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Clean Transportation Program

FINAL PROJECT REPORT

Heavy-Duty Electric Refuse Truck

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Stephanie Ly
Frank Falcone
Primary Authors

Transportation Power, LLC
2415 Auto Park Way
Escondido, CA 92029

Agreement Number: ARV-14-051

Marc Perry
Commission Agreement Manager

Elizabeth John
Branch Manager
MEDIUM AND HEAVY-DUTY ZERO-EMISSION TECHNOLOGIES BRANCH

Hannon Rasool
Director
FUELS AND TRANSPORTATION DIVISION

Drew Bohan
Executive Director

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PREFACE

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

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

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

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-14-605 to fund projects that develop advanced vehicle technology manufacturing facilities in California that produce zero-, near zero-emission, or zero-emission vehicle components. In response to PON-14-605, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards dated February 25, 2015, and the agreement was executed as ARV-14-051 on May 20, 2015.

ABSTRACT

The Heavy-Duty Electric Refuse Truck (HDERT) project was funded by the California Energy Commission to demonstrate the feasibility of utilizing battery-electric systems in Class 8 refuse and waste operations. Refuse trucks are conventionally fueled by diesel, with some natural gas adoption. Since refuse trucks typically operate in or near residential areas on a regular basis, tailpipe emissions can negatively affect residents. Battery-electric systems offer a zero-emissions solution to the refuse truck segment, which typically operate in ranges up to 150 miles.

The HDERT project successfully designed and built three battery-electric refuse trucks using the TransPower electric powertrain in a Peterbilt 520 chassis and with refuse bodies from Amrep Manufacturing Company, LLC, and Labrie Environmental Group, Inc. This was the first electric refuse truck built by TransPower and PACCAR, Inc. using the Peterbilt 520 conventional platform. Sacramento County Department of Waste Management and Recycling and Waste Management Collection and Recycling, Inc. in El Cajon, California demonstrated the electric refuse trucks in real-world conditions with typical refuse duty cycles, driving a total of about 5,470 electric-only miles, preventing about 2,485 diesel gallon equivalents of fuel from being used, and preventing almost 28 tons of carbon dioxide emissions from being released into the atmosphere. Additionally, fleet operators and manufacturers learned many important lessons on how to improve the electric refuse trucks.

Keywords: TransPower, Meritor, electric refuse truck, electric truck, battery-electric, refuse, waste collection, zero-emissions, heavy-duty, Peterbilt, Labrie, Amrep, clean vehicle, clean transportation, electrification

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EXECUTIVE SUMMARY

The United States refuse truck industry operates over 100,000 Class 8 trucks, with 90 percent of them using diesel fuel and about 10 percent using natural gas alternatives. A battery-electric refuse truck emits zero tailpipe emissions and helps manufacturers meet upcoming state regulatory sales requirements. Transportation Power, LLC (TransPower) is an electric powertrain supplier based in Escondido, California, that created a proprietary battery-electric powertrain design named the ElecTruck™ motive drive system and aimed to adapt a similar, modular electric system used in previous drayage truck and yard tractor applications into refuse trucks.

The California Energy Commission awarded TransPower nearly $2.9 million to convert three Peterbilt trucks into fully-operational, battery-electric waste collection trucks that would lead to future commercial developments. To demonstrate the trucks in real-world conditions, TransPower brought in two waste collection organizations as project partners to implement its Heavy Duty Electric Refuse Truck project: Waste Management Collection and Recycling, Inc. (Waste Management) and Sacramento County Department of Waste Management and Recycling (Sacramento County). Waste Management planned to demonstrate one truck at its San Diego facility and Sacramento County intended to demonstrate two refuse trucks.

The ElecTruck™ powertrain was integrated into three Peterbilt 520 chassis. The first truck used a Labrie Environmental Group, Inc. refuse body, while the other two trucks each used a refuse body from Amrep Manufacturing Company, LLC. TransPower adapted subcomponents to the refuse truck configuration with special consideration taken for battery pack placement and refuse side-loading arm functionality. These steps included engineering planning, design studies, securing materials, integrating trucks, and commissioning the finished trucks. All three trucks were built and commissioned at TransPower's facility in Escondido.

Over the course of the demonstration, the three trucks combined had traveled more than 5,400 miles, preventing 2,485 diesel gallon equivalents of fuel from being used, which resulted in saving almost 28 tons of carbon dioxide from tailpipe emissions, about 0.10 tons of oxides of nitrogen, and 0.001 tons of all particulate matter smaller than 10 microns in diameter.

The project partners learned many lessons over the course of the project, such as reducing vehicle roll back on grades, improving regenerative braking, and the need to engage suppliers early in the project to get risk mitigation plans in place at the start. These and other lessons will ultimately help TransPower and Peterbilt go into volume production with the Peterbilt 520EV.

CHAPTER 1: Introduction

TransPower Background

Transportation Power, LLC (TransPower) was founded in 2010 to manufacture drivetrain components for zero-emission medium- and heavy-duty vehicles.[1] In January 2020, Meritor, Inc. acquired TransPower, and TransPower began operating as a subsidiary in support of the brand Meritor Electric Vehicles, LLC, and continued to be based in Escondido, California.

TransPower has converted from diesel to battery-electric power some of the largest road vehicles and yard tractors, with gross combined weights of up to 150,000 pounds, and hauled its first revenue load out of the Port of Los Angeles in 2013. TransPower products remain a competitive solution that is still being applied to medium- and heavy-duty applications today.

TransPower's California-based demonstration vehicles, powered with the proprietary ElecTruck™ drive systems and components, deployed some of the first heavy-duty battery-electric vehicle applications such as:

- High voltage battery packs suitable for medium- and heavy-duty trucks
- A 320 kilowatt (kW) electric Motive Drive System (MDS), which includes a powertrain controller that shifts and synchronizes the motor-transmission so that the manual transmission acts like an automatic transmission.
- An integrated Power Control and Accessory System (PCAS) to operate pneumatic and hydraulic accessories, such as air brakes and power steering.

From 2012 to 2016, with funding from the California Energy Commission (CEC) and South Coast Air Quality Management District, TransPower tested seven battery-electric drayage trucks under the Electric Drayage Demonstration (EDD) program, which accumulated over 51,000 miles. The EDD project led to more advanced drayage trucks in partnership with Peterbilt Motors Company (Peterbilt), a subsidiary of PACCAR, Inc., which supplied the engine- and transmission-less glider trucks for this Heavy-Duty Electric Refuse Truck (HDERT) project.

In addition to having high-profile vehicles like Peterbilt, HDERT project partner Waste Management Collection and Recycling, Inc. (Waste Management) is one of the largest private refuse fleet operators in the U.S., holding about 30 percent of the market share on its own, and is also a leader in alternative fuels with over 6,000 heavy-duty natural gas trucks and more than 250 transfer stations and landfills, whereas municipal refuse and waste departments, like project partner Sacramento County Department of Waste Management and Recycling (Sacramento County), comprise only about 27 percent of the U.S. market share.[2]

CEC funding and partnership played a central role in previous projects, and TransPower used the developments and lessons learned from prior design, build, integration, and demonstration data to engineer the HDERT project. TransPower applied improvements in the ElecTruck™ design and real-world lessons to the three refuse trucks used for this project.

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[1] Vehicle Weight Classes (https://afdc.energy.gov/data/10380)

[2] Tiseo, Ian. 2018. "Market share of landfill volume in U.S." Statista. (https://www.statista.com/statistics/1098982/us-market-share-of-landfill-volume-by-company)

The Refuse Truck Industry

According to the American Trucking Association, there are nearly 4.0 million Class 8 trucks operating in the United States (U.S.).[3] And per the periodical *Business Wire*, there is an estimated total of 100,000 to 136,000 waste-hauling trucks operating in the U.S., with around 40,000 to 50,000 units sold each year.[4] About 90 percent of the refuse trucks in operation today use diesel fuel, and the remainder use natural gas.[5] Moreover, 14 percent of refuse trucks in operation are used and refurbished, which extends their typical engine retirement and results in older and higher-polluting trucks on the road.

Refuse trucks have duty cycle requirements that are typically within 100 to 150 miles of daily range and have high power requirements due to the use of accessories like automated arms, loaders, and forks. Diesel-powered refuse trucks have one of the lowest fuel efficiencies at less than three miles per gallon and are high polluting, which negatively affects residential neighborhoods where they are operated.[6]

Natural gas refuse trucks are significantly cleaner than diesel in terms of tailpipe emissions but remain primarily a fossil fuel source that still produces oxides of nitrogen (NOx) and greenhouse gases (GHG) such as carbon dioxide (CO_2) and methane (CH_4). While renewable natural gas provides an ultra-clean or lower-carbon alternative from feedstock such as organic waste, it has limited infrastructure and supply. As the electric grid moves towards renewable zero-emission energy sources, the potential of electricity as a fuel may offer the cleanest carbon footprint matched with zero tailpipe emissions in a segment that is primarily powered by diesel fuel.[7]

The refuse truck industry is unique in its estimated 10 percent adoption of alternative fuels like natural gas. This scale of adoption is rarely observed in other Class 6 to Class 8 vehicle sectors, with many relying on diesel fuel. Under the recently passed California Advanced Clean Truck Regulation, however, the California Air Resources Board (CARB) mandates that manufacturers increase percentages of zero-emission Class 2b to Class 8 trucks from 9 percent to 50 percent to 75 percent for the years 2024, 2030, and 2035, respectively.[8] Refuse trucks must meet the target by 2040. This mandate specifies that refuse truck manufacturers must meet zero-emission requirements by selling either battery-electric or hydrogen fuel cell trucks ahead of the required deadlines.

There are about 23 manufacturers of waste collection trucks in North America. Original equipment manufacturer (OEM) and HDERT project partner Peterbilt represents one of the largest manufacturers of Class 8 refuse trucks, while project partners Labrie Environmental

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[3] American Trucking Association (https://trucking.org/)
[4] The North American Refuse Truck/Body Manufacturing Market 2018 to 2022 (https://www.businesswire.com/news/home/20180801005744/en/The-North-American-Refuse-TruckBody-Manufacturing-Market-2018-to-2022---Market-Sizing-Key-Segmentation-Demand-Factors-Trends-and-Outlook---ResearchAndMarkets.com)
[5] Natural Gas Vehicle America website (https://www.ngvamerica.org/vehicles/refuse)
[6] Shea, Shannon. 2011. *Clean Cities Niche Market Overview: Refuse Haulers*. United States Department of Energy. DOE/GO-102011 (https://afdc.energy.gov/files/pdfs/51588.pdf)
[7] United States Environmental Protection Agency. 2021. "About the U.S. Electricity System and its Impact on the Environment." (https://www.epa.gov/energy/about-us-electricity-system-and-its-impact-environment)
[8] California Air Resources Board. 2020. "Advanced Clean Trucks." (https://ww2.arb.ca.gov/our-work/programs/advanced-clean-trucks)

Group, Inc. (Labrie) and Amrep Manufacturing Company, LLC (Amrep) are also major refuse body suppliers.

Overhauling and mandating zero-emissions sales and purchases in the refuse sector will require advanced technologies and matching fueling infrastructure. During the initial award of HDERT in 2015, battery-electric refuse trucks were nascent technologies. By 2018, the first vehicle demonstrations were underway at other major refuse OEMs, such as Mack Trucks and Volvo Trucks North America.[9] By late 2020, most major OEMs had made commitments to produce zero-emission refuse trucks, with most announcements focused on battery-electric technology.[10] Similarly, in late 2020, municipalities like Los Angeles and New York City have committed to a 100 percent electric refuse fleet by 2035 and 2040, respectively.[11]

Grant Project Overview

Electrification of refuse trucks represents a segment ideally fit for battery-electric power, with a home base for charging infrastructure, limited mileage range, lots of stop/start regenerative braking opportunities, and beachhead adoption of powertrain technology. TransPower's experience in drayage trucks, school buses, and yard tractors could be applied to the refuse sector, as shown in Figure 1. The HDERT project included plans to build three refuse trucks similar to with two refuse trucks designated for Sacramento County and one refuse truck to Waste Management.

