CALIFORNIA ENERGY COMMISSION

California Energy Commission

Clean Transportation Program

FINAL PROJECT REPORT

Mobile Hydrogen Refueler

Prepared for: California Energy Commission

Prepared by: Gas Technology Institute

Gavin Newsom, Governor

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This report and associated products are part of project activities under the California Energy Commission Grant ARV-14-003, titled "Mobile Hydrogen Refueler." The authors and project team appreciate the support and interest from the project manager and others at the California Energy Commission throughout this project.

PREFACE

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

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

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

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued Program Opportunity Notice (PON)-13-607 to fund hydrogen refueling infrastructure, including a competition for a mobile refueler. In response to PON-13-607, the recipient submitted an application that was proposed for funding in the CEC's notice of proposed awards on May 1, 2014, and the agreement was executed as ARV-14-003 on September 15, 2014.

ABSTRACT

This report and associated products are part of project activities under the California Energy Commission Grant ARV-14-003, titled "Mobile Hydrogen Refueler." This agreement was to design, build, test, and deploy a fully operational, commercial mobile hydrogen refueler using an onboard zero-emission fuel cell to power an onboard hydrogen compressor. This report describes the project team's work on the initial design of component integration and the installation of the integrated mobile refueler equipment in the vehicle platform. This report discusses interim analysis of industry fueling needs and summarizes the project team's activities through the conclusion of the project.

Keywords: Mobile hydrogen refueler, hydrogen fueling, hydrogen

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TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

EXECUTIVE SUMMARY

California has the most extensive fleet of fuel cell electric vehicles in the nation, supported by the nation's largest network of hydrogen refueling stations. Additional stations are under development to become available over the next few years because of California Energy Commission (CEC) Clean Transportation Program funding support. The CEC also funded a mobile hydrogen refueler as a temporary backup fueling solution. The mobile hydrogen refueler consists of equipment to store, compress, chill, and dispense hydrogen fuel into fuel cell electric vehicles (FCEVs). This equipment is integrated to fit into the trailer box of a truck that can be driven to different locations to provide fuel where needed.

The premise of CEC Grant Agreement ARV-14-003 was to build and operate a mobile hydrogen refueler that would support existing infrastructure to increase the resiliency of the refueling network. This report summarizes the initial design decisions, the interim analysis of industry fueling needs, and the effort to meet fueling standards that were beyond the scope of this project.

The initial phase of the project focused on system design and analysis tasks. The body of this report includes details on the vehicle and power system design. Throughout the project period, the team continued to have discussions on the permitting and industry needs for a mobile refueler with the CEC, the California Air Resources Board, the California Fuel Cell Partnership, the Governor's Office of Business and Economic Development, the Office of the State Fire Marshal, hydrogen refueling station operators, and vehicle manufacturers. The project team held several meetings to discuss the scope of the project and system capabilities of the refueler. Mid-project, the team determined that it would be necessary for the refueler to comply with the SAE International J2601:2014 fueling protocol for it to serve industry appropriately. SAE International J2601:2014 is a fueling standard that defines conditions, such as the required hydrogen pressure and temperature, for filling light-duty FCEVs. At that time, the team focused on securing the additional funding necessary to expand the project scope to comply with the advanced fueling protocol.

The project team investigated several opportunities to secure additional funding for the project. The project team held discussions with private companies with needs for mobile refueling solutions, and with state agencies that have mandates for acquiring and operating fuel cell electric vehicles. Furthermore, the project team contacted private station operators and constructed several design iterations and plans to develop a path forward that would satisfy all entities associated with the project and related end use. Unfortunately, the project team was not able to acquire the additional funds during the project period and, without the necessary funding to provide a viable system to the industry, the project concluded when it reached the term end date without constructing and deploying a mobile hydrogen refueler.

