installation of the liquid cooling plates to battery boxes:

Integrated the traction motor into Truck #2:

Began integration of power electronics (drive and auxiliaries) in the truck:

A comparison of actual accomplishments with the goals and objectives established for the period and reasons why any established goals were not met.

- US Hybrid accomplished the goals set for this period by completing the procurement of the liquid cooling plate and fabricating the new liquid cooling battery boxes, receiving motor mount brackets and completing installation of traction motor into the vehicle, as well as beginning integration of power electronics.

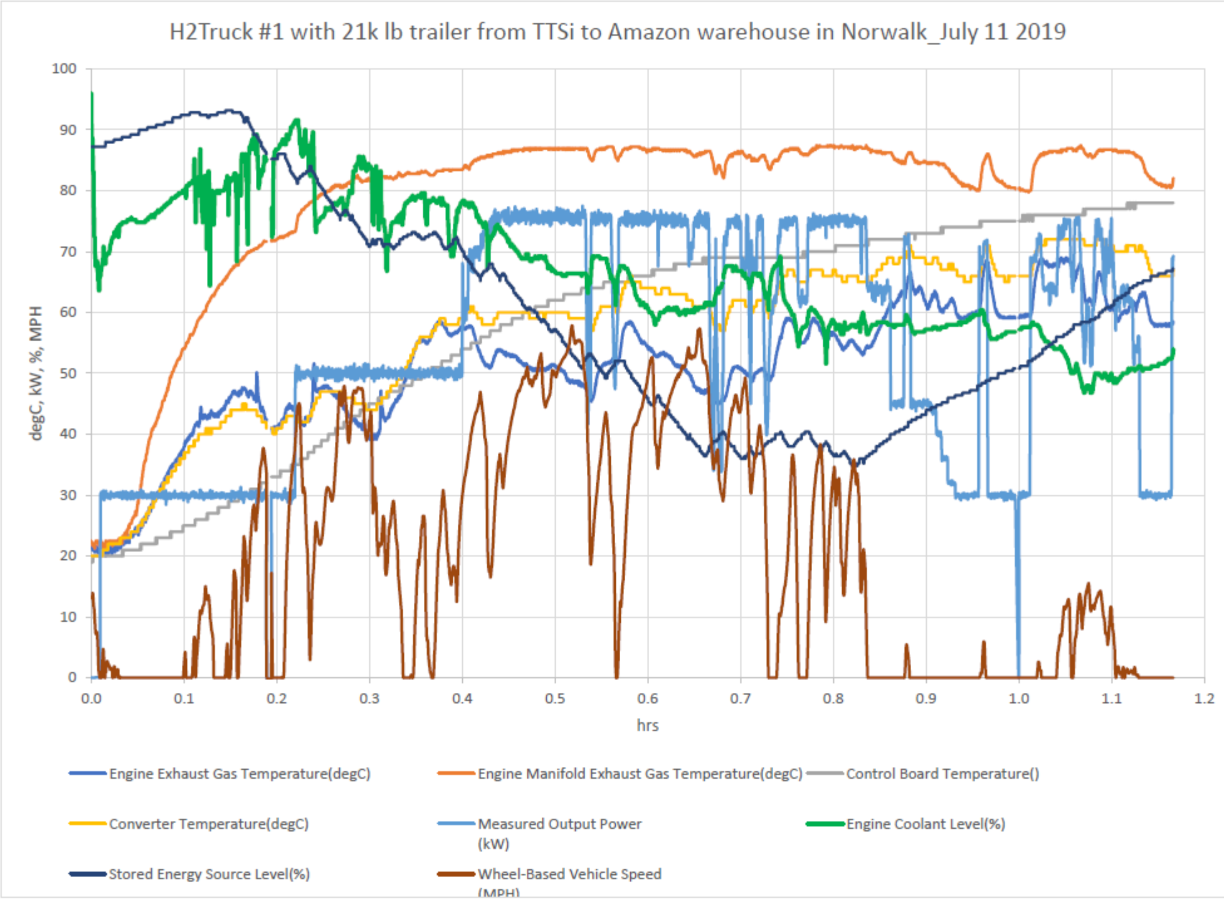
Q2-2019

US Hybrid completed the HV and LV wire harness integration, completed the battery integration (A123, NMC modules, with liquid cooling) in the vehicle, as well as completed the integration of power electronics (drive and auxiliaries) in the truck.

