CALIFORNIA
ENERGY COMMISSION

California Energy Commission

Clean Transportation Program

FINAL PROJECT REPORT

Heavy-Duty Electric Yard Tractor

Prepared for: California Energy Commission

Prepared by: Transportation Power, Inc.

Gavin Newsom, Governor

November 2019 | CEC-600-2019-064

California Energy Commission

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Agreement Number: ARV-14-054

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ACKNOWLEDGEMENTS

TransPower would like to thank and acknowledge the California Energy Commission and leaders in California for clean and sustainable environmental vision and for letting TransPower be a part of it. In addition, TransPower acknowledges the support of its Heavy-Duty Electric Yard Tractor project team, including yard tractor manufacturer Kalmar, and the participating fleet operators that test operated the tractors built under this project: Grimmway Farms, Harris Ranch, IKEA, Devine Intermodal, Blue Diamond Almond Growers, and Raley's.

PREFACE

Assembly Bill 118 (Núñez, Chapter 750, Statutes of 2007) created the Clean Transportation Program, also 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 non-road 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 *Investment Plan Update for the Clean Transportation Program*. The CEC issued Program Opportunity Notice PON-14-605, *Medium- and Heavy-Duty Advanced Vehicle Technology Demonstration* to seek applications from eligible entities for medium- and heavy-duty advanced vehicle technology demonstration projects. Demonstrations funded under this PON were required to enhance market acceptance of advanced vehicle technologies that will lead to vehicle production and commercialization, reduce greenhouse gas emissions, and reduce petroleum use. 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 March 24, 2015, and the agreement was executed as ARV-14-054 on May 27, 2015.

ABSTRACT

The California Energy Commission funded the Heavy-Duty Electric Yard Tractor project to demonstrate the feasibility of utilizing battery-electric power to achieve routine operation of class-8 yard tractors, which haul loads of up to 59,000 kilograms in a variety of applications in California and around the world. Off-road yard tractors are commonly used at warehouses, distribution centers, ports, rail yards, and other commercial and industrial locations, are high consumers of petroleum, and emit high levels of pollution. Because these sites are usually embedded within large populations or within disadvantaged communities, the tractors have a disproportionately negative effect on the health and welfare of thousands of individuals.

The Heavy-Duty Electric Yard Tractor's battery-electric power was an ideal solution for such tractors, using an electric drive system TransPower began developing in 2011. The Heavy-Duty Electric Yard Tractor project enabled TransPower to make numerous improvements to electric propulsion systems and to adapt it to the latest yard tractor model manufactured by Kalmar. A total of five electric tractors were manufactured and demonstrated during the Heavy-Duty Electric Yard Tractor project, fulfilling its goal. The success of the Heavy-Duty Electric Yard Tractor project spurred Kalmar to commit to electrification of its yard tractors on a commercial scale, and by the end of the Heavy-Duty Electric Yard Tractor project Kalmar had purchased 12 more TransPower electric drive systems, with the expectation that tens if not hundreds more would be ordered within the next few years.

Keywords: electric vehicle, yard tractor, heavy-duty, alternative energy, clean vehicle, zero emissions, Clean Transportation Program

Please use the following citation for this report:

Falcone, Frank, Michael Simon. Transportation Power, Inc. 2019. *Heavy-Duty Electric Yard Tractor*. California Energy Commission. Publication Number: CEC-600-2019-064.

TABLE OF CONTENTS

Page

LIST OF FIGURES

Page

LIST OF TABLES

EXECUTIVE SUMMARY

Warehouses, distribution centers, ports, rail yards, and other commercial and industrial locations around the world operate off-road vehicles, such as heavy-duty yard tractors. These tractors consume a lot of petroleum and emit large amounts of pollution. Because these sites are usually located within large populations or within disadvantaged communities, the tractors have a disproportionate negative effect on the health and welfare of thousands of individuals.

This project, the Heavy-Duty Electric Yard Tractors, addressed this problem by utilizing battery-electric drive systems to power such tractors, thus eliminating petroleum consumption and emissions at the point of operation. The Heavy-Duty Electric Yard Tractors project showed that battery-electric power is an ideal solution for heavy-duty yard tractors, and its widespread use in various applications enabled the success of the Heavy-Duty Electric Yard Tractors project in overcoming a variety of barriers, unresolved issues, and knowledge gaps in science and technology, marketing, and costs.

The primary objectives of the Heavy-Duty Electric Yard Tractors project were to demonstrate:

- The reduced cost of manufacturing electric tractors, measured by number of labor hours required to manufacture the vehicles, average cost per hour, and material costs.
- A load-carrying capability equivalent to the most capable yard tractors.
- A sufficient operating range to complete two full shifts of 6.5 to 8 hours each, with minimal down time for charging between shifts.
- The availability levels and mean times between failures comparable to those of conventional diesel tractors.
- The energy cost savings, measured as the cost of electricity used to recharge the tractors deducted from the cost of fuel, to do the same work with diesel tractors.
- Significant emissions benefits, measured as the amount of greenhouse gases and criteria pollutants that would have been produced with diesel tractors performing equivalent work.
- A significant displacement of fossil fuels, measured as the amount of fuel that would have been used by diesel tractors performing equivalent work.
- Overall customer satisfaction with the electric tractors.

For the most part, the Heavy-Duty Electric Yard Tractors project met all of these objectives. Transportation Power, Inc. (TransPower) developed a new variant of its electric drive system for Kalmar's new T2-model yard tractor, which was introduced just as this project was getting underway. TransPower installed the drive system into five T2-model tractors, which entered into service at various locations in California between May 2017 and January 2019. Key new technologies incorporated into these tractors include an advanced onboard alternating current fast charging capability and an automated manual transmission. In addition, one of the five tractors was one of the first heavy-duty vehicles built in the United States using the advanced nickel-manganese-cobalt battery technology used in the Nissan Leaf passenger car. These tractors accumulated a total of more than 30,000 miles and 10,000 hours of service during the project term, displacing more than 50,000 gallons of diesel fuel and associated emissions at the point of use. All five tractors operated regularly until the end of the grant period, and are expected to remain in commercial use until the middle of the next decade. All of the fleets that are continuing to utilize these tractors are prominent California companies, including IKEA, Harris Ranch, Grimmway Farms, Blue Diamond Almonds, and Raley's.

Validation of electric yard tractors in these fleets has demonstrated that electrification of tractors used in warehousing and agricultural applications is feasible and can deliver significant environmental and energy efficiency benefits. A parallel TransPower demonstration project funded under a separate CEC grant, the *Advanced Battery-Electric Port Vehicles*, manufactured two additional electric yard tractors using the same technology and placed them into service with Dole Fresh Fruits at the Port of San Diego. Due to the successes of the Heavy-Duty Electric Yard Tractors and *Advanced Battery-Electric Port Vehicles* projects, Kalmar elected to put electric yard tractors into full commercial production using the system developed by TransPower under these agreements.

CHAPTER 1: Project Background

Problem Statement

Yard tractors are pieces of cargo handling equipment that are operating globally at thousands of ports, warehouses, distribution centers, farms, and other locations where heavy goods must be transported short distances on a frequent or continuous basis. Due to their uneven duty cycles and high-power requirements, yard tractors are inefficient when operated on diesel fuel and produce large amounts of toxic pollutants and greenhouse gases. According to the California Air Resources Board (ARB) in Table 1, a diesel powered yard tractor operates an average of 3,000 hours per year and consume approximately 12,000 gallons of diesel fuel per year. This produces about 340 kilogram (kg) of oxides of nitrogen (NOx), more than 12 kg of Particulate Matter ($PM_{2.5}$), nearly 19 kg of total hydrocarbon (HC) emissions, and more than 123,340 kg of carbon dioxide (CO_2).