CHAPTER 1: Introduction

Problem Statement

California is working to address the effects of climate change by reducing greenhouse gas (GHG) emissions from multiple sectors of the economy. The transportation sector is one of the largest sources of GHG emissions, comprising 51 percent of all California's GHG emissions when accounting for the emissions from transportation fuel production and combustion in vehicles.[1] One method to reduce GHG emissions from transportation is to deploy zero-emission vehicles (ZEVs) in place of internal combustion engine vehicles. California is providing incentives to ZEV customers and investing in infrastructure to support ZEVs, which include battery-electric vehicles and fuel cell electric vehicles (FCEVs). California has the most extensive fleet of FCEVs in the nation, supported by the nation's largest network of hydrogen refueling stations. Additional stations are under development to become available over the next few years with California Energy Commission (CEC) Clean Transportation Program funding support. In Grant Agreement ARV-14-003 with the Gas Technology Institute (GTI), the CEC also funded a mobile hydrogen refueler. The mobile hydrogen refueler was to be a source of fuel on a temporary, backup basis. For example, the mobile refueler could be dispatched to a station if it had a temporary maintenance or fuel supply issue. The mobile refueler also could support ride-and-drive vehicle demonstrations throughout the state, which could increase consumer awareness about ZEV and the likelihood of consumer adoption.

Goals of the Agreement

This project sought to design, build, test, and deploy a fully operational, commercial mobile hydrogen refueler using an onboard, zero-emission fuel cell to power an onboard hydrogen compressor. The mobile refueler was to be based on a medium-duty truck platform and include communication and noncommunication refueling capabilities for hydrogen at 350 bar and 700 bar pressures through a metered fuel dispenser. The mobile refueler was to have the capability to refill either FCEV tanks or the hydrogen storage tanks of a station. FCEV refueling was to occur at existing hydrogen refueling stations, other designated locations, or vehicle demonstration events but was not intended to operate as a roadside service.

[1] Gee, Quentin, Stephanie Bailey, Jane Berner, Michael Comiter, Jim McKinney, and Tim Olson. 2021. *Draft 2020 Integrated Energy Policy Report Update*. California Energy Commission. Publication Number: CEC-100-2020-001-V1-CMD. Figure 1, page 14.

CHAPTER 2
System Design Approach

Work Plan Development

The project team sought to establish the design specifications of the mobile refueler onboard power system, which enables refueling equipment operation. Additional key requirements include the design of the power system, which provides the energy generation sizing and control as well as the vehicle packaging detail. Design and procurement efforts included:

- Designing the size, power, and load capacity requirements for the vehicle and all onboard power systems.
- Designing the vehicle and power control systems to meet the FCEV original equipment manufacturer (OEM) and end-user field operation requirements.
- Specifying and ordering major vehicle and power systems components including:
    - Vehicle.
    - Fuel cell.
    - Power converters.
    - Cooling system.
    - Auxiliary power system.
    - Electric-hydraulic drive system components.
    - Battery energy storage system.

The products from these efforts were:

- Onboard power systems design report.
- Vehicle and power control systems design report.
- List of vehicle and power systems components.