Once vehicle integration was completed, US Hybrid delivered Truck #2 to TTSI on May 29, 2019 and will continue operation support for both trucks.

Q3-2019

Truck #1 is currently still deployed for demonstration at TTSI facility. Please see Q3-2019 operation data for Truck #1 below:

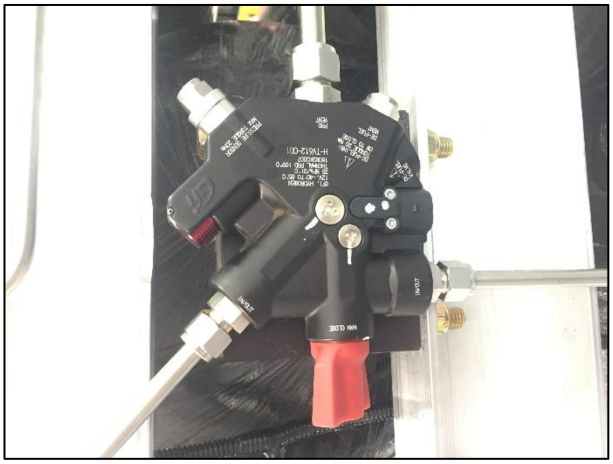


ZECT 2 H2Truck #1 Performance in Q3, 2019

H2Truck #1	Date	Operated Hours (hrs)	Average Power (kW)	Consumed Energy (kWHr)	Consumed H2 (kG)	Average SOC (%)	Average Speed (MPH)	Distance (miles)	kWHr/mi	kWHr/kg H2	H2 Fueling (kG) 23.5 kg Full
7/11/2019	Thu	2.9	36	107	6.8	77	12.5	37	2.9	15.7	9.1
8/13/2019	Tue	2.3	39	90	4.5	68	12	28	3.2	20.0	14.0
9/18/2019	Wed	5.2	21	109.2	7.9	80	8.6	44.72	2.4	13.8	10.1