Figure 1: Peterbilt 520EV

Credit: TransPower

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[9] Cole, Craig. 2020. *Electric power is the future, even for garbage trucks.* (https://www.cnet.com/roadshow/news/emack-lr-electric-garbage-truck)

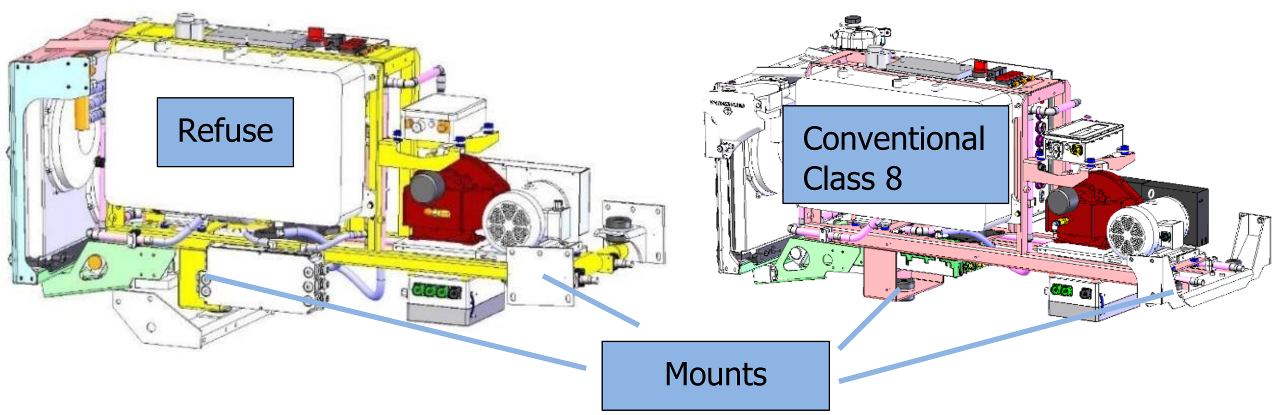
[10] Neil, Dan. 2020. *Electric trash trucks are coming quietly to your town*. Wall Street Journal. (https://www.wsj.com/articles/electric-trash-trucks-are-coming-quietly-to-your-town-11602098620#:~:text=Electric%20trash%20truck%20love%20is%20in%20the%20air.&text=A's%20program%20to%20reduce%20carbon,being%20primarily%20electric%20by%202023.)

[11] Waste 360. 2020. *LA Sanitation commits to 100% electric refuse truck*. (https://www.waste360.com/trucks/la-sanitation-commits-100-electric-refuse-truck-fleet)

CHAPTER 2: Electric Refuse Truck Build

The electrification of the refuse truck initiated a series of new development programs. It required the integration of the TransPower Motive Drive System (MDS), Power Control and Accessory System (PCAS) and Energy Storage System (ESS) into the Peterbilt 520 Chassis with the added refuse handling and storage assemblies. It also required a new electrical design to integrate the ancillary drive and the TransPower motive drive systems into the Peterbilt truck. The unavailability of adequate design detail that shows the electrical schematic for the CNG-fueled conventional drivetrain and its power take-off design made this task unexpectedly challenging. TransPower had to design and integrate an electrical Power Take Off (ePTO) for the waste collection hydraulic system that differed dramatically from a standard TransPower PCAS for an electric Class 8 truck (Figure 2).

Figure 2: Refuse PCAS vs. Class 8 PCAS



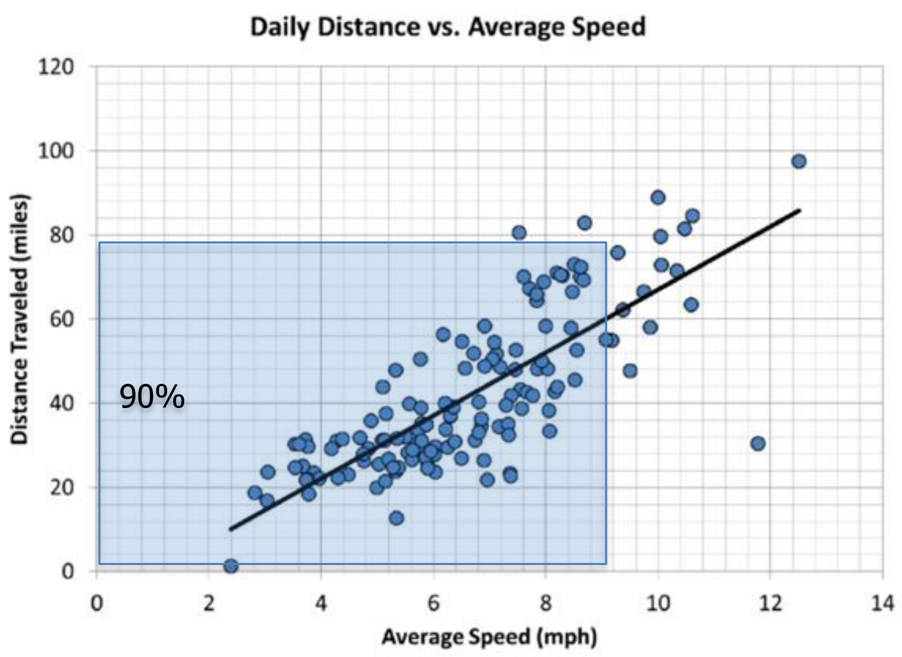
Left, PCAS modified for the refuse chassis with the PTO inverter added and mounts moved to line up with the refuse frame, right is typical class 8 PCAS.

Credit: TransPower

Engineering Design Planning

Using operating data from the fleet operators, research data such as that in Figure 3 from the National Renewable Energy Laboratory, and its own proprietary vehicle performance simulator, TransPower contrasted the distances and speeds against ESS capacity options to find a point that encompassed the best range within the physical design constraints. For example, at an average speed of 10 miles per hour, 79 miles of range can meet the needs of over 90 percent of urban waste routes operating on daily routes of less than 100 miles. Engineers paid particular attention to the trash collection and compaction cycle, which consumes significant energy. TransPower estimated the energy consumption to be about 3.75 kilowatt-hours (kWh) per mile, which equates to about 300 usable kWh of energy. Assuming that 90 percent of the battery can be utilized to meet the required completion of 90 percent of the routes, the total energy storage amount would need to be 330 kWh or more.

Figure 3: Data Points Representing Distances Traveled Versus Average Speed.



Credit: National Renewable Energy Laboratory [12]

Computer Aided Design Studies

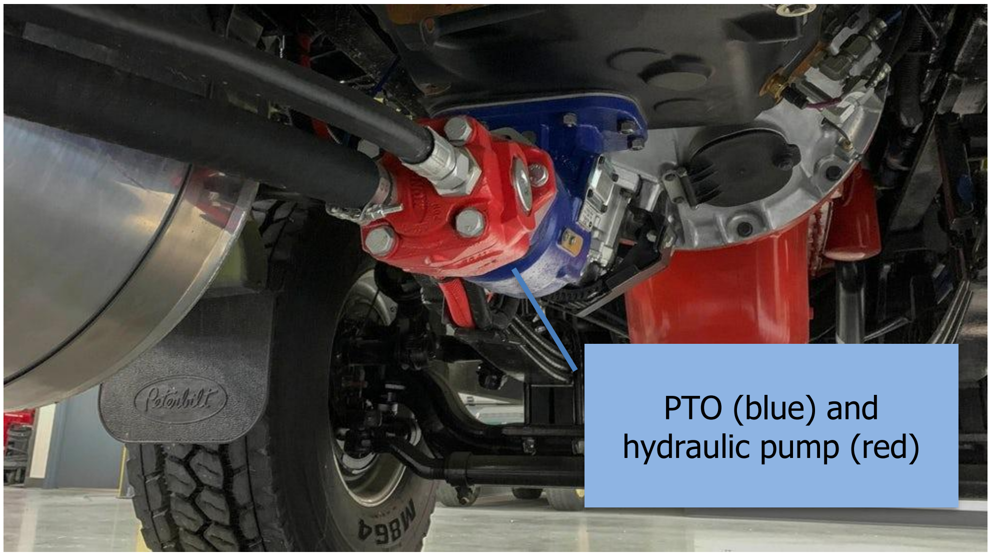
TransPower used computer aided design to model the Peterbilt 520 with the Labrie truck body and side loader system, adding in the batteries and the hydraulic power drive system. After comparing alternatives offered by Peterbilt and supplier Rush Truck Centers of California, Inc., TransPower decided to special order the 520 series truck chassis as gliders directly from Peterbilt instead of taking delivery of completely built trucks and then removing the drivetrain components.[13] This approach was better suited for serial production than receiving complete vehicles requiring extensive disassembly; however, since Peterbilt did not have a glider that was optimized for vehicle electrification, TransPower and Peterbilt collaborated to create electric vehicle gliders. This initially delayed delivery, but it would be to the benefit of future manufacturing through cost reductions and increased efficiencies. Through the process, TransPower and Peterbilt continuously exchanged computer models and refined the glider specification to best suit vehicle electrification.

Because the refuse truck is a cab-over design, compared to a typical class 8 tractor with extended front hood, the PCAS needed some redesigning to accommodate the Peterbilt 520EV; therefore, TransPower developed a specially designed PCAS to fit onto the Peterbilt chassis with the same components it uses for Class 8 trucks, but with the frame and bracket arrangements to fit the 520 cab configuration. The electrical cable design is unique to this truck as well, so the design of both high voltage power cables and low voltage signal cables followed the redesigned structural arrangements. This was schedule-critical, as the power cables were fabricated-to-order in China, and this special order required a three- to four-month lead time.

[12] https://www.nrel.gov/transportation/assets/pdfs/fleet_dna_refuse_trucks_report.pdf
[13] A chassis glider is a rolling chassis without the powertrain and powertrain accessories such as fuel tanks.

A standard internal combustion engine waste collection truck utilizes the power take-off (PTO) unit that is mounted to the transmission. The PTO is powered by the engine to operate the hydraulic pump, which creates the hydraulic pressure required to operate the body's various functions (Figure 4).

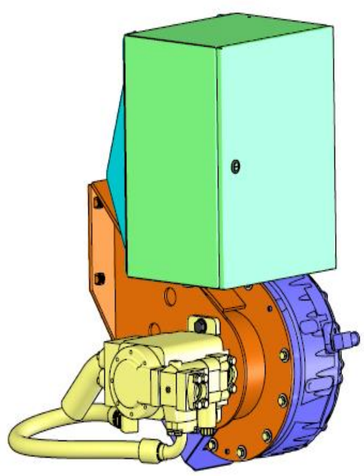
Figure 2: Conventional PTO



Credit: Fleet Maintenance[14]

In the absence of an engine, TransPower designed and installed a more efficient ePTO. The ePTO uses the same type of motor that is used in the powertrain and is mated to a hydraulic pump, as shown in Figure 5. Figure 6 shows the assembly minus the charge box installed onto the chassis.

Figure 3: TransPower ePTO



Detail of the auxiliary hydraulic pump and drive motor (violet), hydraulic pump (yellow) and charge port (green).

Credit: TransPower

[14] https://www.fleetmaintenance.com/equipment/powertrain/article/21165102/the-power-of-ptos

Figure 4: ePTO Installed on the Glider Chassis

Credit: TransPower

Battery Development

The ESS is the largest and heaviest subsystem on the vehicle, typically weighing 4,000 pounds to 8,000 pounds. At the onset of this program, TransPower was using large cell batteries that typically have 200 ampere hours (Ah) to 400 Ah in capacity, which are easy to integrate due to their large prismatic shape, having both terminals on one side of the cell, and requiring fewer cells due to their high capacity (thus requiring fewer electrical connections). The cells in Figure 7 have been used in TransPower's yard tractors and were the most energy dense of the prismatic cells that offered more than 76 watt hours per kilogram (Wh/kg), which is a very low value by modern standards.

Figure 5: CALB 400Ah Cell Data

Size, picture, and cell voltage vs. discharge in Ah

Credit: CALB, USA

The drive train requires a nominal 400 volts of direct current (VDC) battery power which equates to 120 cells per string. One 120-cell string contains 154 kWh of energy and weighs roughly 4,000 pounds, based on TransPower's measurements of the TransPower-designed yard tractor ESS. It occupies two large boxes on either side of the ESS one of which can be seen in Figure 8; however, just one string would have to be used by left-side frame rail because the right side is occupied by the side loader arm, leaving only the back of the cab space for additional batteries while still falling short of the 330 kWh target.