System Design

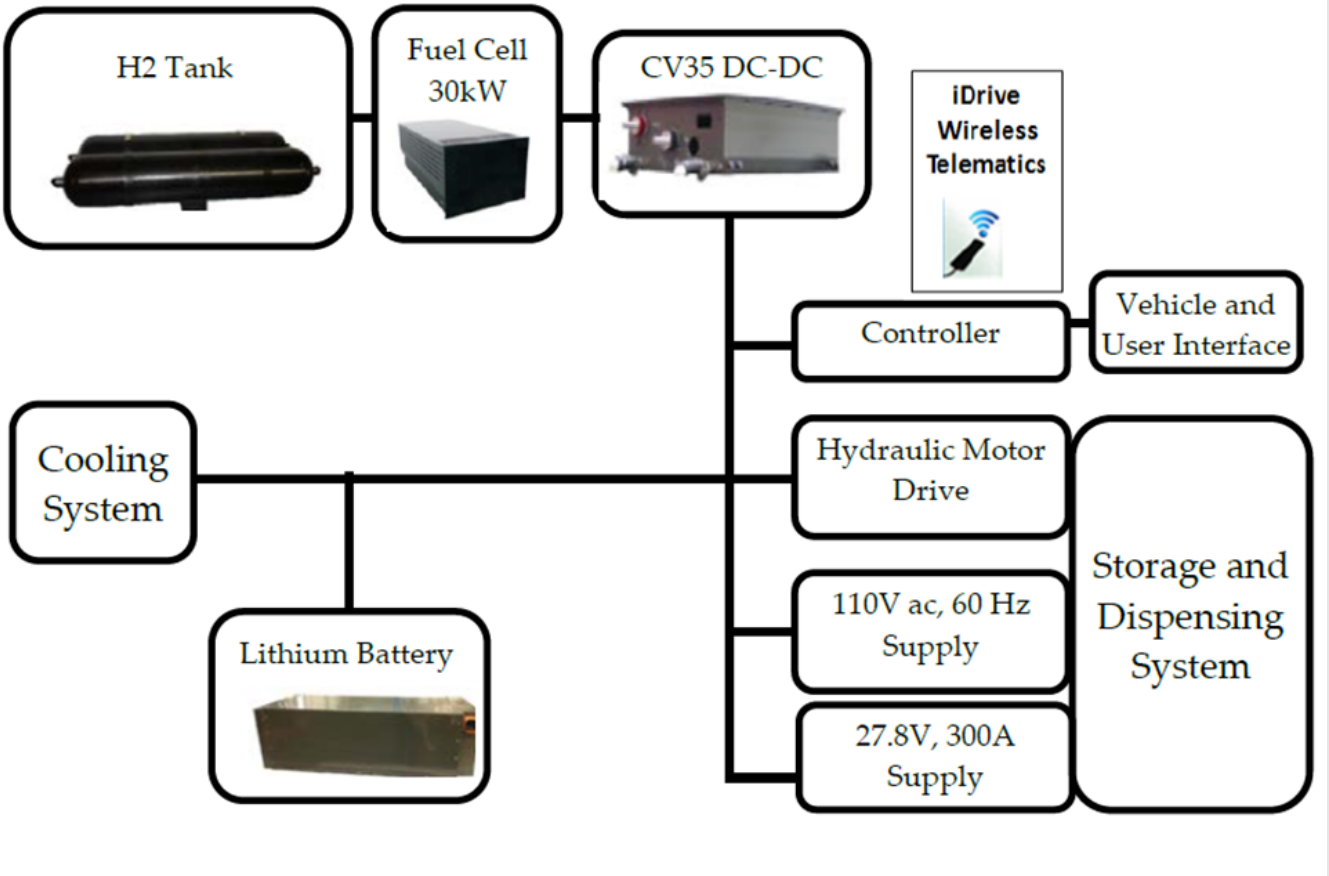
The mobile refueler onboard power system design specified an integrated 30-kilowatt (kW) fuel cell power plant to provide the power required by the mobile refueler during fueling. The onboard power system design allowed the unit to provide fueling with no external power source requirements or interconnection to the station.

The fuel cell-powered, integrated power system design provided the drive for the hydraulic compressor motor with 110 volts alternating current (VAC) at 60 hertz (Hz). It also supplied the 27.6 volts direct current (VDC) power required for hydrogen storage, as well as the dispensing and protection system. Moreover, the integrated power system design provided power to drive the hydrogen cooling system and other vehicle features, including exterior light-emitting diode (LED) lighting, with a 24-volt (V) supply.

The system design included integrating and self-powering the hydrogen cooling system. The design also included the means to disable vehicle operation via interlock during the mobile fueling mode. An ignition interlock device (IID) worked to interrupt the communication between the starter and ignition.

The design used an onboard lithium-ion battery to supply additional power to support operation while in transit and allow at least one fill during any fuel cell power plant shut down. Figure 1 is a simple schematic of how the on-board fuel cell power system was integrated with other components.