Table 1: Diesel-powered Yard Tractor Consumption and Emissions Summary

Category	Amount
Fuel Used (gallon):	12,080 gallons
NOx Emissions (kg):	341.20 kg
$PM_{2.5}$ Emissions (kg):	12.30 kg
HC Emissions (kg):	18.60 kg
CO_2 Emissions (kg):	123,340.40 kg

Source: ARB
(https://www.arb.ca.gov/msei/ordiesel/ordas_ef_fcf_2017_v7.xlsx)

The TransPower Solution

Transportation Power, Inc. (TransPower) committed to reducing these harmful pollutants and greenhouse gases in 2011 when it initiated development of its first prototype battery-electric yard tractors, two of which deployed in 2013 for a demonstration in San Antonio, Texas with major retailer H-E-B. The H-E-B demonstration challenged these early prototype electric vehicles (EV) to operate for more than 11 hours on a single charge, at speeds up to 35 miles per hour (Figure 1). As prototypes often do, the demonstration showed strengths and weakness of the design. While the tractors achieved unparalleled energy efficiency and range in hot summer conditions, several components demonstrated insufficient reliability. The H-E-B demonstration also demonstrated the need for a drive system design that is more easily manufactured and serviceable.

Figure 1: M1 and M2 at H-E-B, San Antonio, Texas, 2013

Photo Credit: Transportation Power, Inc.

From 2013 to 2014, TransPower developed a second-generation (Gen-2) electric drive system for yard tractors. Three new battery-electric yard tractors featured the updated design: one that was funded by the San Joaquin Air Pollution Control District for use by IKEA, a furniture retailer, at its main west coast distribution center in Arvin, California, (Figure 2) and two that were funded by the ARB for use at the Port of Los Angeles (Figure 3). Additionally, the South Coast Air Quality Management District funded TransPower to upgrade the two H-E-B tractors, so H-E-B returned these tractors to California for this purpose.

Figure 2: Gen 2 Tractor at IKEA, Arvin, California, 2014

Photo Credit: Transportation Power, Inc.

Figure 3: Port-Spec Tractor Testing at TransPower, 2014

Photo Credit: Transportation Power, Inc.

To build on the successes of these early demonstration efforts, TransPower teamed up in early 2015 with four prominent California tractor fleet operators – IKEA, Harris Ranch, Grimmway Enterprises, and Devine Intermodal – to propose the Heavy-Duty Electric Yard Tractor (HDEYT) project. TransPower conceived of HDEYT to advance a key California policy goal—promoting zero-emission goods movement, particularly in disadvantaged communities (DAC). TransPower's team requested funding from the CEC to manufacture five new battery-electric tractors, which it would demonstrate for two years in daily service in demanding commercial and agricultural applications. The four fleet partners used the tractors to generate a broad base of operating experience with this technology and to develop multiple paths to market. All five tractors were operated in DACs—while the Devine Intermodal trucks were demonstrated in Sacramento, California, the IKEA, Harris Ranch, and Grimmway Farms tractors were demonstrated in the heavily-polluted and economically-distressed San Joaquin Valley.

The HDEYT project sought to build on the success of the earlier prototype yard tractor projects previously summarized. TransPower's prototype tractors demonstrated increasing levels of productivity in the months leading up to the HDEYT project start in June 2015. The tractor pictured in Figure 2, deployed at IKEA's Arvin, California distribution center nine months before the HDEYT project began, continued to operate in daily service through the entire duration of HDEYT. The HDEYT project aimed to further refine the technology used in yard tractors, to the point where major yard tractor manufacturers such as Kalmar could confidently offer electric yard tractors to their customers on a large-scale commercial basis, relying on TransPower to supply drive system components. To help achieve this goal, TransPower persuaded Kalmar to support the HDEYT project by providing unpowered tractor gliders. Converting these gliders to electric operation proved more challenging than expected, partly because Kalmar switched to a new tractor model, called the T2, shortly after the HDEYT project began, which forced TransPower to make numerous additional design changes. In addition, it took Kalmar and TransPower several months to determine which base tractor parts needed to be kept in the glider kit and which were not needed to support installation of the electric drive system.

The prototype tractors deployed by TransPower prior to the HDEYT project demonstrated superior performance and reliability as compared with competing electric tractors, providing a wealth of data to help guide the drive system refinements sought during HDEYT. Specific improvements pursued during the HDEYT project included reducing the weight and cost of the tractor battery subsystem by making design refinements and adopting more cost-effective manufacturing methods. The HDEYT tractors were also to be among the first vehicles to take advantage of a new lithium-ion battery technology that was being evaluated by TransPower when the project began in 2015. The HDEYT project sought to demonstrate that heavy-duty tractors using TransPower's EV components can meet or exceed the performance standards of conventional diesel vehicles in long-term use, and to expand applications to California's vital agricultural sector. Another goal of the HDEYT project was to demonstrate measurable reductions in petroleum use and harmful emissions in DACs, accomplished by providing environmental and economic benefits where they are most urgently needed. The end goal of the project is successful commercialization of TransPower's promising "ElecTruck™" EV drive system products for yard tractors. Measurable metrics used to validate the success of the HDEYT project will include:

- Number of miles and hours of service achieved with the HDEYT tractors.
- Improvement in vehicle operating range and/or reductions in weight.
- Average reliability/availability of HDEYT tractors as compared with conventional tractors.
- Net reductions in petroleum use, greenhouse gas emissions, and criteria pollutant exhaust over the two-year term of the demonstration.
- Reductions in labor hours and total costs required to build electric tractors.
- Number of commercial orders for ElecTruck™ tractors received during the project.

CHAPTER 2:
Yard Tractor Drive System Design

HEDYT Design Approach

Manufacturing reliable electric yard tractors capable of hauling loads in excess of 45,000 kg is a formidable challenge, but one TransPower addressed effectively in early demonstration projects from 2011 through 2015. TransPower demonstrated its first two electric yard tractors in 2013 with H-E-B in San Antonio, Texas, where they displayed impressive power during four months of operation, but demonstrated the need for several improvements to achieve reliable long-term operation (Figure 4, left photo). Drawing on lessons learned from these first two tractors, TransPower improved its ElecTruck™ battery-electric tractor drive system in 2013 and 2014 and built three second generation prototype tractors. The first of these tractors was deployed in September 2014, at IKEA's California distribution center in Arvin, where it showed substantially improved reliability in the months leading up to the HDEYT project, accumulating more than 3,000 miles in its first six months of use (Figure 4, right photo). Two other tractors using TransPower's improved second-generation system also achieved routine, daily, real-world service, one with Dole Fresh Fruit Company at the Port of San Diego and the other with Total Transportation Services, Inc., a drayage firm near the Port of Los Angeles.

Figure 4: H-E-B Tractor in 2013 (Left) and IKEA Tractor in 2014 (Right)

Photo Credit: Transportation Power, Inc.

The successes of these early electric yard tractors provided the foundation for the HEDYT project, which focused on demonstrating a refined tractor drive system suitable for commercial-scale manufacturing. The components used in the HDEYT vehicles were to be similar to those utilized in the earlier prototype vehicles, with improvements to reflect lessons learned from the earlier vehicles to improve reliability, reduce manufacturing costs, and improve serviceability.

TransPower's First Generation Tractor Design

TransPower's first generation (Gen-1) battery-electric yard tractor design, as installed into the two H-E-B prototype tractors in 2012 and 2013, provided a foundation for more than a decade of electric yard tractor development by showing the potential for TransPower's proprietary drive motor-inverter combination to meet the performance requirements of demanding class-8 tractor duty cycles. The Gen-1 yard tractor combined permanent magnet motors manufactured by Jing-Jin Electric Company (JJE) with a custom-designed Inverter Charger Unit (ICU) developed jointly by TransPower and a California startup company, EPC Power (EPC). The CEC helped fund the ICU during TransPower's first grant in 2011, which EPC supported as a major subcontractor.

In the Gen-1 drive system, the TransPower ICU handled high power loads more reliably than some of the off-the-shelf inverters, many of which constantly failed when tested under high power in our first prototype truck. The ICU also had the unique feature of combining the functions of the inverter, which controls the drive motors, and the battery charger. The ICU power section served the dual function of converting grid AC power to DC power for the batteries and converting battery DC power to AC power for use by the traction motors. Each ICU delivered 150 kW of continuous power for the drive motor and supported battery charging at up to 70 kW. During the H-E-B demonstration in 2013, that single ICU showed that it could meet the tractive power requirements of the heaviest yard tractors and recharge battery packs in two hours. Using the onboard ICUs for battery charging eliminated the need for external battery chargers, which are large and expensive.