Figure 6: Battery-electric Kalmar Yard Tractor with 400Ah CALB ESS

Credit: TransPower

At the proposal's initiation, a compact, a higher energy density, cylindrical 90 Ah KAM cell became available, which boasted 160 Wh/kg at the cell level, and the initial testing was encouraging (Figure 9). The final configuration used modules depicted in Figure 10 containing nine cells in parallel for 810 Ah arranged with 10 cells in series for a 32 VDC module.

Figure 9: KAM Modules Under Test in TransPower's ESS Lab

Credit: TransPower

Figure 10: Assembled 9P10S KAM Modules

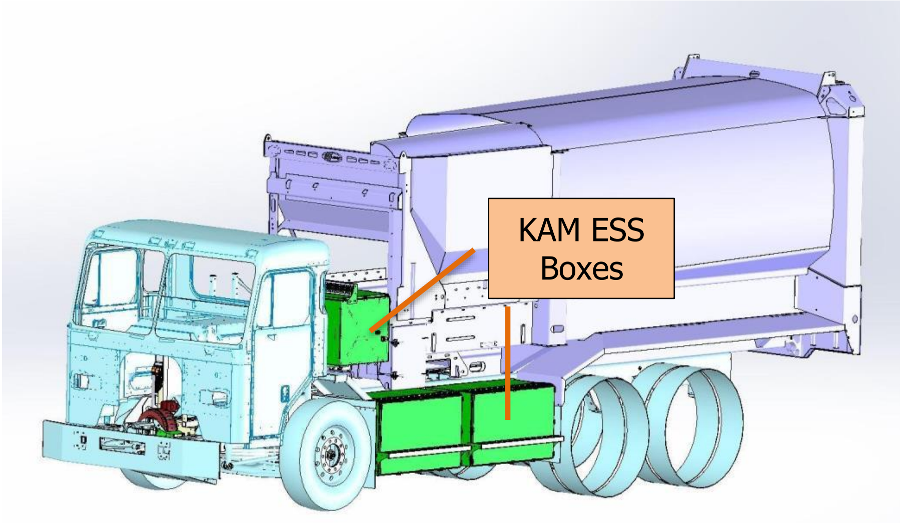
Credit: TransPower

The ESS box contained three of these boxes which would amount to about 96 VDC (Figure 11). Using four boxes created a single 384 VDC, 324 kW ESS that was slightly short of the targeted 330 kWh, and was the best of the available options (Figure 12).

Figure 11: KAM Modules Mounted in Enclosures on a Test Vehicle

Credit: TransPower

Figure 12: 3D CAD KAM ESS Installation



3D CAD picture of the KAM ESS boxes installed on the chassis with two on the frame rail and two behind the cab for 4 total boxes.

Credit: TransPower

Packaging smaller, more energy-dense cells posed a number of challenges. The smaller portions made it easier to customize an ESS to utilize the maximize amount of space; however, because there are many more of the smaller cells than have been used in previous trucks (and in this case the terminals are on opposite ends of the cell), the approach to integration was quite different. Firstly, there was a significant engineering effort that included designing modules to fit into the larger ESS structures, and then TransPower had to reconfigure its proprietary BMS to accommodate the new bus bar design.

During the refuse body design phase and chassis integration, the KAM ESS was installed on a Class 8 testing platform, as two hybrid class 8 tractors took part in separate demonstrations. Numerous issues arose during this testing that did not appear in the lab, most significant of which were:

- The KAM cells quickly began to self-discharge at a rate so high that the TransPower BMS could not equalize the pack and get the lowest cell high enough to declare full charge.
- The KAM cells would rupture without warning and damage components around them.

TransPower worked extensively with Yinhe Electronics to correct the issue, but it was not able to identify why the cells were having such issues. TransPower had already put significant time and money into the KAM cells product and any pivot to another technology would have put the project further behind schedule; however, in the interest of safety and environmental concerns, TransPower chose to move forward with another battery company and to redesign the ESS enclosures.

While it is typically difficult for a small start-up to gain the attention of mainstream ESS suppliers, TransPower had been courting Envision Automotive Energy Supply Corporation (Envision), which manufactured cells for the Nissan Leaf. Envision supplied modules with lithium-manganese-cobalt-oxide (NMC) cell technology that was designed and built to OEM standards, and thus presumably of much higher quality than what had been used prior.

The increase in energy density improved TransPower's Class 8 vehicle from a weight and range standpoint. The original Class 8 truck boasted 215 kWh of energy storage that was contained in five separate enclosures some, which can be seen in Figure 13 with two on each frame rail and one located behind the cab. The tractor in Figure 13 was rated for 70 loaded miles of range and weighed 22,500 pounds.

Figure 13: TransPower's Original Class 8 Drayage Truck

Credit: TransPower

Figure 14 shows the NMC TransPower system applied to the Peterbilt 579 Class 8 truck. This approach differs from previous TransPower demonstration vehicles in that each box is a 400 VDC, 44 kWh ESS string. The total ESS is comprised of multiple numbers of these individual strings. The trucks in Figure 14 are utilizing only the frame rails for energy storage, not the back of cab, and have eight strings for 352 kWh of energy, with total tractor weight of only 21,500 pounds that is capable of 120 miles of range. The new ESS technology produced a vehicle that had about 65 percent more energy storage, 70 percent more range, and weighed 5 percent less.

Figure 14: TransPower NMC-powered Peterbilt 579 truck bodies

Credit: Peterbilt Motors Company

When TransPower applied this system to the Peterbilt 520 refuse chassis, it placed four strings along the left side frame rail and three strings behind the cab, as shown in Figure 15. This resulted in nearly 310 kWh of total energy storage, which is less than the desired 330 kWh but is estimated to weigh 1,500 lbs. less than the KAM solution, thus increasing payload.

Figure 15: Peterbilt 520 with Seven Strings of the NMC ESS

Credit: TransPower

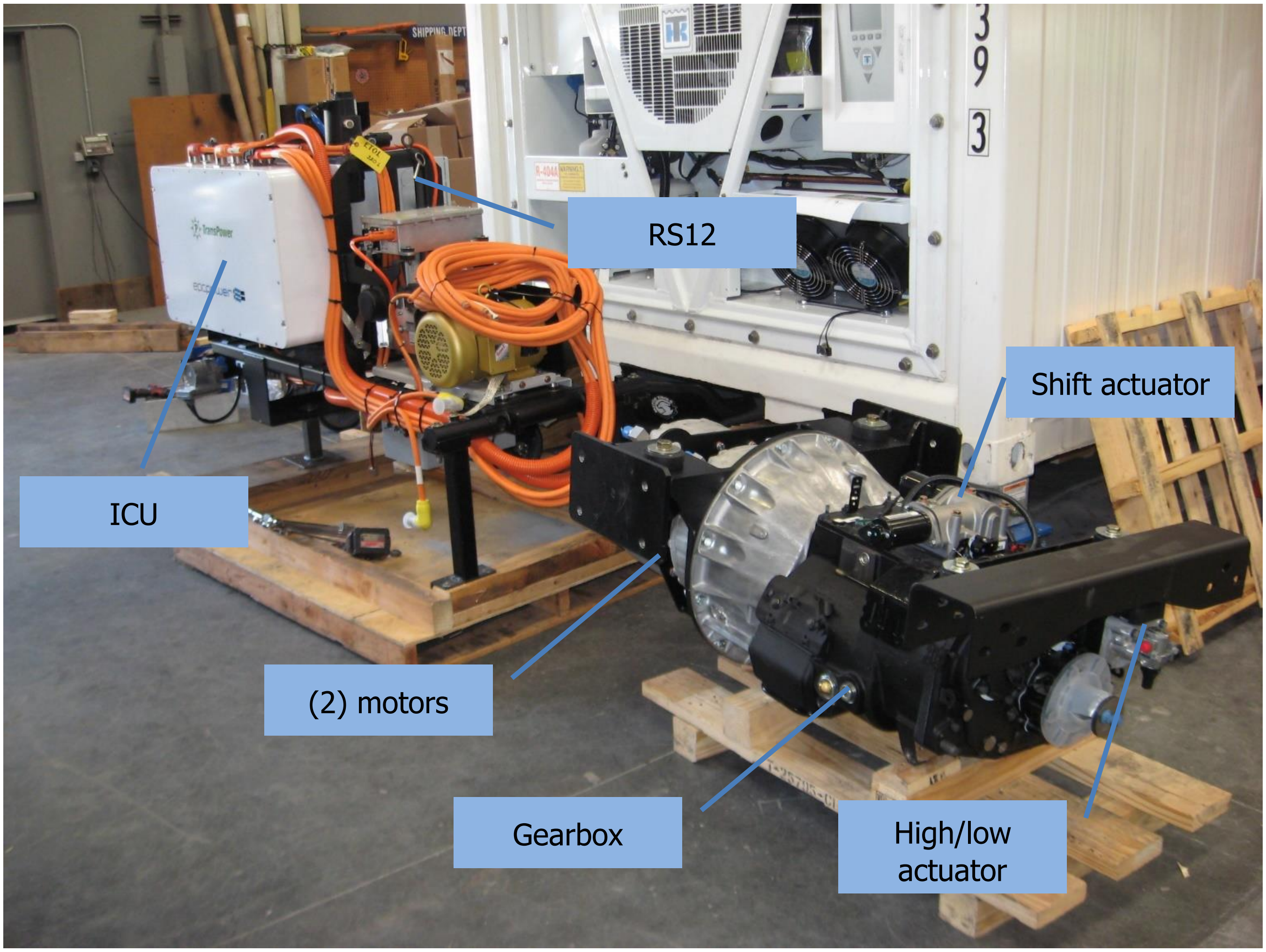
Remaining Integration

While the ESS is the largest single subsystem, the completed chassis requires the MDS, the PCAS, and the refuse body, which was manufactured and installed at the body builder's facility.

MDS and PCAS

The MDS is the powertrain of a truck. For the HDERT, it consists of two 150 kW electric motors, an Eaton 10-speed gearbox (more commonly known as a transmission) with a controllable gear shifter and a high/low range actuator, a powertrain control module (PCM) that manages the powertrain and other systems based on information it receives from various sensors around the vehicle, and two motor inverters, one of which is the inverter-charger unit (ICU) that converts alternating current (AC) electricity into direct current (DC) electricity that charges the batteries, and other is an inverter-only unit called the RS12 that converts AC electricity to DC electricity to operate the vehicle (Figure 16). During the validation and testing phase Truck 1, however, technicians found that the original ICU proved to produce far less power than what was advertised, so TransPower replaced it with another RS12 inverter that was converted to an ICU.