Figure 1: Onboard Fuel Cell Power System Diagram

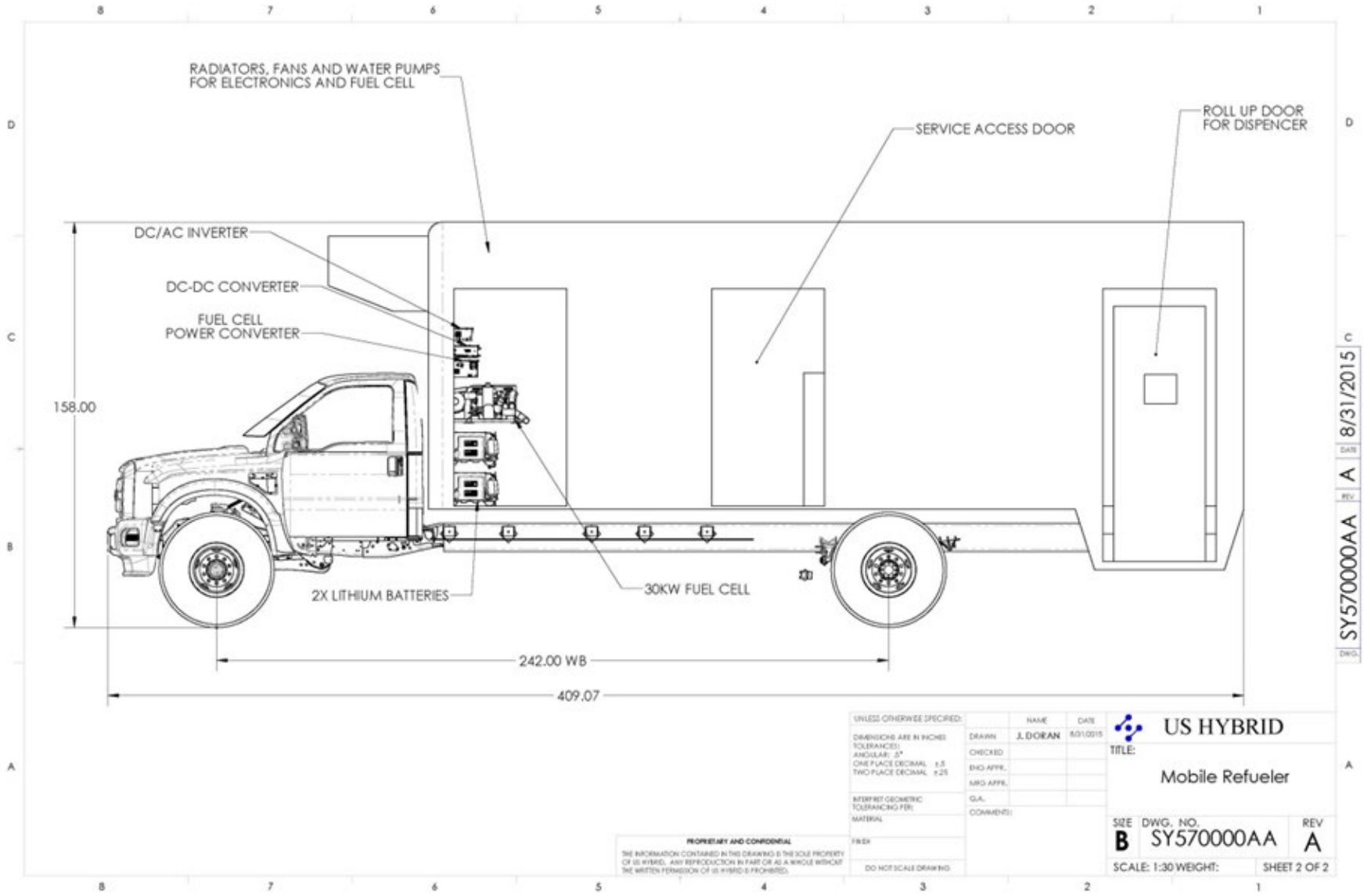


Source: Gas Technology Institute

The vehicle platform for the refueler was a Ford F-650 chassis with a custom box design to house the power system, hydrogen storage, fueling dispenser, and safety protection system. The project team built the custom box on a standard chassis to accommodate a long bed for the power system box integration. The project team modified the vehicle control system and driver interface to ensure that the vehicle would be immobilized during fueling and accommodate a driver interface capable of displaying fueling information and drive mode information.