The Gen-1 yard tractor design incorporated two separate battery strings in the energy storage subsystem (ESS), providing 215 kilowatt-hours (kWh) of total energy storage capacity. This capacity was instrumental in achieving H-E-B's 11-13 hour operational requirements. To house this much energy storage, 14 battery modules were required, each consisting of 16 prismatic lithium-iron-phosphate ($LiFePO_4$) batteries rated at 300 ampere-hours (Ah) each. Accommodating this large battery subsystem required mounting of six modules under the tractor cab plus another eight modules outside the frame rails. This integration approach, pictured in Figure 5, mounted other components such as pumps, controller hardware, and power distribution systems in various locations around the tractor, wherever they would fit. This resulted in numerous, drawbacks including:

- Difficulty servicing of the center-mounted ESS modules;
- Electromagnetic interference with other low voltage components caused by stringing high voltage components about the vehicle;
- Partly due to the large weight of the battery subsystem, the tractors weighed in at approximately 11,790 kg after integration, a significant increase over their production weight of 7,250 kg.

Figure 5: Gen-1 Tractor

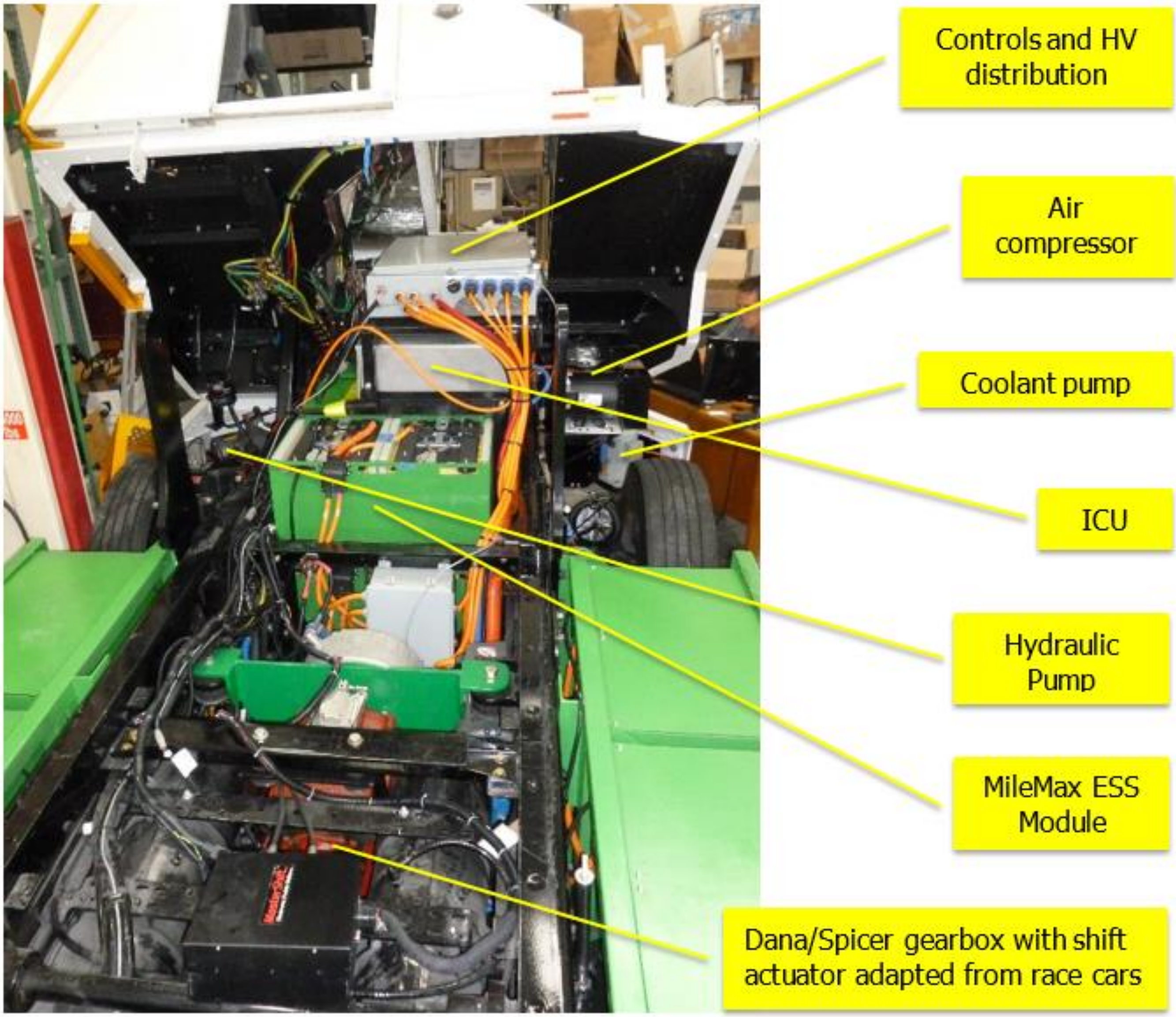


Photo Credit: Transportation Power, Inc.

In addition to these issues, using an automated manual transmission (AMT) such as a Dana/Spicer gearbox – which has a shift actuator derived from the auto racing industry – limited the Gen-1 design. This first attempt by TransPower to utilize an AMT demonstrated the potential of this technology to improve vehicle operating efficiency; however, this particular AMT configuration was too frail to use in demanding yard tractor duty cycles. The H-E-B tractors required frequent repairs due to damage to the AMT shifting mechanism. The H-E-B tractors also required frequent replacement of battery management system (BMS) sensors that were located in battery modules, and these modules were very difficult to access. These shortcomings pointed to the need for design improvements to significantly improve tractor reliability, robustness, and serviceability.

TransPower's Second Generation Yard Tractor Design

To address the issues experienced with the Gen-1 yard tractor design in 2013, TransPower developed and built a second-generation (Gen-2) yard tractor design in 2014 and demonstrated one tractor at IKEA and two tractors at the Port of Los Angeles. Key improvements featured in the Gen-2 design included:

- TransPower designed a Power Control and Accessory Subsystem (PCAS) to use the same space as a diesel engine and to consolidate the accessories and vehicle supervisory controls into one assembly.
- TransPower completely redesigned the ESS around a different battery product from China Aviation Lithium Battery (CALB), a battery supplier.
- TransPower upgraded the powertrain, also called the motive drive subsystem (MDS)
- TransPower upgraded the transmission to an Eaton gearbox using TransPower controls designed into a dedicated Powertrain Control Module (PCM).
- An automotive grade accessory inverter created by German company Lenze and designed for vehicle use replaced the industrial, failure-prone inverters used on earlier tractors.
- Controller Area Network (CAN) controlled automotive grade cooling pumps replaced the industrial pump.
- TransPower reduced the tractor weight from 11,790 kg to about 8,620 kg, primarily by reducing the size and weight of the ESS.

One of the most important advances of the Gen-2 design was the strengthening of the MDS, which adopted a heavier-duty Eaton manual transmission. This modification enabled TransPower to take advantage of an improved AMT product developed by Eaton over the preceding few years. The AMT advances the technology of transmitting torque from electric motors, combining rugged off-the-shelf manual transmissions with state-of-the art shifting controls and software. As previously discussed, TransPower's first-generation AMT used a shifting mechanism designed for racing cars and demonstrated the essential feasibility of an AMT, but revealed that the racing car shift mechanism was not robust enough for heavy-duty vehicles. To overcome this difficulty, TransPower teamed with transmission giant Eaton in 2013 and 2014 and upgraded the AMT to use Eaton's more robust shifting servomechanism. This device is visible near the bottom of the photo shown as Figure 6, mounted on top of the Eaton transmission.