Figure 16: MDS, Inverters, Motors, and Gearbox Laid Out as if Installed



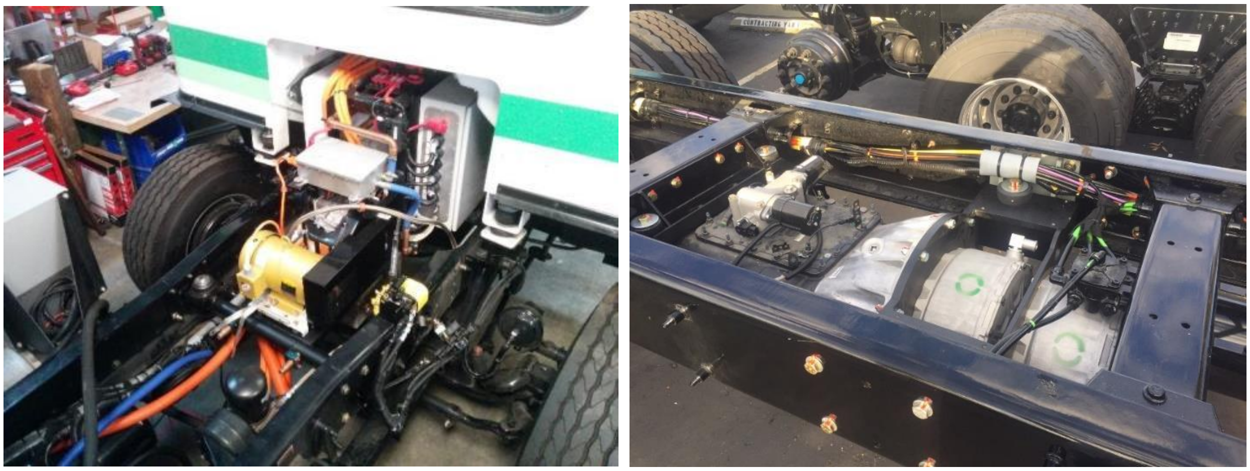
Credit: TransPower

The two motors were connected to the gearbox, which is actuated by controlling the shift actuator and the high/low range actuator. The gearbox has 10 available gears, but due to the wider torque band of electric machines, only five of them are needed. The third, fifth, seventh, eighth, and nineth gears make up the five speeds used in the refuse truck. The PCM (not pictured) was mounted just rearward of the gearbox. Due to space constraints, the inverters were physically mounted to the PCAS. The inverters produced up to 150 kW of continuous power, with the ICU doubling as an onboard AC charger capable of charging at 70 kW. The PCM also contained the controller and control hardware that are required to move the shift actuator and change the high/low range as needed. To accomplish the shifting, the PCM reduced the torque, which caused the gearbox to shift to neutral, which then commanded the inverters to spin the motors at a prescribed speed, shifting into the next gear, and then returning torque control back to the driver.

The balance of the PCAS contained what TransPower has called the Supervisory Control Module (SCM), which performs functions such as receiving torque requests from the driver, displaying information on the dash, managing the ESS, and controlling the various electrified accessories that are required to replace all of the functions originally performed by the diesel.

All of the assemblies were then installed into the glider body, as shown in Figure 17. The PCAS was located mostly underneath the cab, while the MDS gearbox and motors were mounted more forward, ahead of the axle between the frame rails. The PCM (not pictured) was then mounted behind the gearbox.

Figure 17: PCAS and MDS Mounted into the Chassis



Credit: TransPower

The Refuse Body

The final step of the build process was the installation of the refuse-specific body. Installation of the refuse body required the prototype glider to be shipped to Phenix Enterprises, Inc. in Pomona, California to have the refuse body and automated side-loader installed, and then returned back to TransPower's facility (Figure 18).

Figure 18: Truck Chassis Being Loaded on a Flatbed to Ship to Body Installer

Credit: TransPower LLC

The first truck used a Labrie refuse body; however, Labrie did not have the same refuse bodies in stock for Truck 2 and Truck 3, so TransPower used an Amrep refuse body for the second and third trucks. As the attachment points for the refuse body on the Peterbilt truck were the same for both Labrie and Amrep, TransPower did not have to redesign or re-engineer the remaining trucks.

Other Materials

Electric vehicles require electric vehicle supply equipment (EVSE, more commonly known as "chargers") into which they plug when they need to charge. Level 1 home chargers typically discharge alternating current at 3.3 kW to 7.2 kW, and Level 2 public chargers can go up to 19kW.[15] AC chargers require an ICU within the vehicle to convert the AC power to DC. Direct current fast chargers (DCFC) are external chargers that converts the AC to DC, and will typically charge at 50kW. TransPower's proprietary EVSE is somewhat different from most in that it is a three-phase AC charging system capable of a 70 kW charge rate. The TransPower EVSE used a 208 VAC 3-phase connection that can draw 194 amperes (amps) of AC current. The TransPower EVSE also employed a step-down transformer to reduce the available 408 VAC 3-phase power to three-phase 208 VAC. TransPower used a Meltric shore power plug (Figure 19) and safety protection hardware to create the custom-designed EVSE (Figure 20) that supports the fast AC charger and ICU onboard the vehicle.

Figure 19: Meltric Brand Shore Power Plug and Receptacle

Credit: Meltric Corporation[16]

[15] "What is the difference between charging levels?" (https://freewiretech.com/difference-between-ev-charging-levels/#:~:text=Level%202%20Charging&text=Summary%3A%20L2%20chargers%20operate%20at,in%208%20hours%20or%20less)

[16] Meltric Corporation website (https://meltric.com/)

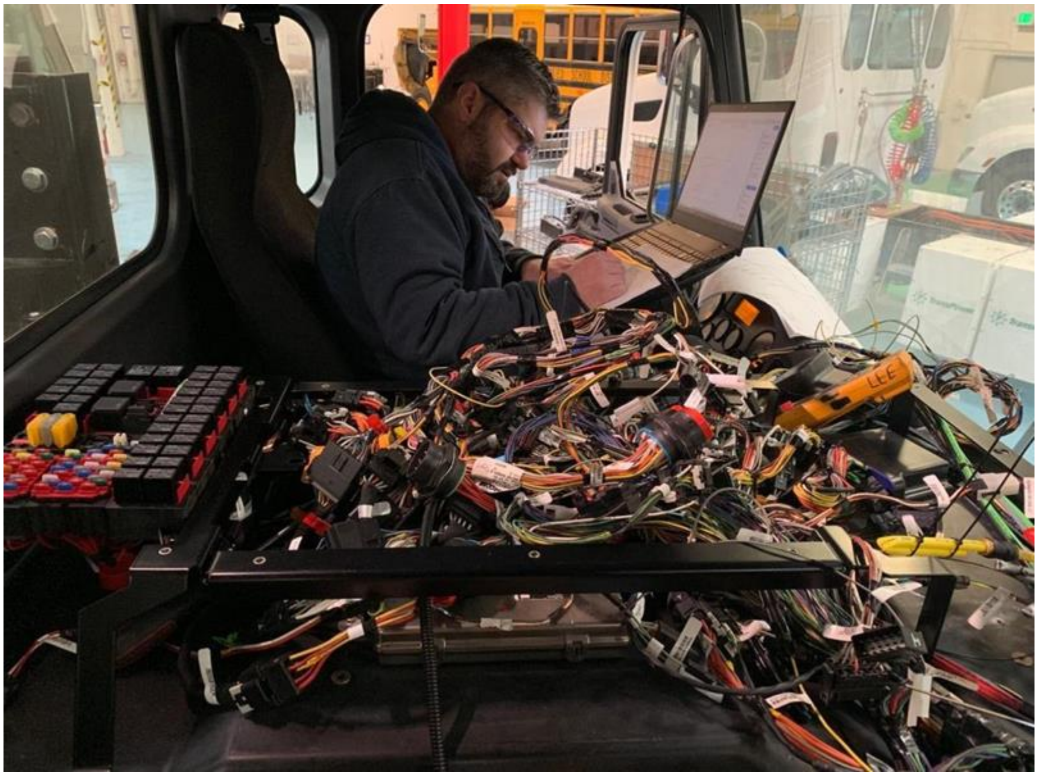
Figure 20: Complete EVSE with Transformer and Charge Control Box

Credit: TransPower

Commissioning

With a complete vehicle and a charger installed at the demonstration site, TransPower began the process of commissioning the vehicle, which means that the various systems and features were tested and that the vehicle demonstration and data collection can commence. This included ensuring that all the dash controls functioned and gauges could be read properly, that the vehicle can be charged and driven, and that the right-hand drive option was functional. TransPower first drove the prototype truck in January 2018, and there were some challenges. The cab and chassis documentation TransPower received from Peterbilt did not match the vehicle it had delivered to TransPower. Peterbilt's parent company, PACCAR, had a team of engineer assist TransPower, but doing so required multiple trips to sort out the wiring and to provide TransPower with guidance. Because the chassis for this is a relatively old design, it has many analog switches required extensive wiring (Figure 21). This is in contrast to modern controller area network (CAN) architecture, where two CAN cables can transmit commands to nearly all of the various components on a vehicle, drastically reducing the amount of wiring used in a vehicle.

Figure 21: TransPower Technician Wiring the Cab to the Motive System



Credit: TransPower

Once the high voltage wiring and the cab controls were sorted, TransPower began driving the truck for short distances and charging them. During this, technicians noted that the vehicle had persistent electro-magnetic interference (EMI), which caused ESS current measurement errors, CAN communication errors, shift actuator measurement errors, speed sensor measurement errors, and BMS cell voltage sensing measurement errors , and ultimately caused the controllers for various systems to fault and stop working. Technicians reviewed the grounding and bonding scheme of the system that was responsible for properly routing 12 VDC current back to the battery and found it to be deficient. This system was responsible for properly routing 12 VDC current back to the battery to ensure that components do not build up a voltage in reference to one another and allows enclosures to send EMI to ground versus radiating it back out and causing damage. Reliability improved after the technicians moved some of the low voltage wiring away from the most common sources of EMI, such as the powertrain motors.

TransPower had other difficulties that its technicians had never previously encountered, such as the right-hand drive feature that is typical on refuse trucks, which required both analog and CAN interfaces that were not documented in the original schematics. Overcoming the challenges of having to mirror the right side of the cab so that it had all the same features as the left side again required the assistance from PACCAR to ensure that both left- and right-side driving stations functioned.

Validation Testing

TransPower commissioned the vehicles for operation and driving as they came off the line; however, technicians determined that each truck lacked the hydraulic power to operate the lift arm and the compactor when they were both empty, let alone full of waste material. The hydraulic system for the arm and compactor did not reliably operate the lift arm and the body until mid-2018. To ensure reliability, TransPower put 700 testing miles on the truck before delivering it to Sacramento County in March 2019 (Figure 22).

Figure 22: HDERT Truck 1 in Service

Credit: TransPower

As previously stated, TransPower used a glider body rather than buying whole diesel trucks and removing unnecessary equipment; however, TransPower did not know that in doing so it recategorized TransPower from a vehicle modifier to a vehicle manufacturer within the National Highway Transportation Safety Administration's (NHTSA) regulatory framework. Vehicle modifiers are only required to not reduce a vehicle's Federal Motor Vehicle Safety Standards (FMVSS) and they do not have to provide any evidence to show that a vehicle still complies with FMVSS. Manufacturers, however, must assess and prove that the changes made still maintain FVMSS requirements and the manufacturer must register that vehicle with NHTSA stating as such. In using the glider body, TransPower became responsible for ensuring compliance with FMVSS rule number 121, which applies to the antilock braking system (ABS). Because TransPower changed the powertrain and weight distribution from the original, NHTSA-approved vehicle, TransPower deemed it necessary to have the vehicle recertified as proof that the vehicle was FMVSS compliant. To accomplish this, TransPower required two things:

1. The ABS supplier, Bendix, needed to test the vehicle and provide a report stating that the ABS as installed by TransPower met the FMVSS requirements.
2. An independent testing entity – in this case, Link Engineer – had to perform a prescribed test and certify that the ABS worked as reported.

Having met FMVSS compliance, TransPower registered the vehicles with NHTSA so they could begin on-road demonstrations.

Permits and Registration

After having met the manufacturer requirements for the ABS, TransPower had several steps it needed to follow to prepare the three trucks for on-road demonstration with fleets. First, they must be titled in the state of California for on-road use with the California Department of Motor Vehicles (DMV). This first step required the Manufacturer Certificate of Origin, weight declarations, and vehicle identification number verification. Next, TransPower drafted lease agreements for Sacramento County, Waste Management, and their respective legal teams. Finally, the trucks needed automotive insurance in order to complete DMV registration. Once the vehicle title, license plates, registration card, and license plate sticker were received and applied, the trucks were ready for on-road use.

Even though the three HDERT refuse trucks had zero tailpipe emissions, TransPower followed the traditional emissions process as conventionally fueled trucks to receive the emissions certifications, and secured temporary test exemptions from the United States Environmental Protection Agency and CARB for one-year periods.