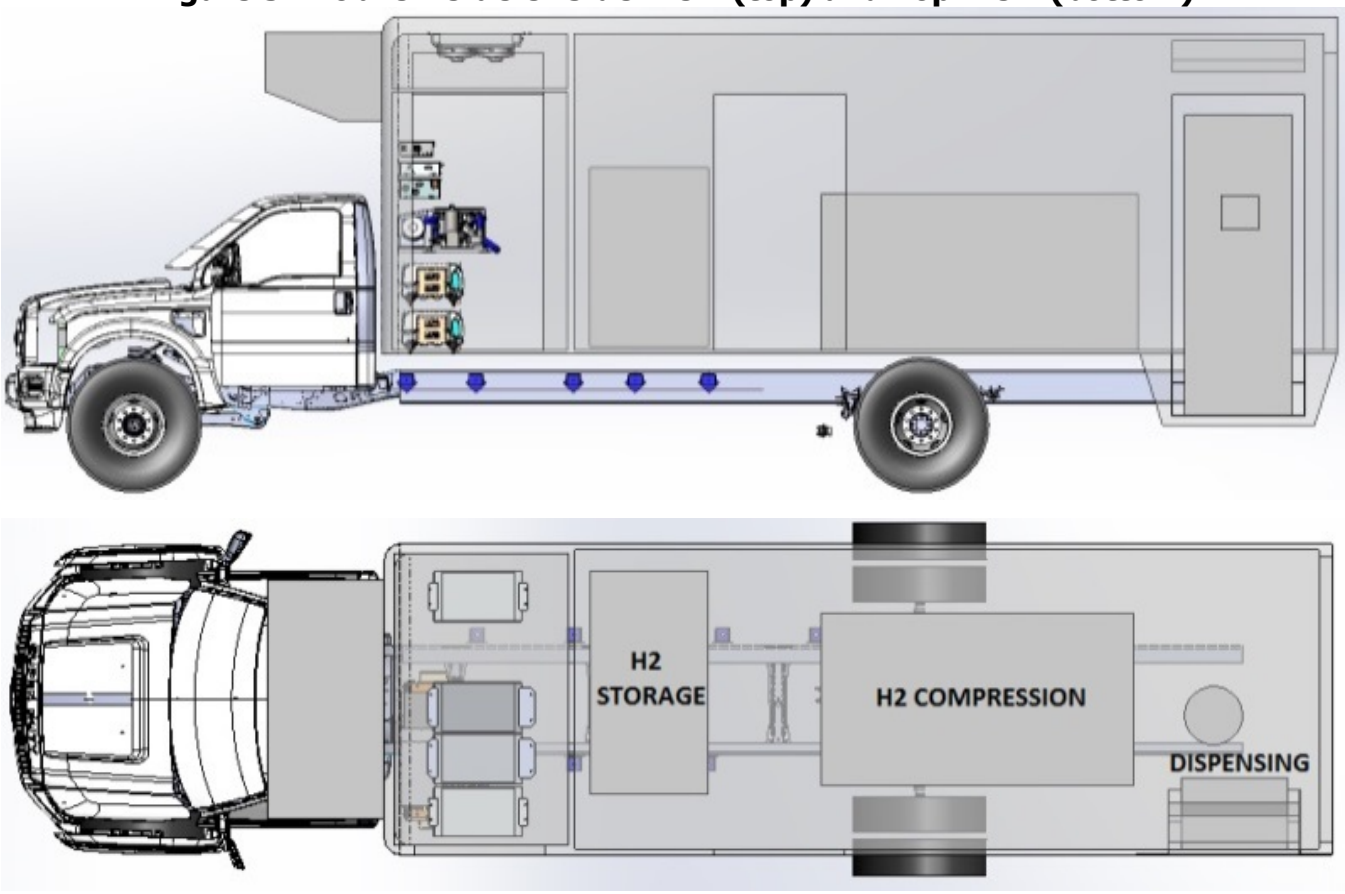
The following figures and table show the vehicle chassis and box configuration, as well as the vehicle specifications. The team designed the custom box to meet the relevant safety codes and standards and package the power system, storage, and dispensing (including the precooling unit and compressor) equipment properly.