Figure 6: Gen-2 PCAS and MDS Installed in the Tractor

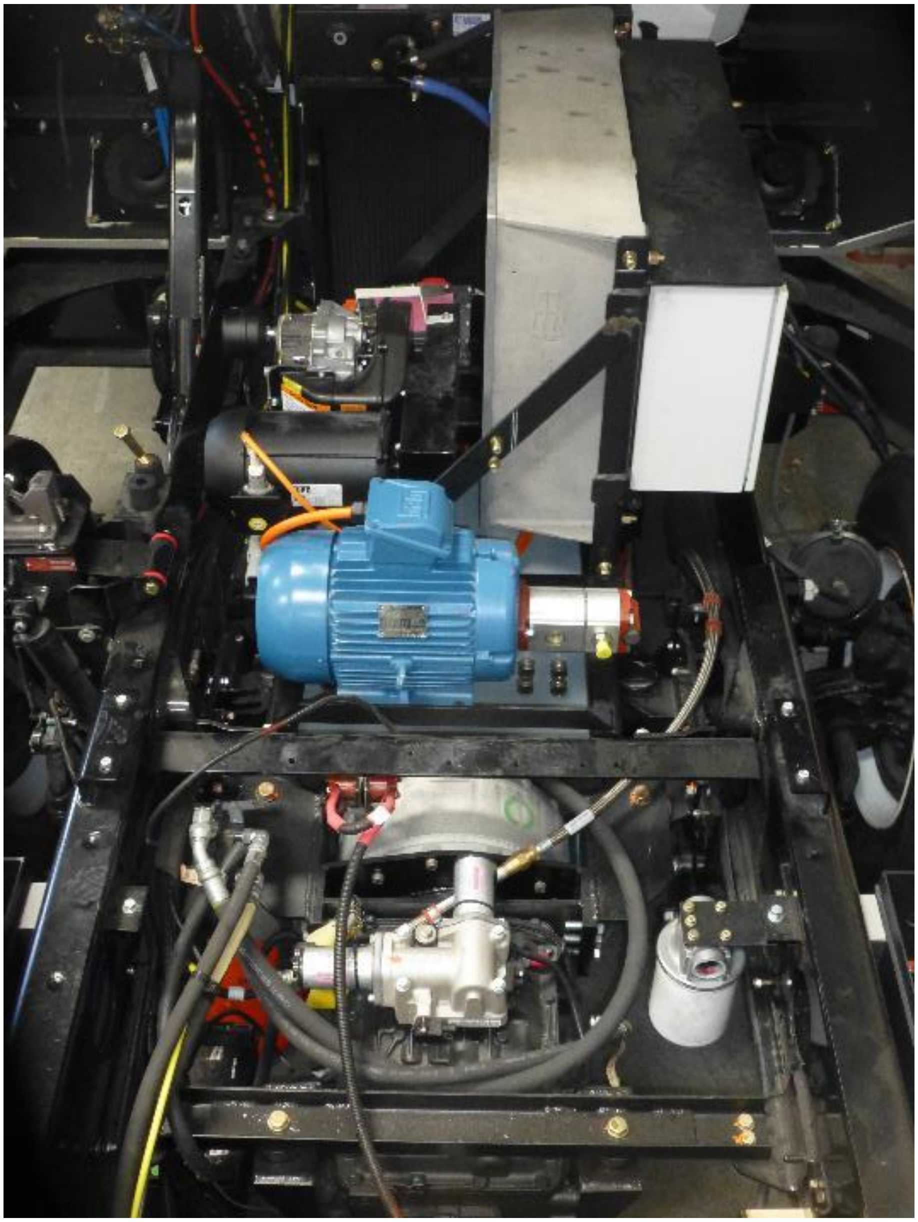


Photo Credit: Transportation Power, Inc.

All other electric vehicles used either direct drive between the electric motor and axle, which limited performance, or automatic transmissions, which relied on inefficient torque converters that sap valuable electric energy from the battery pack whenever the vehicle is running. The AMT provided improved performance at both high and low speeds, while enabling use of a more efficient manual transmission, which reduced energy consumption and increased operating range. The yard tractor variant of TransPower's AMT used Eaton's medium-duty six-speed transmission. For higher power on-road class-8 trucks, TransPower developed an AMT variant that used Eaton's 10-speed transmission. All five tractors built during the HDEYT project used the Eaton-based AMT motive drive subsystem, and TransPower continued fine-tuning AMT shifting software throughout the HDEYT project as it acquired data from trucks and tractors in actual service.

Another key Gen-2 design improvement was the removal of battery modules from the area underneath the cab, which enabled TransPower to consolidate vehicle controls and accessories in this location. This gave rise to development of TransPower's PCAS, a new system integration concept to accommodate the major components used for vehicle control and electrically-driven accessories, including the ICUs discussed above. In the Gen-1 tractors, the ICUs and PCAS components were mounted directly to vehicles, spread around in various locations, and connected with cables. This required TransPower to develop and maintain dozens of different electrical, mechanical, and fluid interfaces with the base vehicle and made it difficult to access and service components once installed. Figure 6, referenced above, shows the integrated PCAS concept installed into one of TransPower's Gen-2 prototype tractors. The large metallic box near the top of the photo is the ICU, the largest component of the PCAS. Directly to the right of the ICU is a white box containing system-level controls, and just below the ICU are the hydraulic motor and pump used to pump cooling fluid through the drive system. Figure 7 shows another view of a Gen-2 PCAS assembly.

Figure 7: PCAS Assembly Developed for Gen-2 Yard Tractor System

Photo Credit: Transportation Power, Inc.

TransPower pre-integrated the PCAS components into a specially designed structure and connected the many wiring and cooling components before installation into the tractor. This approach of pre-integrating all of the PCAS components into a single structure not only reduced TransPower's assembly time, but helped accelerate market acceptance of TransPower's ElecTruck™ system because the drive system kits would be easy for original equipment manufacturers (OEM) to install into vehicles while still on their own assembly lines.

As stated above, a key lesson learned during operation of the Gen-1 H-E-B tractors was that the Gen-1 battery arrangement made it extremely difficult to service batteries or other components in the battery modules, such as the BMS sensors. TransPower also learned that installing 14 large battery modules into a vehicle is exceedingly complex. Hundreds of hours of labor were required to fabricate and wire these many different battery modules. The battery arrangement adopted for the Gen-2 design, pictured in Figure 8, consisted of just four battery modules—upper and lower modules on each side of the tractor. This greatly reduced the time required to install and service batteries.

Figure 8: CALB ESS

Photo Credit: Transportation Power, Inc.

Design Improvements Enabled by HDEYT

TransPower built on all of the design work described in the preceding subsections by making significant additional improvements to its yard tractor design during the course of the HDEYT project.

HDEYT Engineering Preparations

A project kickoff meeting in June 2015, initiated the HDEYT design effort. At this meeting, TransPower made plans to send representatives to meet demonstration partners, establish points of contact, and gather site-specific specifications. The ultimate goal was to visit and assess each site and to complete a demonstration site survey document for each location.

Another key goal of the project kickoff meeting was scope definition. Some projects require extensive research and development and some do not. This project fell into the latter category, as TransPower intended to build on an already successful platform. The overall goal, therefore, was to make key improvements to the design while retaining as much of the prior Gen-2 design as possible. Lessons learned from earlier demonstration projects led to some planned improvements, while a risk analysis report prepared TransPower for new challenges, including:

- Improved resistance to corrosives. TransPower expected exposure to a water/carrot solution at Grimmway Farms to cause corrosion, potentially affecting electrical wiring and connectors.
- Wheelbase reduced from 132 inches to 122 inches.
- Improved access to the rear deck and driving compartment to provide safety on par with the diesel tractor.
- Improved low speed brake regen to improve efficiency.
- Lowered the base rear axle ratio to improve start-on-grade.

TransPower's HDEYT Project Manager Frank Falcone, Engineering Director Ameya Jathar, and Lead Designer Adam Thorp visited five different fleet operator sites (Blue Diamond, Farmers Rice Co-op, Harris Ranch, Grimmway Farms, and IKEA) from August 19, 2015 to August 21, 2015. To determine the operating requirements of the fleet operators, TransPower reviewed the sites and consulted the operators. TransPower emailed customer site surveys ahead of time, which the fleet operators completed before TransPower's arrival. These investigations helped in the development of specifications such as the required differential axle ratio, along with other tractor options.