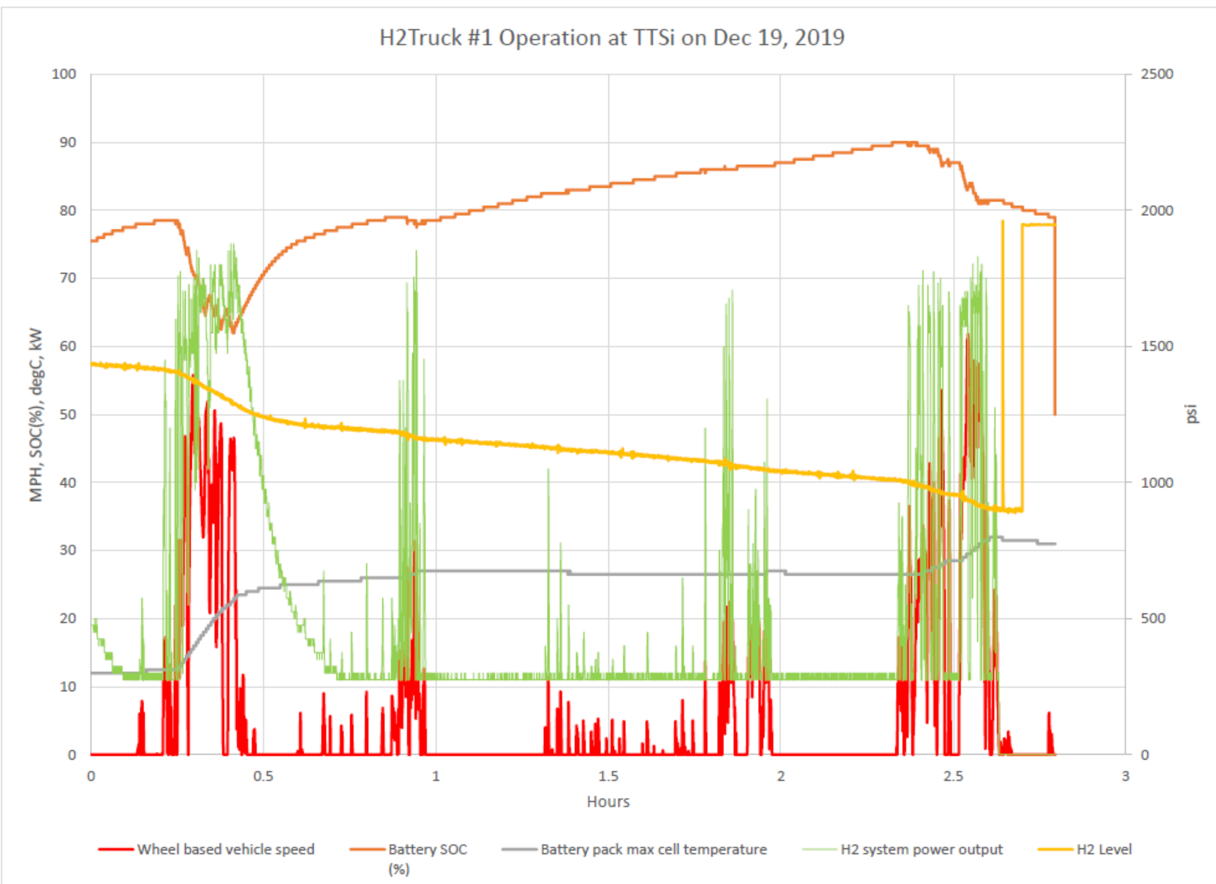
After being deployed in May 2019, Truck #2 experienced an issue with its hydrogen valves and had to return to our facility in Torrance. We are currently waiting for the GFI incoming shipment in order to repair the hydrogen valves and redeploy the vehicle.

The issue with the valves (pictured below) were that that needed replacement because they weren't responding to the "Open" command.



Q4-2019

Truck #1 is currently still deployed for demonstration at TTSI facility. Please see Q4-2019 operation data for Truck #1 below:

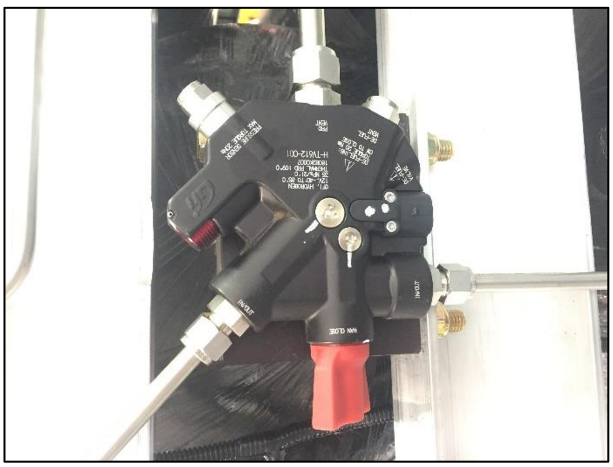


ZECT 2 H2Truck #1 Performance in Q4, 2019

H2Truck #1	Date	Operated Hours (hrs)	Average Power (kW)	Consumed Energy (kWHr)	Consumed H2 (kG)	Average SOC (%)	Average Speed (MPH)	Distance (miles)	kWHr/mi	kWHr/kg H2	H2 Fueling (kG) 23.5 kg Full
11/20/2019	Wed	1.6	13.9	22.2	1.6	85	7	11.2	2.0	13.9	0
12/17/2019	Tue	3.2	29.6	94.7	5.6	77	9.5	30.4	3.1	16.9	0
12/19/2019	Thr	2.8	19.5	54.6	2.5	81.0	5.8	16.2	3.4	21.8	4.9

After being deployed in May 2019, Truck #2 experienced an issue with its hydrogen valves and had to return to our facility in Torrance. For most of Q4 we were waiting for the GFI incoming shipment in order to repair the hydrogen valves and redeploy the vehicle.