Figure 2: Mobile Refueler Vehicle Layout



Source: Gas Technology Institute

Figure 3: Mobile Refueler Side View (top) and Top View (bottom)



Source: Gas Technology Institute

Table 1: Mobile Refueler Vehicle Specifications

Category	**Specification**
Fuel Capacity	50 gallons
Drive Type	4x2 Dual Rear Wheel
Engine	Ford 6.8L V10 engine
Horsepower (HP) and Torque	320 HP, 460 pound-feet (lb.-ft)
Transmission	Ford TorqShift® HD 6-Speed Automatic
Wheelbase	158”-242” F-650 Gas & Diesel, Kick-up Frame, Regular Cab
Maximum Gross Vehicle Weight Rating	26,000 pounds, F-650 Pro Loader

Source: Gas Technology Institute

US Hybrid performed axle-loading analysis to ensure that the vehicle loading distribution met the manufacturer axle-loading requirement. The following figure is the analysis report.

Figure 4: Axle-Loading Analysis Report

Item	Component	Weight (Wi) lbs
1	Chassis Front F650 Gas	5,538
2	Chassis Rear	4,303
3	24' Box	3,500
4	24V/12V Battery	40
5	LV Wiring	50
6	Tanks + Racks	2,000
7	Compressor	3,800
8	Dispensor	300
9	Chiller	1,121
10	Heat Exchanger	200
11	HV Wiring/HVDU	100
12	Water Cooler	150
13	N2 Bottles	450
14	HD30	165
15	FC Cooling	75
16	Electronics	175
17	Electronics Cooling	45
18	HV Battery	400
	Total Lbs.	22,412
	Limit Lbs.	26,000
	Margin	3,588

9,841

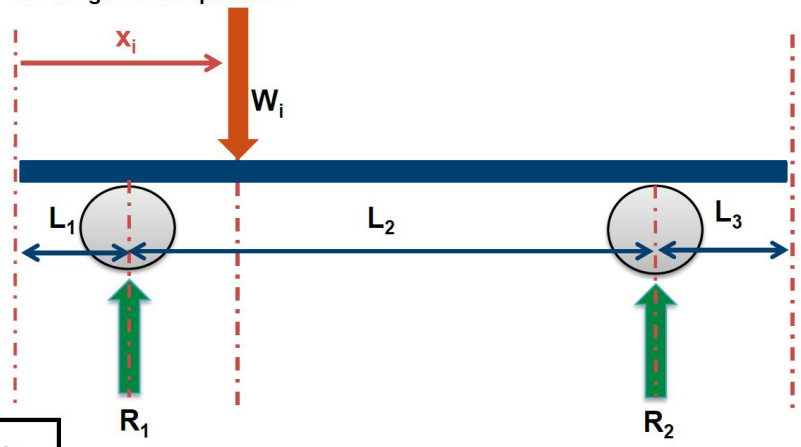
L1=	39.4 in
(Wheelbase) L2=	242 in
L3=	72 in
L(total)=	353.4 in
Front of Box	115.62 in

US Hybrid

Weight Distribution
By Jarod Doran
Last updated on 8/28/2015

Xi: distance from front of chassis to the C.G. of component i

Wi: weight of component i



		Limit:	Available
R1=	8,019.67 lb	10,000 lbs	1,980.33 lbs
R2=	14,392.33 lb	19,000 lbs	4,607.67 lbs
Body + Payload=	12,571 lb	16,159 lbs	3,588 lbs
Payload=	9,071 lb		

Source: US Hybrid

CHAPTER 3:
Project Approach

While designing the mobile refueler, ordering the vehicle and components, and integrating those components, the project team took steps to prepare for the deployment of the mobile refueler in the field and ensure its success. These steps included having meetings with relevant stakeholders to plan for the permitting process and determine where the project should deploy the mobile refueler once fully assembled. For the permitting discussions, the Gas Technology Institute worked with the Governor's Office of Business and Economic Development to assist with outreach to state and local officials in authorities having jurisdiction to support the deployment. There were several project meetings to discuss the appropriate path forward and set up additional contacts at the state level. The project team met with the California Fuel Cell Partnership (CaFCP) and the Office of the State Fire Marshal to discuss permitting and plans for allowing the refueler to operate at several locations across the state. The project team also shared details with experts at the Orange County Fire Authority, who had supported installation of several hydrogen refueling stations in the past and had experience permitting similar projects.