The HDEYT project team took photos of wash bays, service garages, and other areas of interest. One key conclusion, which was expected, is that the HDEYT tractors would require additional protection against water, mud, and corrosive liquids. Most of the HDEYT tractors would have to operate on dirt/mud surfaces, pull trailers through wash bays, and become exposed to environmental challenges such as carrot washout runoff and wash chemicals.

To illustrate, Figure 9 is a Grimmway carrot washout bay. Here, the vehicle drives onto a tilted surface, rubs against a steel rail to guide it, opens the sides of its trailers, and empties the carrots into troughs where they are washed off with water. Conveyor belts then carry the carrots into a building for processing.

Figure 9: Grimmway Farms Carrot Wash Facility

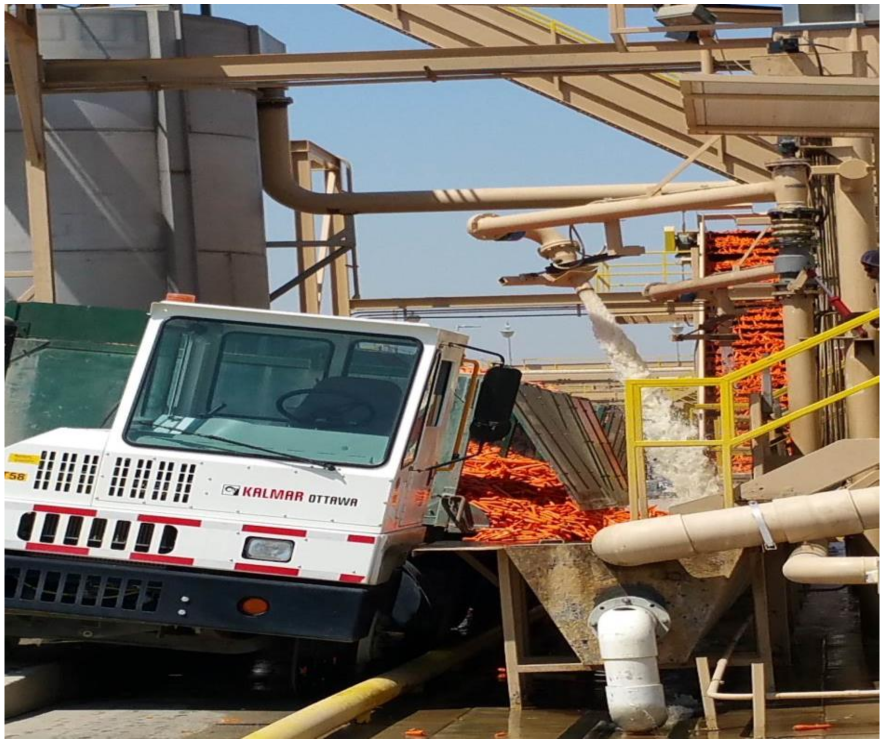


Photo Credit: Transportation Power, Inc.

Frank Falcone, Ameya Jathar, and Adam Thorp continued the engineering preparations in October 2015, by visiting Kalmar's headquarters in Ottawa, Kansas, to review Kalmar manufacturing processes to investigate the possibility of integrating TransPower's hardware into Kalmar's production line. This visit introduced the TransPower team to the realities of production manufacturing, as well as familiarizing Kalmar engineering personnel with TransPower's powertrain. TransPower's project team toured the Kalmar production line and got a feel for the workflow that completes a tractor out every 15 minutes. Kalmar expressed interest in being able to produce TransPower tractors much in the way they produce a diesel tractor. TransPower saw this as a very positive step toward TransPower's long-term plan to commercialize electric yard tractor technology.

All parties agreed that a development flow would commence where Kalmar would be included in TransPower's design reviews to help catch as many problems as possible before the assembly line completes a tractor. To accomplish this, TransPower built the initial tractors to verify the vehicle designs and glider requirements. The next tractors were gliders ordered from Kalmar and built up at TransPower to assess and improve the glider. Kalmar's production line built the final tractor from a kit that TransPower shipped to Kalmar in preparation for full production. The final goals were for Kalmar's manufacturing facility to build a tractor with a TransPower powertrain and to increase TransPower's throughput by being able to order a TransPower specific glider from Kalmar.

Following the visit to Kalmar, TransPower received excellent computer-aided design (CAD) data, electrical schematics, and CAN software files, all of which were required to expedite the engineering process.

Adaptation to New T2 Tractor Design

Shortly after commencing work on the HDEYT project, TransPower learned that Kalmar no longer manufactured the yard tractor model that TransPower used in earlier demonstration projects. Kalmar's new T2 yard tractor design would be the basis for all Kalmar tractors for the HDEYT project. While the older Kalmar model and the T2 look very similar, the T2 has different dimensions and required many design changes to TransPower's drive system.

TransPower was able to assess PCAS fitment and solidify ESS modifications within the New Kalmar T2 tractor chassis. As designed for the previous generation Kalmar yard tractor, the PCAS assembly interfered with a cross member and the cap engine cowl in the new T2 design, requiring PCAS parts to be shifted while the whole assembly was placed lower within the engine bay. Figure 10 is a computer illustration of the new PCAS assembly.

Figure 10: Illustration of New PCAS Assembly for T2 Tractor

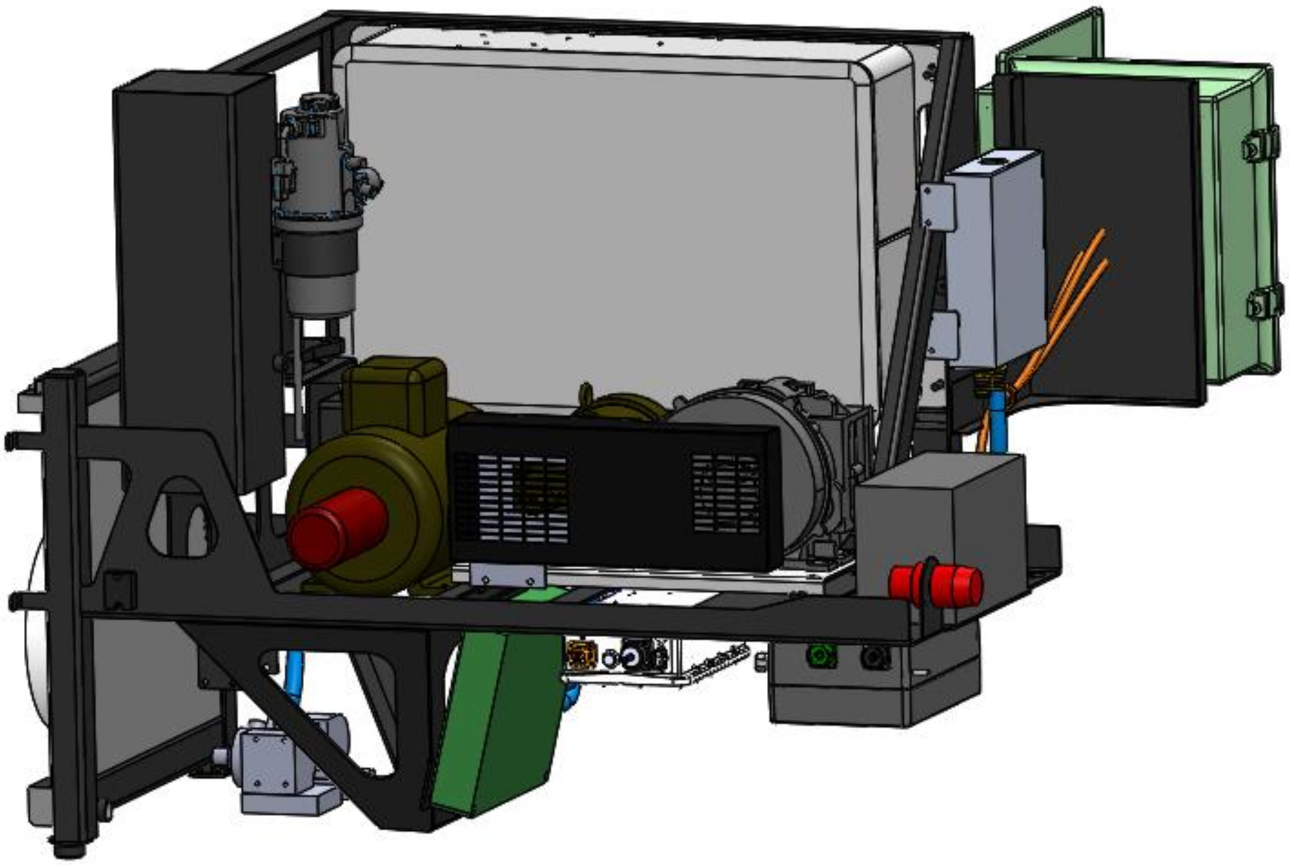


Photo Credit: Transportation Power, Inc.