CHAPTER 3: On-Road Demonstration

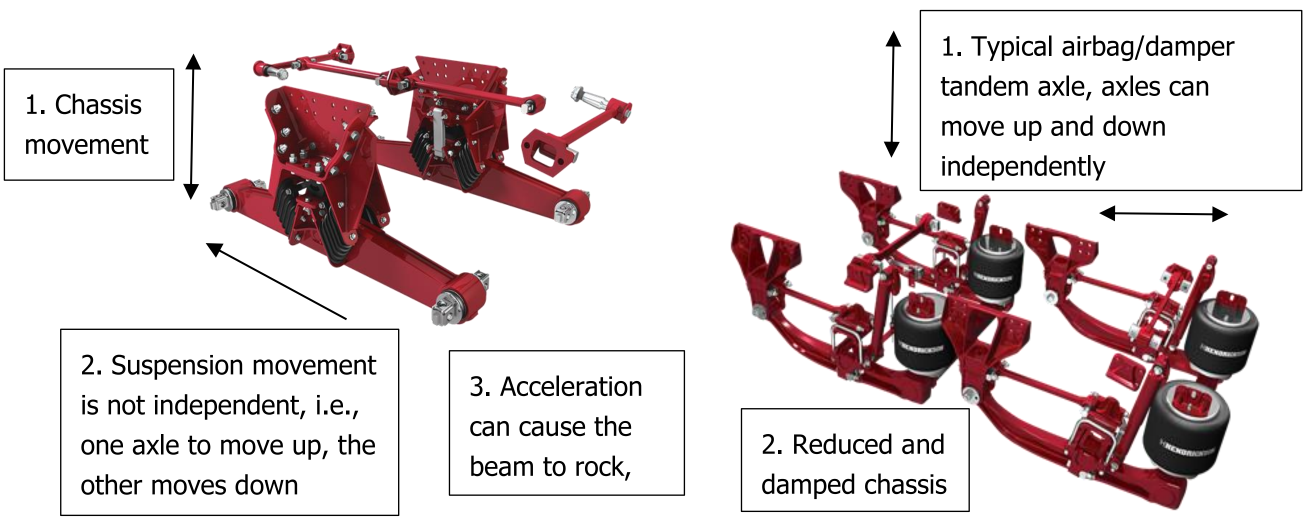
Overview

The HDERT project had an original plan of building and demonstrating three Class 8 refuse trucks in real-world fleet settings. While TransPower successfully completed building the three trucks, demonstration occurred for only two of them. TransPower learned that the unusually severe operating conditions posed key challenges.

Key Challenges

The first had to do with the trucks' slip control and its interaction with where the trucks often operate (rough landfills, muddy and slippery land fill roads) in combination with the walking beam style tandem rear suspension depicted in Figure 23, which while very rugged does not absorb road impacts as well as an air sprung suspension typical of a Class 8 tractor. On the beam style suspension, when one axle to travels upward, the other must travel downwards, and if the body comes down after an impact, the suspension does not absorb shock because both axles cannot travel upwards at the same time; instead, the chassis bounces on the tires.

Figure 23: Example of Walking Beam vs. Typical Tandem Rear Axle Suspension



On the left, a walking beam tandem axle suspension; on the right, a typical airbag tandem.

Credit: TransPower

The second challenge pertained to roll back that occurred when the vehicle came to a stop on a very steep hill. TransPower-powered electric vehicles have a proprietary slip control algorithm that reduces torque to address the average speed difference between the front and rear wheels, the speed difference between the rear wheels, and then the rate of acceleration of the rear wheels. By reducing torque, the system usually reduces wheel spin and hop, which helps maintain traction and control and reduces the likelihood that oscillations – or bouncing - will develop. The walking beam suspension used by refuse trucks caused a lot of bouncing at the rear of the vehicle because the trucks do not have any shock absorbers, and that can cause a lot of opportunities for the tires to lose traction and slip. Additionally, rapid acceleration caused the walking beam to rock the drive wheels off the ground, causing an oscillation to develop. For example, when the powertrain initiated and accelerated, the truck rocked on the walking beam, took weight off the drive wheels, and caused slip, which then reinitiated the acceleration in a repeating cycle. This also happened when the driver stepped on the accelerator to counteract the rapid deceleration of the truck caused by the PCM. This cycle exacerbated and perpetuated the oscillation. TransPower calibrated the algorithm to address the wheel acceleration so that it did not initiate an oscillation, allowing the vehicle to accelerate but still dampened an oscillation caused by road conditions, such as a bump or pothole.

Addressing truck roll back was also challenging. In a typical modern vehicle, the powertrain will command the ABS module to hold the brakes while the driver applies the accelerator and then release the brakes once engine torque is sufficiently high enough to prevent the truck from rolling back. This feature is especially useful in a refuse operation where the truck is often driving on steep and narrow streets. The project vehicles' ABS systems were not controllable by TransPower, so TransPower had to improve upon its hill start assist and roll back reduction algorithms that are part of TransPower's proprietary creep control suite of features.

Another complication in preventing roll back was the trucks' cab design. On a typical Class 8 tractor, the operator can apply the brake and accelerator simultaneously. The TransPower system allows the powertrain to provide torque for a limited time so that the driver can launch without any roll back; however, the refuse trucks' steering columns on both the left-hand and right-hand side of the trucks are between the driver's legs. With both the accelerator pedal and the brake pedal on the right side of steering column, the driver's left foot could not access the brake pedal, thereby preventing the driver from applying both pedals simultaneously. Therefore, TransPower had to calibrate the creep function to recognize roll back and quickly increase torque to prevent it.

Another unforeseen complication the technicians found was how the ABS behaved when the trucks were loaded versus when they were empty. An unloaded vehicle requires less torque than a loaded vehicle. Since TransPower could not control the algorithm for the ABS, technicians could only place the ABS in one setting. If the ABS was calibrated for loaded trucks only, there was too much torque when unloaded, and that caused surging due to the creep control algorithm Conversely, if the technicians calibrated for an unloaded truck, there was insufficient torque to stop roll back when the trucks were loaded. Ultimately, the TransPower calibrations were able to use speed, direction, and acceleration measurements to provide functionality, which, while not as good as an ABS-based anti-roll back, was effective enough to serve the purpose.

After technicians and engineers deemed the trucks safe to operate, they were shipped to their respective demonstration locations in Sacramento County and El Cajon, California. TransPower successfully commissioned all three trucks and they were able to operate on public roads, and the project team drove the three trucks a combined distance of more than 5,400 miles; however, the performance of the trucks in actual operating conditions varied. Fleet operators compared these trucks to existing conventionally-fueled trucks running on natural gas or diesel. Sacramento County operated the first truck (Truck 1) for several months, but the truck was continuously breaking down in the field so that it needed to be towed back to the yard and it required significant downtime in order to be repaired. Due to the poor and inconsistent performance of their first truck, Sacramento County declined to demonstrate the second truck. This second truck (Truck 2) was instead used at the TransPower facility for testing and quality improvement purposes. The third truck (Truck 3) was deployed to Waste Management in El

Cajon, California where it completed a successful demonstration in real waste collection routes, and did so with fewer breakdowns and repairs without the roll back and oscillation issues mentioned above.

The HDERT project tracked on-road use data through GPS data loggers installed on the trucks. These data loggers reported geolocation and general truck performance. TransPower used a telematics cloud software for both engineering tracking and fleet-customer interfaces.

TransPower calculated what the diesel emissions of all three electric refuse trucks would have been using CARB's Emission Factor (EMFAC).[17] In all cases, particulate emissions smaller than PM10 and NOx emissions are very low, presumably due to new vehicle pollution control devices and low-NOx engines.

Sacramento County Department of Waste Management and Recycling

Sacramento County provides weekly waste removal services in the greater Sacramento area for residential and business customers. It began using natural gas refuse trucks in 1998, with most of the fuel sources coming from renewable natural gas from landfills, which led to significant carbon footprint reductions and fuel cost savings. By 2018, Sacramento County owned 425 heavy-duty on-road vehicles, and it has plans to eventually run a fully zero-emission refuse truck fleet.

On January 30, 2020, the Clean Cities Coalition Network in Sacramento held meetings with TransPower, Sacramento County, and Peterbilt to discuss the demonstration of Truck 1 and the future commercial viability of battery-electric refuse trucks in general. TransPower presented the HDERT project, detailing refuse truck duty cycles and the performance requirements.

Infrastructure

In March 2019, TransPower installed the EVSE at Sacramento County's corporation yard at the North Area Recovery Station in North Highlands, California in March 2019, ahead of the May 2019 delivery of the Peterbilt 520EV refuse truck. TransPower provided the 70kW charging system to Sacramento County. A TransPower field service technician guided Sacramento County electricians with the installation of the EVSE and ensured compatibility with the truck's onboard ICU system.

Refuse Truck 1

TransPower completed Truck 1 integration and commissioning at its facility and then sent the truck to a Peterbilt dealer for it to perform a thorough pre-delivery inspection before delivering the truck to Sacramento County. During the inspection, the inspector found that a fire extinguisher and warning triangles were missing from the truck. Since both of those items are required safety items, TransPower purchased them and had them installed before the truck was deployed. The TransPower field service team conducted in-person training in March 2019 and taught Sacramento County employees how to operate the truck and the various sub-components, how to use the EVSE, and the what the best practices are for driving and maintaining the electric refuse truck.

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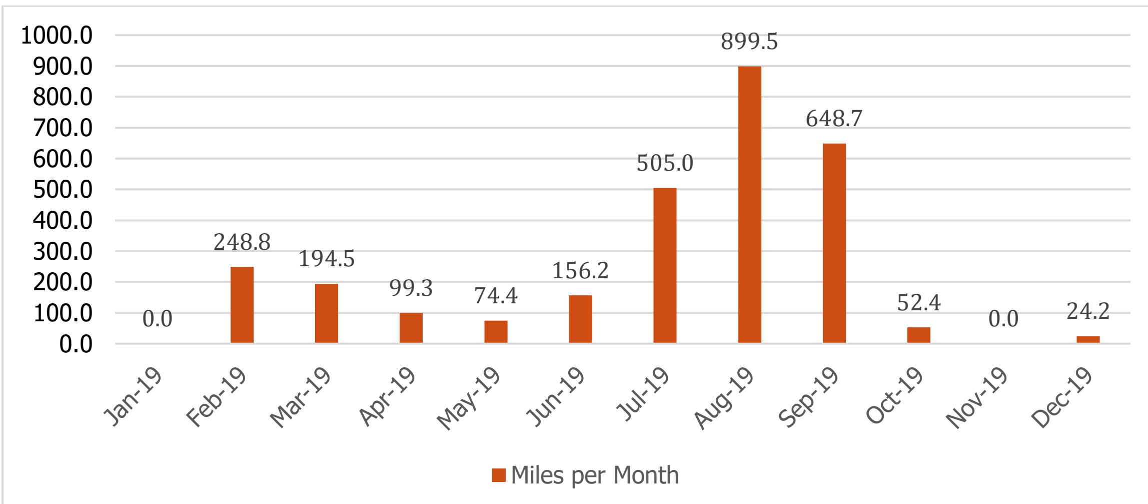
[17] https://arb.ca.gov/emfac/emissions-inventory

After receiving the truck, Sacramento County notified TransPower of missing items that are customary to refuse operations, including several on-board cameras, a second fire extinguisher, reflectors, adjustments on the hydraulic arm movements, and other accessories. The typical operating requirements of refuse trucks involved many safety precautions due to their being operated in residential areas, urban areas, and in-between cars. In April 2019, the fleet operator requested moving the EVSE station to better align with parking. The TransPower field team completed removal and re-installation of the EVSE. While the EVSE was being moved, TransPower shipped the refuse truck from Sacramento to Long Beach for the week-long Advanced Clean Truck Expo, that was held in early May 2019 to showcase the unique prototype technology. By this time the vehicle accumulated about 617 total miles (Figure 24).

Figure 24: Graph of Truck 1 Monthly Mileage in 2019



Credit: TransPower

In August 2019, the refuse truck accumulated its highest mileage at nearly 900 miles with 423 hours of drive time. In the same month, TransPower received several service orders from Sacramento County for the truck. The drivers reported hydraulic leaks and other repair issues, which TransPower resolved within a month. Table 1 summarizes mileage, kWh, kWh per mile, and diesel gallon equivalents (DGE) consumed.