Throughout the project period, the team also had open discussions about industry needs for the mobile refueler with the CEC, the California Air Resources Board (CARB), CaFCP, hydrogen refueling station operators, and the FCEV OEMs. Furthermore, the team participated in CaFCP Working Group meetings. The project team presented to the working group in March 2015 on the attributes of the mobile refueler and discussed potential usage scenarios with key stakeholders in the industry. This venue allowed the team to interact with several potential users to discuss best practices for deployment and utilization.

Discussions with stakeholders highlighted several challenges for the mobile refueler as designed. Challenging areas included fueling protocols (including fill rate, temperature of fills, and noncommunication fills), permitting at sites, and contractual arrangements. Station owners and vehicle OEMs endorsed requiring the mobile refueler to meet the SAE J2601:2014 fueling protocol, which was outside the scope of work for the project. Some stations also had limited space or site layouts unconducive to temporarily hosting the mobile refueler. There were additional concerns about the length of time it would take the station owners to enter into contract to acquire hydrogen from the mobile refueler.

With the information the project team obtained from these discussions, the project team and CEC staff held a "critical project review" meeting March 30, 2016, to discuss the project path and system design. The parties determined that it would be necessary for the refueler to be able to comply with the SAE International J2601:2014 fueling protocol for it to serve the industry appropriately. At that time, the team focused on securing additional funding necessary to comply with the advanced fueling protocol. The project team investigated several opportunities to secure funding for the project. This investigation included discussions with private companies that have needs for mobile fueling solutions (such as AAA), and with state agencies (such as the California Department of Transportation, known as Caltrans) that have mandates for acquiring and operating zero-emission vehicles.

Moreover, the project team contacted private station operators and constructed several design iterations and plans to develop a path forward that would satisfy all the entities associated with the project and related end use. The project team also searched for new team members that would provide additional match funding to enable completing the system within the term of the project agreement. The most promising plan was for OneH2 to become a project team member that would support building the final system. The team pursued a plan to collaborate with the California Department of Transportation (Caltrans) to deploy the refueler at several sites where fleets of Caltrans FCEVs would be in service. Caltrans also was exploring ways to contribute funding to the project to support the additional equipment and design necessary for compliance with SAE International J2601:2014. Unfortunately, even with significant efforts undertaken by all entities involved, the project team was not able to acquire additional funds during the project period. As there was no interest in producing a system that would not meet industry needs, and in the interest of protecting public funds, the CEC and project team decided to conclude the project.

CHAPTER 4: Conclusions

The goal of CEC Grant ARV-14-003 was to build and operate a mobile hydrogen refueler to provide temporary fueling services on a backup basis at various locations throughout the state. This report summarizes the initial design decisions, the components of the design, and the strategy for integrating these components to deliver a mobile refueling solution that would be the first of its kind in California.

This report includes descriptions and graphics for the system design and analysis tasks that composed the initial phase of this project. Throughout the project period, the team conducted stakeholder outreach to prepare for mobile refueler deployment. The project team had open discussions on the industry needs for a mobile refueler with the CEC, CARB, CaFCP, station operators, and FCEV OEMs. In several meetings, these stakeholders discussed the scope of the project and the system capabilities of the refueler. These meetings revealed that the technical capabilities of the mobile refueler were no longer sufficient for the intended users, and that it was necessary to expand the scope of the project to make it successful. Despite best efforts, the project team did not find a clear path forward to meet the higher fueling standards, and the CEC and project team decided to conclude the project.

The project team still believes that trying to deliver the project to meet the fueling standards was the right thing to do, but it led to insurmountable issues with scope and budget. With the benefit of hindsight, the following recommendations may be useful for pursuing similar projects in the future. This project may have benefited from having an "anchor" end-user (a single fueling customer with a single set of requirements), which could have helped focus and validate the scope of work from its inception. Similarly, the gathering of additional feedback from end users and key stakeholders such as vehicle OEMs in initial stages could have reduced the likelihood of unexpected requirement changes during the project. Even with these recommendations implemented, the issues encountered in this project still may have been unavoidable because the project coincided with significant industry change. During such periods of change, it is very difficult to predict where industry will go and what new requirements will surface, even with established partnerships and comprehensive, regular stakeholder outreach.

GLOSSARY

ALTERNATING CURRENT (AC)—Flow of electricity that constantly changes direction between positive and negative sides. Almost all power produced by electric utilities in the United States moves in current that shifts direction at a rate of 60 times per second.