Figure 11: ESS Integration Concept Developed in Late 2015

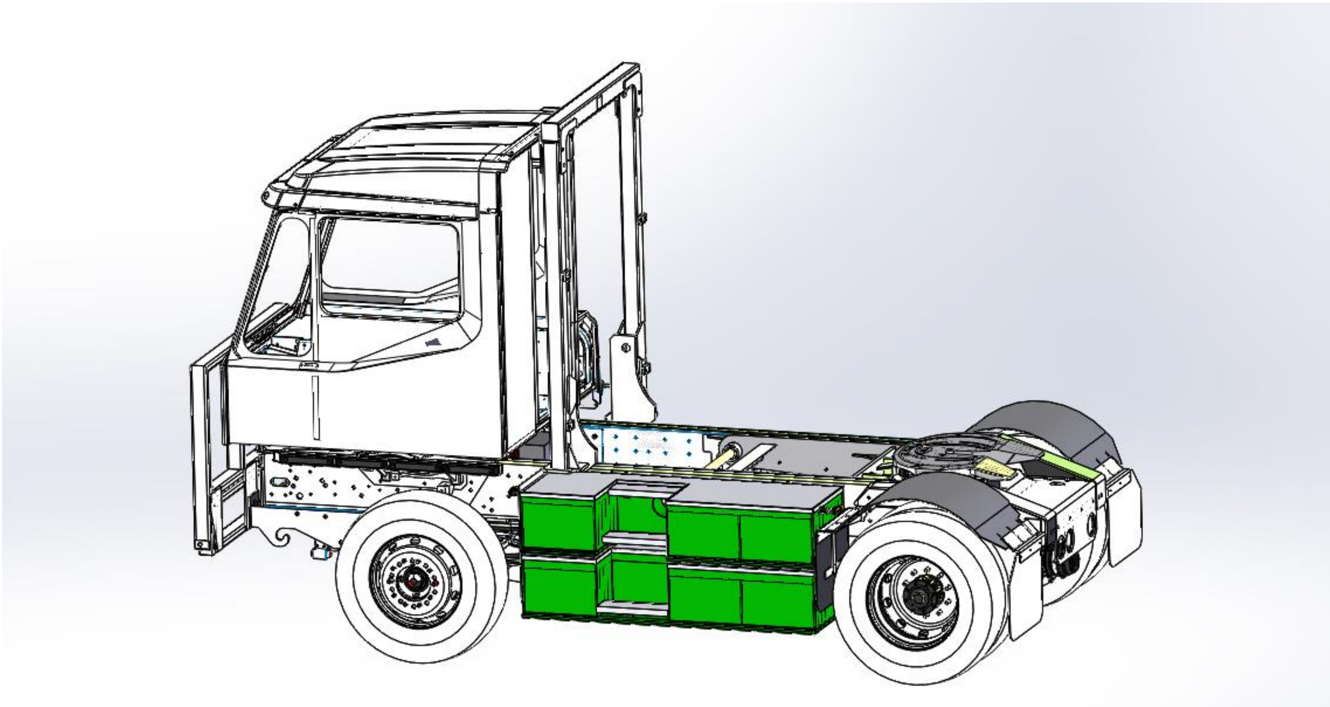


Photo Credit: Transportation Power, Inc.

A key takeaway from TransPower's 2015 site visits was that all future tractors would require safe access steps on the side of the tractor with non-slip surfaces placed within the width of the wheels. Responding to requests from Kalmar and tractor operators, TransPower redesigned the battery subsystem to install steps into the middle of it. The T2 needed the modification in order to conform to the tractor dimensions. TransPower accomplished this by shifting battery cells to the lower box and using space underneath the frame rails. The redesign also allowed access to the boom pin, allowing the customer to remove it without having to remove the ESS. To facilitate higher volume production, TransPower designed the mounting structures with the idea of producing gliders with the structures already in place. Figure 11 is a CAD illustration showing how the new ESS modules will be mounted on a tractor.

Beginning with its Gen-2 tractor system in 2014, TransPower utilized 400 Ah batteries manufactured by CALB. This basic configuration, consisting of 120 CALB cells, was adapted to four of the five HDEYT tractors. The intricate design of TransPower's new Gen-3 battery enclosure design, however, still ended up taking more than a year to develop. Figure 12 is an early-2016 computer model of the complete tractor assembly with the new ESS and PCAS installed. This more refined illustration clearly shows the side steps incorporated into the design for easier and safer access to the rear deck.

TransPower ordered one set of 400 Ah CALB battery cells for the first tractor; however, when TransPower attempted to purchase more of these cells for the second through fifth tractors, CALB informed TransPower that it was discontinuing manufacturing of the 400 Ah cells, and recommended that TransPower switch to its 180 Ah cells. After some analysis, the data confirmed that the existing ESS structure could accommodate the 180 Ah cells, so TransPower ordered a batch of the 180 Ah cells for one additional tractor. TransPower expected this to be the best chance of minimizing extensive new ESS design tasks.

Figure 12: Illustration of T2 with Drive System Installed

Photo Credit: Transportation Power, Inc.

Figure 13 is a battery design developed in mid-2016 based on use of the 180 Ah cells. In October 2016, however, TransPower identified several unexpected design challenges relating to use of the 180 Ah cells.