The issue with the valves (pictured below) were that that needed replacement because they weren't responding to the "Open" command.



After a delay from the supplier, we finally received the valve shipment in Mid-December and began repairing the hydrogen valves in order to redeploy Truck #2.

Q1-2020

During the beginning of Q1 2020, Truck #2 was redeployed to TTSI in Mid-January. Unfortunately, due to seasonal downturn of activities, the vehicles were not being used. Due to the COVID-19 pandemic, TTSI suspended all Alternative Fuel Vehicle Programs until business returned to "somewhat normal". Please see statement below that was released by TTSI:

"Due to the result of the current business climate caused by COVID 19, we are suspending our Alternative Fuel Vehicle Program until business returns to "Somewhat" normal.

To reduce operating costs, we will be removing non-essential equipment from insurance which will include the AFVs and other TTSI Equipment. This is in effort to not have employee layoffs.

Once business returns to "Somewhat" normal, the equipment will be added back to insurance for operations. We are hoping this suspension will be for a very short period."

Because of this, US Hybrid will be waiting until business returns back to normal and will continue operation support and data collection on both vehicles.

Q2-2020

Because of the continuing COVID-19 pandemic, TTSI continued to suspend/limit all Alternative Fuel Vehicle Programs until business returned to "somewhat normal" as stated above. Truck #2 was last operated in March 2020. As business slowly begins to return back to normal, TTSI will gradually prepare to reintroduce AFV Programs back into rotation at the port. Additionally, we are currently waiting for the DMV, which has been extremely backed up due to the pandemic, to give us the registration to operate the vehicle again. We expect to receive the up to date registration by Mid-August 2020.

Q4-2020

FC Vehicle #2 was deployed on June 7, 2019. In order for Vehicle #2 to complete the 24-month field demonstration, it was suggested to extend the contract. US Hybrid submitted an official no cost contract extension on October 27, 2020 for a contract extension through 9/30/2021.

The reason for the contract extension is to allow the vehicles to complete their full demonstration period. During Q4-2019, seasonal downturn of activities at TTSI meant the vehicles received minimal usage. Unfortunately, this was followed by the COVID-19 pandemic, in which TTSI suspended all Alternate Fuel Vehicle Programs until business returned to "somewhat normal."

As business slowly begins to return to normal, US Hybrid is confident that we will be able to complete the demonstration period by the new revised deadline.

Currently, fuel cell vehicle #2 is fully operational at TTSI and is being used for the longer run drayage deliveries with major customers.

In summary:

Two fuel cell trucks were designed, developed, and deployed for demonstration at Port of Los Angles and Port of Long Beach by US Hybrid. TTSI operated the trucks at the ports. The drivers really liked the smooth tuck operation especially at low speed as they engage with the trailers and maneuver in the lot with virtually no operating noise. The feedback from the operators on the two Fuel Cell trucks were like that of the operators of the electric truck in how quiet the drive is. Despite its overall success, the project's two years of operation of the Fuel Cell trucks did teach us the following items that can be improved moving forward:

1) Battery capacity must be increased from 42 kWh to 84 kWh to balance the power equation Battery Power to Fuel Cell Power

2) Battery must be actively cooled. The high temperature of the battery limited the traction performance.

3) The Tanks H2 capacity didn't support a driving range that would allow the trucks to do two round trips to the warehouses East of the ports. In order to do this, tank capacity must be increased from 30 kg to 60 kg.