ASSEMBLY BILL (AB)—A proposed law, introduced during a session for consideration by the Legislature, and identified numerically in order of presentation; also, a reference that may include joint, concurrent resolutions, and constitutional amendments, by Assembly, the house of the California Legislature consisting of 80 members, elected from districts determined on the basis of population. Two Assembly districts are situated within each Senate district.

AUTHORITY HAVING JURISDICTION (AHJ)—An organization, office, or individual responsible for enforcing the requirements of a code or standard, or for approving equipment, materials, an installation, or a procedure.

CALIFORNIA AIR RESOURCES BOARD (CARB or ARB)—The "clean air agency" in the government of California, whose main goals include attaining and maintaining healthy air quality; protecting the public from exposure to toxic air contaminants; and providing innovative approaches for complying with air pollution rules and regulations.

CALIFORNIA DEPARTMENT OF TRANSPORTATION (Caltrans)—Responsible for the design, construction, maintenance, and operation of the California State Highway System, as well as that portion of the Interstate Highway System within the state's boundaries.

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

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

Funding for the Commission's activities comes from the Energy Resources Program Account, Federal Petroleum Violation Escrow Account, and other sources.

CALIFORNIA FUEL CELL PARTNERSHIP (CaFCP)—The California Fuel Cell Partnership is an industry/government collaboration aimed at expanding the market for fuel cell electric vehicles powered by hydrogen to help create a cleaner, more energy-diverse future with no-compromises to zero emission vehicles.

CLEAN TRANSPORTATION PROGRAM—Formerly known as the Alternative and Renewable Fuel and Vehicle Technology Program, created by Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007), the program with an annual budget of about $100 million supports projects that develop and improve alternative and renewable low-carbon fuels, improve alternative and

renewable fuels for existing and developing engine technologies, expand transit and transportation infrastructures, and establishing workforce training programs, conduct public education and promotion, and create technology centers, among other tasks.

DIRECT CURRENT (DC)—Electricity that flows continuously in the same direction.

ELECTRIC VEHICLES (EV)—A broad category that includes all vehicles that are fully powered by electricity or an electric motor.

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

FUEL CELL ELECTRIC VEHICLE (FCEV)—A zero-emission vehicle that runs on compressed hydrogen fed into a fuel cell "stack" that produces electricity to power the vehicle.

GOVERNOR'S OFFICE OF BUSINESS AND ECONOMIC DEVELOPMENT (GO-Biz)—The Governor's Office of Business and Economic Development (GO-Biz) serves as the State of California's leader for job growth and economic development efforts. They offer a range of services to business owners including: attraction, retention and expansion services, site selection, permit assistance, regulatory guidance, small business assistance, international trade development, and assistance with state government.

HORSEPOWER (HP)—A unit for measuring the rate of doing work. One horsepower equals about three-fourths of a kilowatt (745.7 watts).

HYDROGEN (H_2)—A colorless, odorless, highly flammable gas, the chemical element of atomic number 1.

KILOGRAM (kg)—The base unit of mass in the International System of Units that is equal to the mass of a prototype agreed upon by international convention and that is nearly equal to the mass of 1000 cubic centimeters of water at the temperature of its maximum density.

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

LIGHT-EMITTING DIODE (LED)—A semiconductor diode that emits light when a voltage is applied to it and that is used in a variety of applications including commercial, residential and traffic signal lighting.

ORIGINAL EQUIPMENT MANUFACTURER (OEM)—refers to the manufacturers of complete vehicles or heavy-duty engines, as contrasted with remanufacturers, converters, retrofitters, up-fitters, and re-powering or rebuilding contractors who are overhauling engines, adapting or converting vehicles or engines obtained from the OEMs, or exchanging or rebuilding engines in existing vehicles.

TORQUE—The amount of turning force applied to move one pound a distance of one foot. The unit of measure is pound-foot (lb.-ft).

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

ZERO EMISSION (ZE)—An engine, motor, process, or other energy source, that emits no waste products that pollute the environment or disrupt the climate.

ZERO-EMISSION VEHICLE (ZEV)—Vehicles that produce no emissions from the on-board source of power (e.g., an electric vehicle).