Figure 13: ESS Design Based on Use of CALB 180 Ah Cells

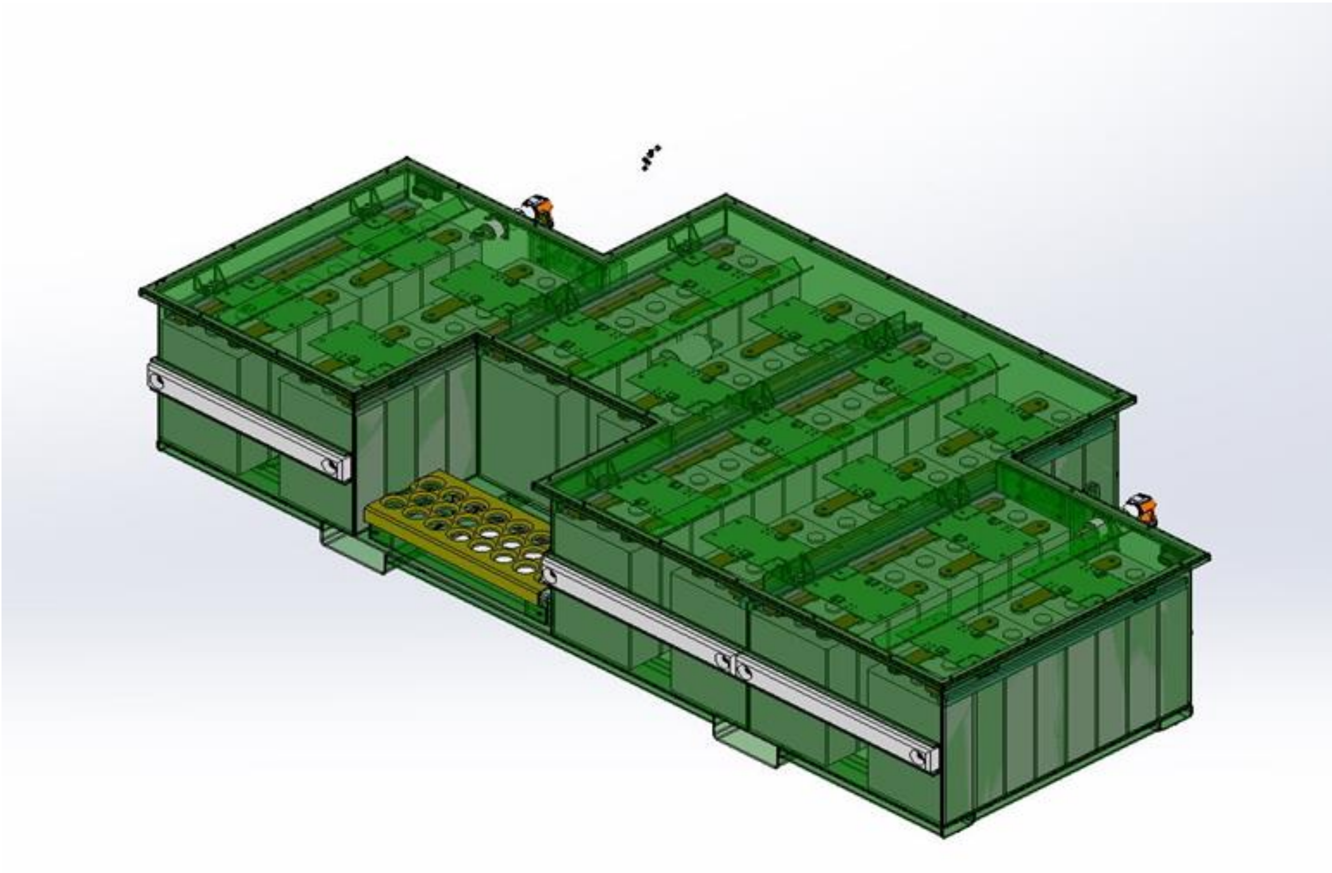


Photo Credit: Transportation Power, Inc.

One key issue was that the design for the BMS board dimensions accommodated only the wider 400 Ah cell and thus would not fit cleanly onto the 180 Ah cell. Since redesigning the BMS board was not a practical option, TransPower made a number of mechanical changes needed to adapt the wider BMS boards to a 180 Ah cell configuration, which would increase the cost of the physical installation considerably, while potentially reducing the tractors' operating range by as much as 10 percent.

In response to these issues, TransPower suspended is efforts to redesign the ESS around the 180 Ah cell and explored other options for procuring 400 Ah cells as originally planned. TransPower determined that CALB could supply enough 400 Ah cells for three of the HDEYT tractors and all but 20 of the cells required for the fourth. Another TransPower cell supplier, Winston, had a compatible 400 Ah cell that could be used to complete the fourth tractor. Accomplishing this allowed four of the five HDEYT tractors to be built with the same ESS design as originally developed for the first tractor. For the fifth tractor, TransPower used Nissan nickel manganese cobalt (NMC) batteries, and designed a multi-purpose battery enclosure for the Nissan batteries during the second half of 2017. This was the last major design effort undertaken during the HDEYT project. The results of HDEYT design activities are discussed further in the following chapter.

CHAPTER 3:
Electric Tractor Manufacturing

Early Manufacturing Preparations and Challenges

Dave Wood, Kalmar's vice president of sales and marketing, visited TransPower in May 2015. He toured TransPower's former manufacturing facility in Poway, CA. He observed a tractor at a local port, discussed improvements in the new T2 chassis, and discussed the possibilities of integrating TransPower hardware into Kalmar's production process. Dave gave his Kalmar colleagues a very favorable report on TransPower's progress and lent optimism to TransPower taking next steps in Kalmar manufacturing integration. Dave suggested that Kalmar and TransPower engineers visit each other's respective sites to assess what can be done from a design standpoint to forward this goal.

Following the TransPower visits to the five operating sites in August 2015, and after receiving confirmation that all HDEYT fleet operators preferred the Kalmar Ottawa tractor, TransPower purchased the first Kalmar tractor (Tractor #1). TransPower ordered a complete tractor, including the engine and transmission to get a feel for how the T2's operates under power. TransPower then removed the engine and transmission following the drive testing. Due to the success of the T2 drive test, TransPower planned to purchase the remaining four tractors from Kalmar as unpowered gliders, which are tractors without engines or transmissions.

TransPower's tractor production efforts ramped up very slowly throughout 2016, taking more time than originally projected because redesign of the drive system for the new T2 tractor turned out to be more difficult than was anticipated when the project started. Fortunately, the grant period provided enough time to complete the design work, integrate the drivetrains, and deploy all five tractors. Kalmar built the first HDEYT base diesel tractor for conversion and delivered it to TransPower in April 2016.

Unfortunately, the tractor showed up in the wrong configuration. The frame was too short, lacked specified reinforcements, and options were missing. Since TransPower planned to remove roughly 70 percent of the base tractor content, it decided to order a new frame with the proper length and to install it using the existing tractor parts rather than have Kalmar manufacture a new tractor. A local shop near TransPower's manufacturing facility assembled the new frame and then delivered it to TransPower. TransPower technicians disassembled the existing tractor and relocated the retained parts to the new frame (Figure 14). Kalmar provided a technician to help TransPower with re-routing wiring harnesses and tubing.

Figure 14: First Kalmar Base Tractor Converted During HDEYT Project

Photo Credit: Transportation Power, Inc.

First Tractor Conversion

Conversion of the first tractor (Tractor #1) began in earnest in mid-2016. One of the first components built in-house by TransPower was the main PCAS structure. Figure 15 shows this welded structure during early stages of fabrication.

The local shop near TransPower completed the tractor frame swap in July 2016 and returned the reconfigured tractor to TransPower for component integration. Figure 16 is a photo of the tractor with the new frame, which has the wheelbase length that is required to allow installation of the battery modules between the axles.

Figure 15: First PCAS Main Structure Being Fabricated

Photo Credit: Transportation Power, Inc.

Figure 16: Tractor #1 After Frame Replacement

Photo Credit: Transportation Power, Inc.

In parallel with development of the ESS design based on 180 Ah cells, TransPower proceeded to manufacture the first HDEYT tractor using one set of CALB 400 Ah cells. TransPower welded the ESS modules together for the first tractors in September, 2016. This process took much longer than anticipated due to the numerous specialized structures that had to be welded to the structure. Simultaneously, TransPower also test-fitted the new PCAS structure into the first tractor and then the hydraulic motor was test-fitted into the PCAS (Figure 17). At the same time, technicians successfully installed the third-generation (Gen-3) MDS into Tractor #1.

Figure 17: Test Fitting of First PCAS into Tractor #1

Photo Credit: Transportation Power, Inc.

Figure 18 shows the MDS installed into the first tractor, prior to final painting. The Gen-3 MDS did not change much from the Gen-2 versions installed into the three prototype yard tractors in 2014. Its main elements are the JJE permanent magnet motor, which provides 100 kW of continuous power and 150 kW of peak power, and the Eaton 6-speed AMT. The JJE motor is the metallic-colored disk to the left and the Eaton transmission is the large black box to its right. The motor and transmission are mated using a customized structure designed and developed by TransPower, which has proven to be extremely durable.

Figure 19 shows the mounting of empty ESS enclosures on the first tractor, prior to the integration of the CALB 400 Ah batteries into the boxes.