Table 1: Summary of Truck 1 Output

Month	Miles	kWh	kWh/mile	DGE
Jan-19	0	0	0	0
Feb-19	249	660	3	113
Mar-19	195	732	4	89
Apr-19	99	225	2	45
May-19	74	167	2	34
Jun-19	156	513	3	71
Jul-19	505	1,580	3	229
Aug-19	900	1,696	2	409
Sep-19	649	1,672	3	295
Oct-19	52	293	6	24
Nov-19	0	0	0	0
Dec-19	39	53	1	18
TOTAL:	**2,918**	**7,591**	**3.0**	**1,325**

Credit: TransPower

In March 2020, several events occurred that took the truck out of service. Most notably, the COVID-19 pandemic was beginning and had caused shutdowns throughout the industry. Various public agencies and private entities began implementing social distancing practices, and COVID guidelines required TransPower to scale back in-person work schedules; however, refuse collection and the employees in that sector were considered to be essential operations and they continued to work.

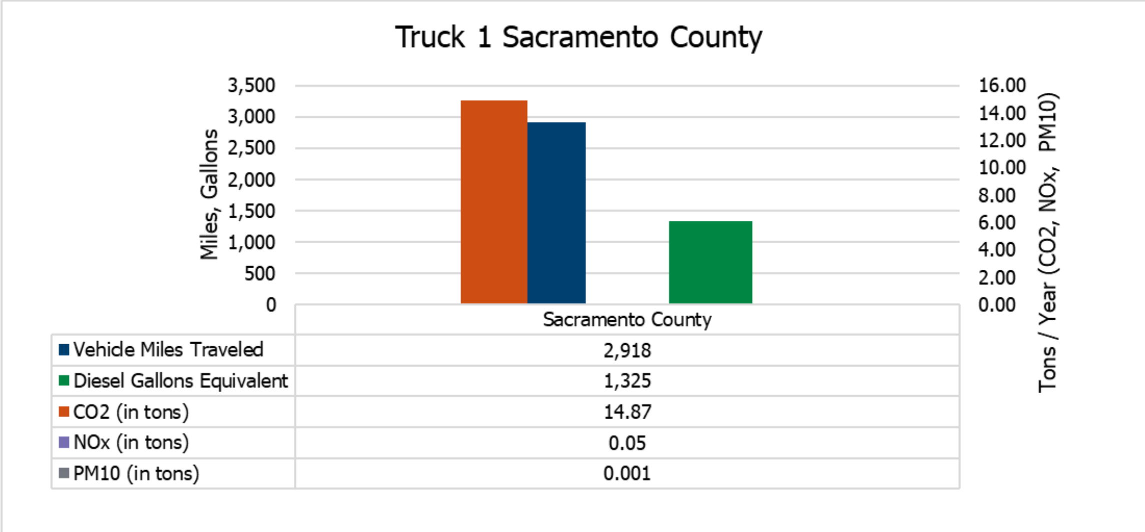
Then, in early March 2020, the truck needed a repair that required the truck to be brought back to the TransPower facilities. On March 16, 2020, Sacramento County decided to not continue a second year of demonstration, and instead ended participation in the demonstration due to the lease on the truck ending on March 30, 2020. Sacramento County had originally intended to complete the two-year planned testing period and demonstrate a second truck, but Sacramento County was not pleased with the extent of service repairs needed and the non-reliability of the truck in the field.

In Fall 2020, TransPower loaded the truck with about six tons of recycling trash that was provided by Waste Management so that TransPower test engineers could simulate real-world weight conditions during software controls improvements.

Refuse Truck 1 Emissions Summary

Overall, HDERT Truck 1 drove more than 2,900 miles and consumed about 7,500 kWh, with a consumption rate of about 3.0 kWh per mile, and is on par with many light-duty battery-electric vehicles. Truck 1 saved about 1,325 DGEs and 15 tons in CO_2, with very minor savings in NOx and PM10 (Figure 25).

Figure 25: Graph of Truck 1 Emissions Reductions



Credit: TransPower and CARB

Refuse Truck 2

As stated in the previous section, Sacramento County was originally going to demonstrate Truck 2, but the truck was never deployed to the fleet. TransPower was in the process of trying to determine if there were other fleets that would be able to install the infrastructure and demonstrate the truck prior to the CEC agreement ending, but this truck remained with TransPower and served as a valuable test truck.

FMVSS Testing Support

TransPower built Truck 2 with the Amrep body instead of the Labrie body, and it too underwent FMVSS testing at the Bendix facility in Ohio to represent future electric Peterbilt 520EV trucks that had TransPower as the final manufacturer. TransPower used Truck 2 as a test vehicle at its facility before being shipped to Peterbilt Motors in September 2020 in Texas to use as a test vehicle at their facilities. Table 2 summarizes the total number of test miles, kWh, kWh per mile, and diesel gallon equivalents (DGE) consumed.

Table 1: Summary of Truck 2 Output

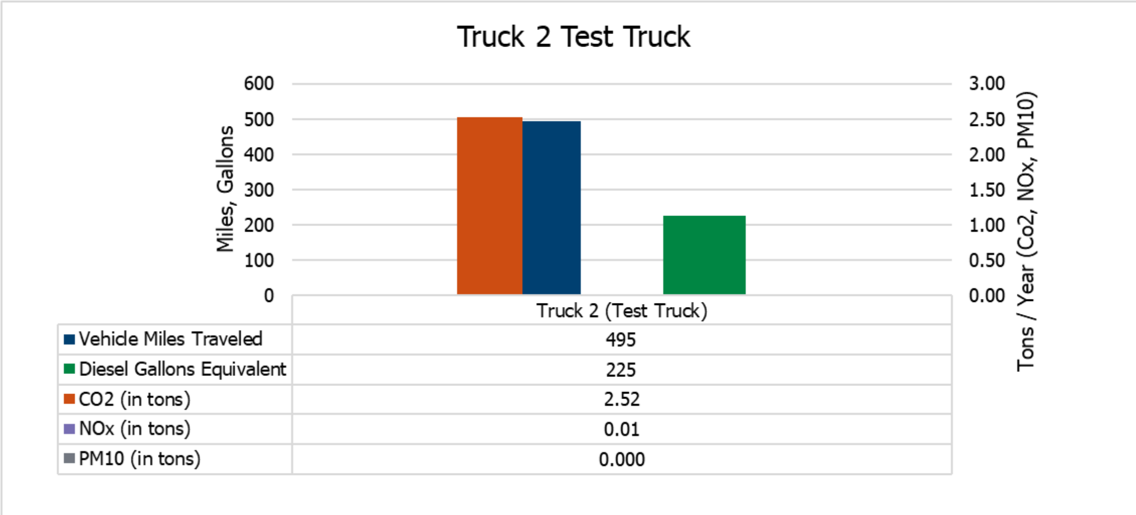
Time Period	Miles	kWh	kWh/mile	DGE
Nov-19 to Feb-21 TOTAL	**495**	**1,440**	**3.0**	**225**

Source: TransPower

Refuse Truck 2 Emissions Summary

Using the same method and tool as used in Truck 1, HDERT Truck 2 drove about 495 miles and consumed about 1,440 kWh, with a consumption rate of about 3.0 kWh per mile. Truck 2 saved about 225 DGEs and 2.5 tons in CO_2, with, again, very minor savings in NOx and PM10 (Figure 26).

Figure 26: Graph of Truck 2 Emissions Reductions



Credit: TransPower and CARB

Refuse Truck 3

Truck 3 was identical to Truck 2 and was deployed to Waste Management in El Cajon.

Waste Management Deployment

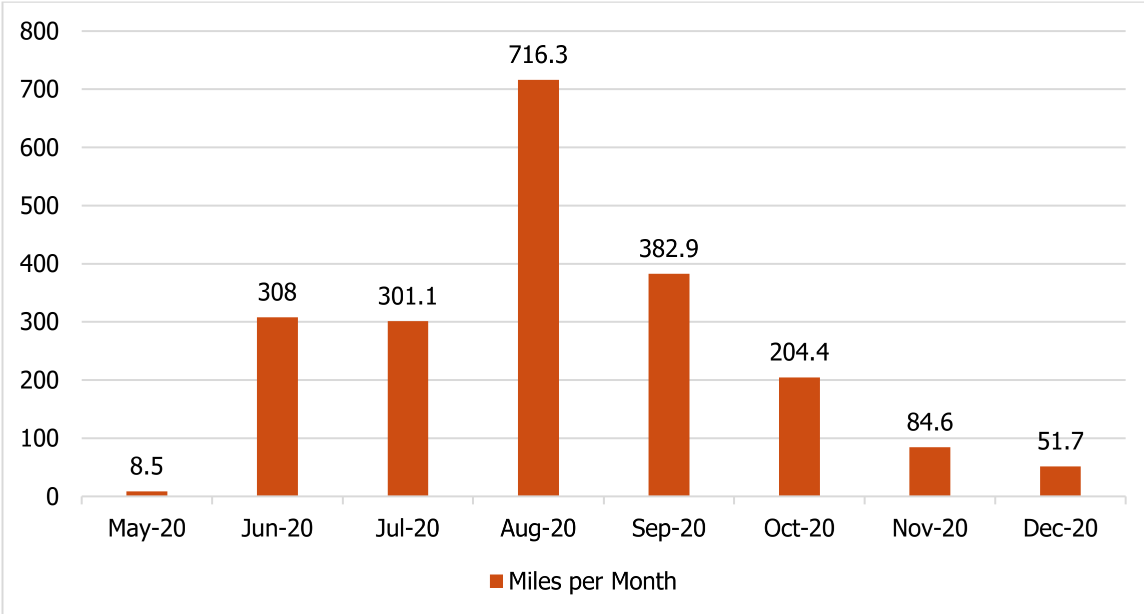
Waste Management chose to demonstrate Truck 3 from its El Cajon location, and on January 30, 2020, it displayed the truck at El Cajon City Hall, highlighting the collaboration between it and TransPower (a local company) to demonstrate the Peterbilt 520EV as an all-battery-electric automated side loader.

The data collected for Truck 3 proved to be an excellent learning environment for TransPower. Each Waste Management truck typically has smart fleet technology, including onboard computers, cameras, and geographic tracking that were not installed on the other two demonstration trucks. Successfully integrating those electronic devices into the truck required additional work before it was deployed into the field. Input from the Waste Management drivers inspired the roll back calibration improvements previously discussed, as well as those in regenerative braking, which was key in reducing total battery energy consumption.

The average consumption during the entire demonstration was about 4.0 kWh/mile. The highest consumption rate was more than 6.0 kWh/mile, most of which was attributed to the ePTO loads that support the body hydraulics. The lowest consumption rate was about 3.0 kWh/mile, which is typical of an unloaded vehicle with little to no ePTO use.

Waste Management drove Truck 3 for nearly 2,060 miles, consuming more than 8,300 kWh on real-world routes throughout the San Diego area despite experiencing several downtimes and delays due to repair issues (Figure 27). Unlike Truck 1, though, that was tested in Sacramento, Waste Management in El Cajon and TransPower's facility in Escondido are in the same county, and a TransPower technician was able to make timely repairs, often on the same day.

Figure 27: Graph of Truck 3 Monthly Mileage in 2020



Credit: TransPower

In August 2020, the Truck 3 accumulated its highest mileage at more than 700 miles. In the same month, TransPower received several service orders from Sacramento County for the truck. The drivers reported hydraulic leaks and other repair issues, which TransPower resolved within a month. Table 3 summarizes the mileage, kWh, kWh per mile, and diesel gallon equivalents (DGE) consumed.

Table 2: Summary of Truck 3 Output

Month	VMT	kWh	kWh/mile	DGE
May-20	9	35	4	4
Jun-20	308	989	3	140
Jul-20	301	1,274	4	137
Aug-20	716	2,656	4	325
Sep-20	383	1,618	4	174
Oct-20	204	1,037	5	93
Nov-20	85	467	5	39
Dec-20	52	309	6	24
TOTAL:	**2,058**	**8,385**	**4.0**	**935**

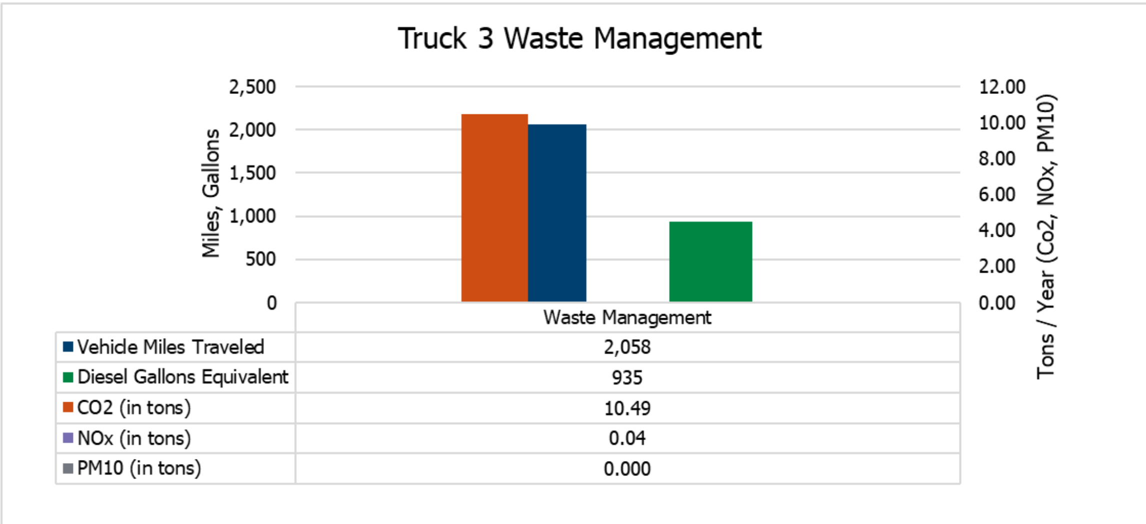
Source: TransPower

To gain more feedback, TransPower requested that the Waste Management drivers who drive the truck complete a poll. The respondents rated the overall experience as positive or very positive. Entering into the demonstration, the drivers expected that the truck would be exactly like or worse than a natural gas or diesel truck. The drivers found the truck very easy to charge, and their favorite features included the future technology aspect and lack of engine noise and vibration. The least favorite part of the truck was the reliability because the more miles that Truck 3 accumulated, the more often it started to break down.

Refuse Truck 3 Emissions Summary

Using the same method and tool as used in Truck 1 and Truck 2, HDERT Truck 3 drove more than 2,050 miles and consumed about 8,385 kWh, with a consumption rate of about 4.0 kWh per mile. Truck 3 saved about 225 DGEs and 2.5 tons in CO_2, with, again, very minor savings in NOx and PM10 (Figure 28).

Figure 28: Graph of Truck 3 Emissions Reductions



Credit: TransPower and CARB

CHAPTER 4: Lessons and Improvements

Key lessons and future improvements

From the manufacturer and integrator's perspective, Peterbilt and TransPower learned many lessons from the demonstration of the HDERT project waste collection trucks. The key lessons were:

- Take a more conservative approach to selecting energy storage supply and suppliers to reduce the risk to the project. Sacramento County and Waste Management stated that they would have preferred a reliable electric truck with shorter range than a truck with a longer range that is constantly being repaired.
- Get ahead of body interface complexity by engaging the chassis supplier up front. Ensure the supplier has adequate schematics and discuss integration strategies with the main engineering disciplines (mechanical, electrical, and controls).
- Identify new or challenging operational requirements (roll back, regenerative braking expectations, etc.) by doing more customer operational research, riding along on routes, try to truly understand how the vehicle is used.
- Take FMVSS into consideration up front. Consider if it makes the most sense to integrate a glider or supply a kit to an OEM and let the OEM certify the FMVSS. If the glider route is chosen, write an FMVSS task into the proposal.
- Better understand the energy consumption of the refuse body. Visit the refuse body manufacturer, discuss energy consumption with the applicable engineers, and attempt to source bodies that use more efficient means of operation.

Commercialization and Design Improvements

Based on this project and other similar deployments, TransPower was awarded a non-exclusive supplier agreement with PACCAR for the Peterbilt and Kenworth brands. PACCAR selected TransPower to supply a second-generation EV power kit for the 579 Class 8 tractor and the 520EV refuse truck. There are many key differences between the first-generation HDERT model and second-generation models, such as energy storage, which increased from 308 kWh to 396 kWh (which exceeded the estimated 330kWh requirement originally sought in the first-generation design); a power increase from 320kW to 500kW; and an increase in torque, from 1,348 Newton-meters (Nm) to 2,200 Nm, which puts the new powertrain in line with typical diesel performance. TransPower and PACCAR also selected an electrified body instead of a hydraulic body, which reduced refuse body energy consumption and, when combined with further regenerative braking refinements, brought energy consumption to under 3 kWh/mi while enabling the truck to achieve a range of over 100 miles (Table 4).

Table 4: Peterbilt 520EV Refuse Truck First vs. Second Generation Comparison

Details and Specifications	First Generation 520EV (HDERT Refuse Trucks)	Second Generation 520EV (Production-Ready)
Model Year	2015	2022
Electric System	Remote mount	Integrated tandem eAxle
Battery Capacity	308 kWh	396 kWh
Usable Battery Capacity	246 kWh (80% usable)	356 kWh (90% usable)
Battery Chemistry	Lithium Nickel Manganese Cobalt	Lithium Iron Phosphate
Peak Power	320kW	500 kWh
Torque	1,348 Nm	2,200Nm
Estimated Range	40-60 miles loaded	100 miles loaded
EVSE Plug	70kW TransPower Meltric, AC on-board charging	90kW-180kW CCS-1 standard, DC Fast Charging capable
Final Vehicle Manufacturer	TransPower	PACCAR
Power Controls & Accessories	TransPower	TransPower
Dealer & Maintenance	TransPower	Peterbilt and Kenworth Dealerships

Credit: TransPower

CHAPTER 5: Conclusion

The mileage driven and energy consumed during the HDERT project was key to the commercialization of TransPower electric powertrain systems and Peterbilt development of electric refuse trucks (Table 5).

Table 5: HDERT Fleet Demonstration Summary

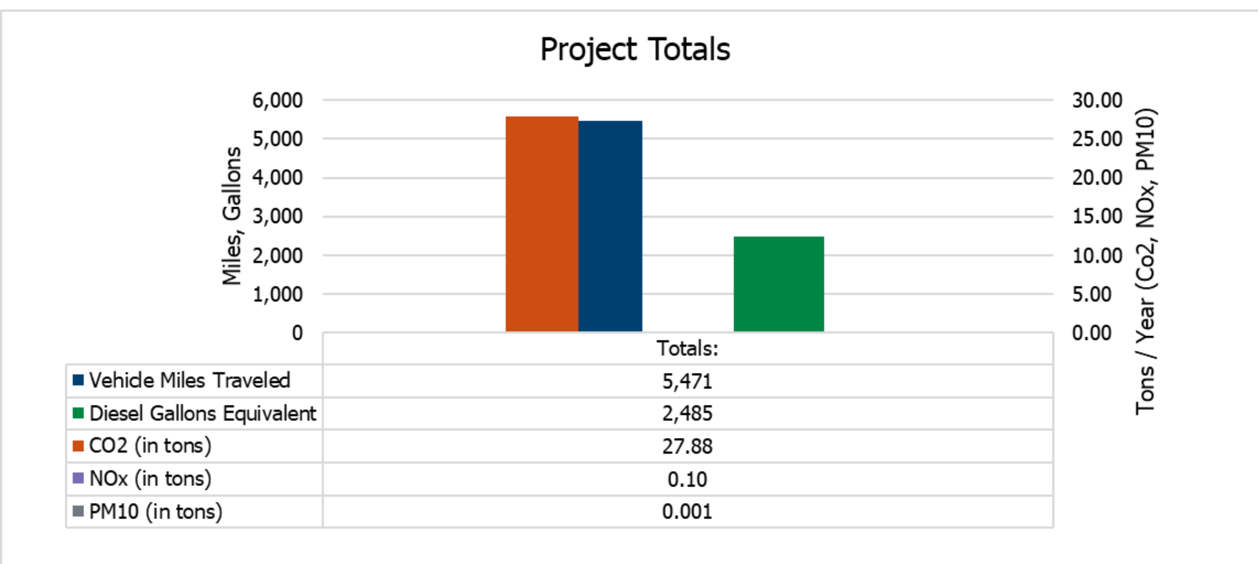
Vehicle	Total VMT	Total kWh	Avg. kWh/mi	Total DGE
Truck 1	2,918	7,591	3.0	1,325
Truck 2	495	1,440	3.0	225
Truck 3	2,058	8,385	4.0	935
Fleet Totals:	**5,471**	**17,416**	**3.3**	**2,485**

Credit: TransPower

Refuse Truck Total Emissions Summary

By adding up the totals of all three trucks, the HDERT project trucks drove more than 5,470 miles and consumed nearly 17,420 kWh, with a consumption rate of about 3.0 kWh per mile. HDERT saved about 2,485 DGEs and nearly 28 tons of CO_2, with, again, very minor savings in NOx and PM10 (Figure 29).

Figure 29: Total Emissions Reduced by All Three Demonstration Vehicles.



Credit: TransPower and CARB

Post-Project Commercialization

Due to project's modest success and lessons learned, PACCAR was able to secure a CARB Executive Order in mid-2020 for the Peterbilt Model 520EV refuse truck to certify it as a commercially-available truck for sale in the state of California. Immediately following the

Executive Order, Peterbilt listed the 520EV eligible for California Hybrid and Zero-Emission Voucher Incentive Project (HVIP). The HVIP program offers point-of-sale vouchers at $120,000 for battery-electric refuse trucks, of which there are notably only three commercial models as of February 2021. Currently, about 10 Peterbilt refuse trucks are planned for commercial production by the end of 2021. The engineering designs underway are using data from the HDERT project to inform critical design features that were requested by fleet operators.

Additionally, PACCAR's selection of TransPower for the electric powertrain and battery system for the Peterbilt 520EV and other heavy-duty platforms was another direct success, which the HDERT project made possible. The investment from the CEC led to further industry investments in electric refuse trucks and has created more jobs in California. TransPower anticipates additional jobs to be created in engineering and technician support as the company shifts operations over completely to Meritor and increased jobs at dealerships and other repair facilities. Moreover, this project allowed TransPower to introduce battery-electric refuse trucks to refuse body manufacturers, which can, in turn, engineer more energy-efficient refuse bodies, reducing the carbon footprint of heavy-duty electric refuse trucks even further.

GLOSSARY

AIR QUALITY MANAGEMENT DISTRICT (AQMD)—Air districts issue permits and monitor new and modified sources of air pollutants to ensure compliance with national, state, and local emission standards and to ensure that emissions from such sources will not interfere with the attainment and maintenance of ambient air quality standards adopted by the California Air Resources Board (CARB) and the United States Environmental Protection Agency (U.S. EPA).

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.

ALTERNATIVE-FUEL VEHICLE (AFV)—A vehicle designed to operate on an alternative fuel (e.g., compressed natural gas, methane blend, electricity). The vehicle could be either a dedicated vehicle designed to operate exclusively on alternative fuel or a nondedicated vehicle designed to operate on alternative fuel and/or a traditional fuel.

CLEAN TRANSPORTATION PROGRAM—Created by Assembly Bill 118 (Nunez, Chapter 750, Statutes of 2007), 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, and expand transit and transportation infrastructures. Also establishes workforce training programs, conducts public education and promotion, and creates technology centers, among other tasks.

AMERICANS WITH DISABILITIES ACT (ADA)—One of the most significant federal laws governing discrimination against persons with disabilities, passed in 1990. Prohibits discrimination against individuals with disabilities in employment, housing, education, and access to public services. The ADA defines a disability as any of the following: 1. "a physical or mental impairment that substantially limits one or more of the major life activities of the individual." 2. "a record of such impairment." or 3. "being regarded as having such an impairment."

AMPERE-HOUR (Ah)—A unit of electric charge, usually used for batteries. This unit combines the amount of current with how long that current can be sustained until the battery completely discharges. Large batteries have several ampere-hours, but cell phones and other small devices have batteries with a total charge measured in milliampere-hours. This measured quantity is called battery capacity.[18]

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.

BATTERY ELECTRIC VEHICLE (BEV)— BEVs utilize energy that is stored in rechargeable battery packs. BEVs sustain their power through the batteries and therefore must be plugged into an external electricity source in order to recharge.

[18] University of Calgary, Energy Education Website (https://energyeducation.ca/encyclopedia/Ampere_hour)

BATTERY MANAGEMENT SYSTEM (BMS)—Systems encompassing not only the monitoring and protection of the battery but also methods for keeping it ready to deliver full power when called upon and methods for prolonging its life. This includes everything from controlling the charging regime to planned maintenance.

CALIFORNIA AIR RESOURCES BOARD (CARB)— The state's lead air quality agency consisting of an 11-member board appointed by the Governor, and just over thousand employees. CARB is responsible for attainment and maintenance of the state and federal air quality standards, California climate change programs, and is fully responsible for motor vehicle pollution control. It oversees county and regional air pollution management programs.[19]

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

CALIFORNIA ENVIRONMENTAL PROTECTION AGENCY (Cal/EPA)—A state government agency established in 1991 for unifying environmental activities related to public health protection in the State of California. There are five boards, departments, and offices under the organization of Cal/EPA including the California Air Resources Board (CARB), State Water Resources Control Board (SWRCB) and its nine Regional Water Quality Control Boards (RWQCB), Department of Pesticide Regulation (DPR), Department of Toxic Substances Control (DTSC) and Office of Environmental Health Hazard Assessment (OEHHA). The Cal/EPA boards, departments, and offices are directly responsible for implementing California environmental laws, or play a cooperative role with other regulatory agencies at regional, local, state, and federal levels.[20]

CARBON DIOXIDE (CO_2)—A colorless, odorless, nonpoisonous gas that is a normal part of the air. Carbon dioxide is exhaled by humans and animals and is absorbed by green growing things and by the sea. CO_2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO_2 also serves as the reference to compare all other greenhouse gases (see carbon dioxide equivalent).

CLEAN CITIES COALITION NETWORK—As part of the U.S. Department of Energy's Vehicle Technologies Office, Clean Cities coalitions foster the nation's economic, environmental, and energy security by working locally to advance affordable, domestic transportation fuels, energy efficient mobility systems, and other fuel-saving technologies and practices. Since beginning in 1993, Clean Cities coalitions have achieved a cumulative impact in energy use equal to nearly

[19] California Air Resources Board (https://ww2.arb.ca.gov/)
[20] California Environmental Protection Agency (https://calepa.ca.gov/)

8 billion gasoline gallon equivalents through the implementation of diverse transportation projects.[21]

COMPUTER-ASSISTED DESIGN (CAD)—The use of computers to aid in the creation, modification, analysis, or optimization of a design.

CONTROLLER AREA NETWORK (CAN)—A serial network technology that was originally designed for the automotive industry, especially for European cars, but has also become a popular bus in industrial automation as well as other applications. The CAN bus is primarily used in embedded systems, and as its name implies, is a network technology that provides fast communication among microcontrollers up to real-time requirements.[22]

DIESEL GALLON EQUIVALENT (DGE)—The amount of alternative fuel it takes to equal the energy content of one liquid gallon of diesel fuel.

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

EATON CORPORATION (EATON)—A power management company made up of over 99,000 employees that do business in more than 175 countries. Its energy-efficient products and services help customers effectively manage electrical, hydraulic, and mechanical power more reliably, efficiently, safely, and sustainably.[23]

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

ELECTRIC VEHICLE SUPPLY EQUIPMENT (EVSE)— An electric vehicle charging station, also called EV charging station, electric recharging point, charging point, charge point, electronic charging station (ECS), and charger, is an element in an infrastructure that supplies electric energy for the recharging of plug-in electric vehicles—including electric cars, neighborhood electric vehicles and plug-in hybrids.

ELECTRONIC CONTROL MODULE (ECM)—A system that controls a series of actuators in the diesel engine to ensure optimal engine performance through electronic control. Modern diesel engines have a number of sensors within the engine and machine, which provide readings to the electronic control unit (ECU).

ENERGY STORAGE SUBSYSTEM (ESS)—TransPower's systems that employ many technological advances to safely accommodate the large quantities of batteries required for large electric vehicles.

GREENHOUSE GAS (GHG)—Any gas that absorbs infrared radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO2), methane (CH4), nitrous oxide (NOx), halogenated fluorocarbons (HCFCs), ozone (O3), per fluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

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[21] U.S. Department of Energy, Energy Efficiency and Renewable Energy, Clean Cities (https://cleancities.energy.gov/about/)
[22] Copperhill Technologies (https://copperhilltech.com/a-brief-introduction-to-controller-area-network/)
[23] Eaton Corporation (https://www.eaton.com/us/en-us/company/about-us.html)

GROSS VEHICLE WEIGHT (GVW)—The maximum operating weight/mass of a vehicle as specified by the manufacturer including the vehicle's chassis, body, engine, engine fluids, fuel, accessories, driver, passengers, and cargo, but excluding that of any trailers.

GROSS VEHICLE WEIGHT RATING (GVWR)—The maximum weight of the vehicle as specified by the manufacturer. Includes total vehicle weight plus fluids, passengers, and cargo.[24]

INVERTER-CHARGER UNIT (ICU)—Converts DC power from the battery subsystem into AC power for the main drive motors. While the vehicle is plugged in for recharging, it converts AC power from the grid into DC power to recharge the battery pack.

KILOWATT (kW)—One thousand 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 4 kW each hour.

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

LIQUEFIED NATURAL GAS (LNG)—Natural gas that has been condensed to a liquid, typically by cryogenically cooling the gas to minus 260 degrees Fahrenheit (below zero).

LITHIUM-ION (Li-Ion) BATTERY—A type of rechargeable battery. In the batteries lithium ions move from the negative electrode to the positive electrode during discharge and back when charging.

LITHIUM IRON PHOSPHATE (LiFePO4)—In reference to a type of rechargeable battery, specifically a lithium-ion battery, which uses LiFePO4 as the cathode material and a graphitic carbon electrode with a metallic backing as the anode. The specific capacity of LiFePO4 is higher than that of the related lithium cobalt oxide chemistry, but its energy density is less due to its lower operating voltage. Because of low cost, low toxicity, well-defined performance, and long-term stability, LiFePO4 is finding a number of roles in vehicle use, utility scale stationary, and backup power applications.[25]

METHANE (CH_4)—A light hydrocarbon that is the main component of natural gas and marsh gas. It is the product of the anaerobic decomposition of organic matter and enteric fermentation in animals, and is one of the greenhouse gases. Methane is more than 25 times more potent a greenhouse gas than carbon dioxide at trapping heat in the atmosphere.[26]

MOTIVE DRIVE SUBSYSTEM (MDS)—Converts electrical power from the battery subsystem and inverter-charger unit (ICU) into mechanical power to drive the vehicle's wheels.[27]

NATIONAL RENEWABLE ENERGY LABORATORY (NREL)—The United States' primary laboratory for renewable energy and energy efficiency research and development. NREL is the only Federal laboratory dedicated to the research, development, commercialization, and

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[24] U.S. Department of Energy (https://afdc.energy.gov/data/10380)
[25] Wikipedia (https://en.wikipedia.org/wiki/Lithium_iron_phosphate_battery)
[26] U.S. Environmental Protection Agency (https://www.epa.gov/gmi/importance-methane#:~:text=Methane%20(CH4)%20is%20a,%2Dinfluenced)%20and%20natural%20sources)
[27] Transportation Power, Inc. (http://www.transpowerusa.com/downloads/ElecTruck-Drive-System-and-Related-TransPower-Capabilities-May-2012.pdf)

deployment of renewable energy and energy efficiency technologies. Located in Golden, Colorado.[28]

NATURAL GAS (NG)—Hydrocarbon gas found in the earth, composed of methane, ethane, butane, propane, and other gases.

NITROGEN OXIDES (OXIDES OF NITROGEN, NOx)—A general term pertaining to compounds of nitric oxide (NO), nitrogen dioxide (NO_2), and other oxides of nitrogen. Nitrogen oxides are typically created during combustion processes and are major contributors to smog formation and acid deposition. NO_2 is a criteria air pollutant and may result in numerous adverse health effects.

ORIGINAL EQUIPMENT MANUFACTURER (OEM)—Makes equipment or components that are then marketed by its client, another manufacturer, or a reseller, usually under that reseller's own name.

PARTICULATE MATTER (PM)—Unburned fuel particles that form smoke or soot and stick to lung tissue when inhaled. A chief component of exhaust emissions from heavy-duty diesel engines.

POWER CONTROL AND ACCESSORY SUBSYSTEM (PCAS)—A TransPower system that contains most of the power and control electronics used in the ElecTruck™ system, along with the electrically-driven accessories that enable operation of power steering, braking, air conditioning, and other accessories using stored battery energy.

POWER TAKEOFF (PTO)—Secondary engine shaft (or equivalent) that provides substantial auxiliary power for purposes unrelated to vehicle propulsion or normal vehicle accessories such as air conditioning, power steering, and basic electrical accessories. A typical PTO uses a secondary shaft on the engine to transmit power to a hydraulic pump that powers auxiliary equipment, such as a boom on a bucket truck. You may ask us to consider other equivalent auxiliary power configurations (such as those with hybrid vehicles) as power take-off systems.

POUND (LBS)—A pound or pound-mass (abbreviations: lb, lbm, lb_m or ℔) is a unit of mass used mainly in the imperial and United States customary. The most common definition today is the international avoirdupois pound which defined as exactly 0.45359237 kilograms, and which is divided into 16 avoirdupois ounces. So, 1 pound = 16 ounces. The symbol comes from the Roman word libra (hence the abbreviation "lb") while the name pound is a Germanic adaptation of the Latin phrase libra pondo, "a pound by weight". Note that the pound is a unit of mass, not a weight unit. The unit of weight is the pound-force.[29]

PROCESS CONTROL SYSTEM (PCS)—Functions as a piece of equipment along the production line during manufacturing that tests the process in a variety of ways and returns data for monitoring and troubleshooting. Sometimes called an industrial control system.[30]

RENEWABLE NATURAL GAS (RNG)—Or biomethane, is a pipeline-quality gas that is fully interchangeable with conventional gas and thus can be used in natural gas vehicles. RNG is essentially biogas (the gaseous product of the decomposition of organic matter) that has been processed to purity standards. Like conventional natural gas, RNG can be used as a

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[28] National Renewable Energy Laboratory (https://www.nrel.gov/)
[29] Pound Definition https://how-many-ounces-in-a-pound.com/
[30] The Balance (https://www.thebalancesmb.com/process-control-systems-pcs-2221184)

transportation fuel in the form of compressed natural gas (CNG) or liquefied natural gas (LNG).[31]

SOUTH COAST AIR QUALITY MANAGEMENT DISTRICT (SCAQMD)—The air pollution control agency for all of Orange County and the urban portions of Los Angeles, Riverside, and San Bernardino counties. This area of 10,740 square miles is home to over 17 million people—about half the population of the whole state of California. It is the second most populated urban area in the United States and one of the smoggiest. Its mission is to clean the air and protect the health of all residents in the South Coast Air District through practical and innovative strategies.

UNITED STATES ENVIRONMENTAL PROTECTION AGENCY (U.S. EPA)—A federal agency created in 1970 to permit coordinated governmental action for protection of the environment by systematic abatement and control of pollution through integration or research, monitoring, standards setting, and enforcement activities.

VEHICLE MILES TRAVELED (VMT) - Refers to miles driven using electric power over a given period of time. The more general term, VMT, is a measure of overall miles driven over a period of time.[32]

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

WASTE MANAGEMENT COLLECTION AND RECYCLING, INC. (WASTE MANAGEMENT)—An American waste management, comprehensive waste, and environmental services company.[33]

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).

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[31] U.S. Department of Energy (https://afdc.energy.gov/fuels/natural_gas_renewable.html)
[32] U.C. Davis - International EV Policy Council (https://phev.ucdavis.edu/wp-content/uploads/Exploring-the-Role-of-Plug-In-Hybrid-Electric-Vehicles-in-Electrifying-Passenger-Transportation.pdf)
[33] Waste Management Webpage (https://www.wm.com/us/en/inside-wm/who-we-are)