Figure 18: MDS Installed Into Tractor #1

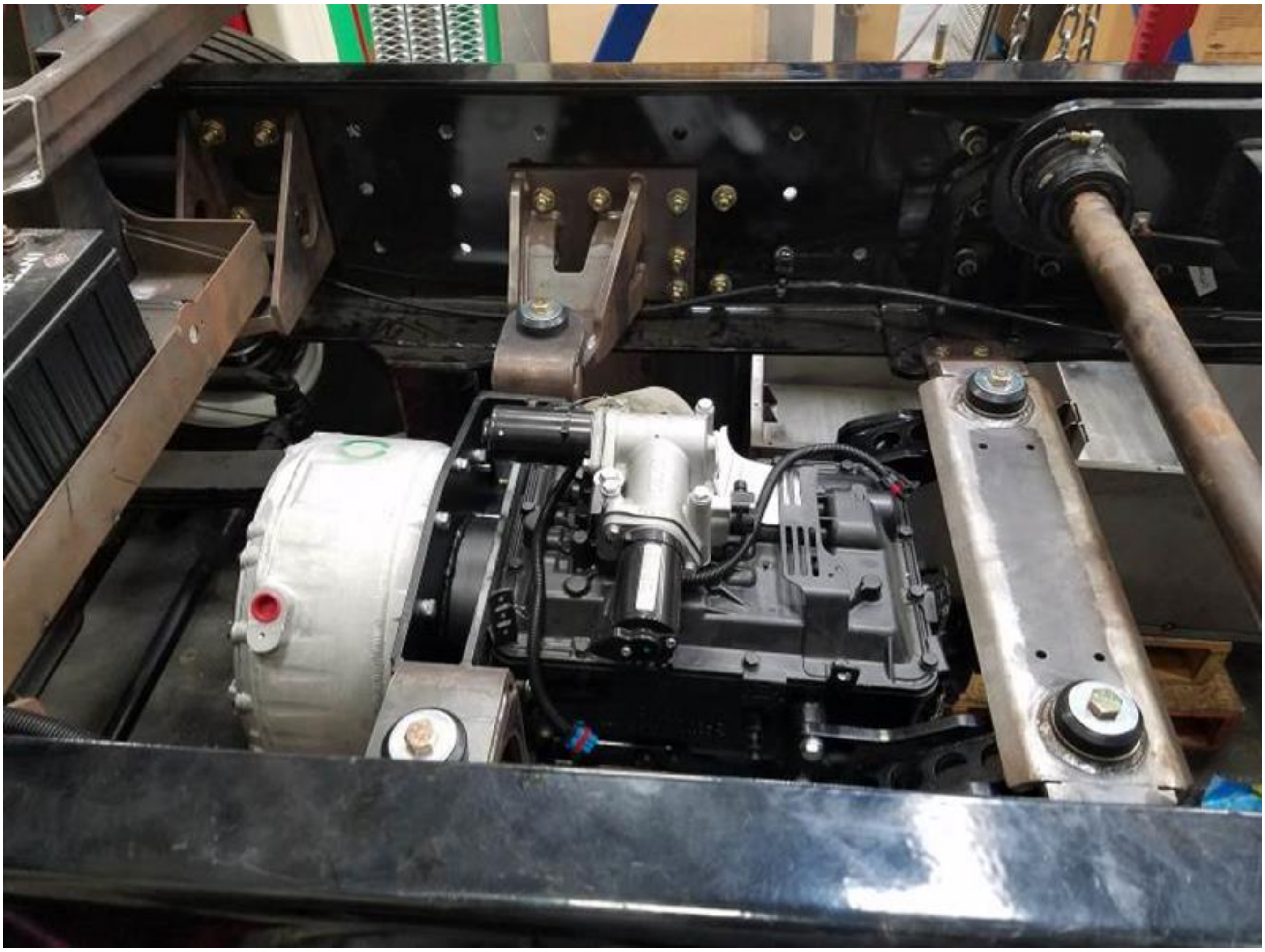


Photo Credit: Transportation Power, Inc.

Figure 19: ESS Enclosures Mounted to Side of Tractor #1

Photo Credit: Transportation Power, Inc.

During final assembly of the first HDEYT tractor during the fourth quarter of 2016, TransPower moved to its new headquarters in Escondido, California. This move provided a 40 percent increase in work area for TransPower's growing team, but caused some additional disruption to the HDEYT project, the completion of which was delayed until March 2017, many months later than originally planned. The switch to the new T2 tractor model, Kalmar's delivery of the first base tractor with incorrect dimensions, disruptions in TransPower's battery supply, and the move to Escondido all contributed to this delay.

Figure 20 shows the first HDEYT nearing completion in TransPower's new Escondido facility.

Figure 20: First HDEYT Tractor Nearing Completion in New Escondido Facility

Photo Credit: Transportation Power, Inc.

Representatives from Grimmway Farms, the fleet operator selected to receive Tractor #1, visited TransPower on April 26, 2017. They test drove the tractor and were pleased with the product. TransPower then transported the tractor on May 1, 2017, to the Advanced Clean Transportation (ACT) Expo in Long Beach, California (Figure 21) and on May 4, 2017, delivered the tractor to Grimmway Farms for demonstration use and data collection.

Additionally, TransPower executed a five-year supply agreement with Kalmar. TransPower and Kalmar announced this agreement on May 1, 2017 in conjunction with the rollout of the first electric T2 tractor at the ACT Expo. The development of a first-tier supplier relationship with a major OEM such as Kalmar could not have occurred without the support of the CEC and this grant.

Figure 21: Tractor #1 on Exhibit at 2017 ACT Expo

Photo Credit: Transportation Power, Inc.

Conversion of Remaining HDEYT Tractors

Tractor #1 became the template for not only all five HDEYT tractors, but also for two tractors converted on a parallel CEC project, *Advanced Battery-Electric Port Vehicles* (ABEPV). After delivery of Tractor #1 to Grimmway Farms in May 2017, TransPower switched its focus to building the remaining four HDEYT tractors. Figure 22 shows PCAS assemblies in July 2017 for the IKEA tractor under HDEYT and a tractor for the ABEPV project.

Figure 22: Building the Tractor PCAS Assemblies

Photo Credit: Transportation Power, Inc.

After a month or two of operations, Grimmway Farms found that the ESS mounts on Tractor #1, while very strong in vertical loads, were inadequate to handle movements along the horizontal or diagonal axes, as when one side of the truck struck a bump or dip. The upper portion of the mounts did not exhibit any issues because the mounts are attached to, and are reinforced by, the frame, but the lower ESS boxes tried to swing side to side and that fatigued the mounts. This failure turned out to be a problem that technicians could not fix in the field, so Grimmway returned the tractor to TransPower's Escondido facility. Technicians determined that the removal and replacement of the ESS on the tractor would be much easier if performed with the tools and other resources available at TransPower. Additionally, Kalmar wanted to borrow the tractor for an exhibit at the North American Commercial Vehicles (NACV) exhibition in Atlanta in late September 2017. Returning the tractor to TransPower provided an opportunity to clean up the tractor and prepare it for the show. Figure 23 is a photo of the frame of the Grimmway tractor after the removal of the ESS enclosures. TransPower successfully replaced the ESS mounts with stronger versions and transported the tractor to the NACV exhibition as planned, then returned to service with Grimmway Farms in October 2017.

Figure 23: Tractor #1 Having Its ESS Mounts Replaced, August 2017

Photo Credit: Transportation Power, Inc.

Due to the design changes to the battery mounting structure, TransPower could not install the ESSes for the remaining tractors until Grimmway operations validated the new ESS mounts on the tractor. When TransPower determined that the new ESS mounting could handle the workload, it took several weeks to have the additional sets of the upgraded mounts manufactured for the other HDEYT project tractors. Additionally, the company manufacturing the PCAS structures and battery boxes for HDEYT project made errors that required the disassembly of the vehicles to return the structures and boxes for rework. This caused even more delays to project completion, which resulted in tractors #2 through #5 not being deployed until 2018.

Use of Nissan Leaf Batteries

In addition to the delays described above, Tractor #4, designated for deployment with IKEA, required different dimensions than the Grimmway tractor due to IKEA's request for a tractor with a dual rear axle. This reduced the space available for batteries and made it impossible to install the same ESS that the Grimmway tractor used.

By this time, TransPower had already determined that CALB's smaller 180 Ah cells were not a desirable replacement for the 400 Ah cells TransPower was able to procure for four of the five HDEYT tractors, so TransPower needed a different battery solution for the fifth tractor anyway. Rather than make unique, one-time modifications to the existing CALB-based ESS to fit the IKEA tractor, TransPower elected to make the IKEA tractor the first vehicle to use a new battery product it had decided to purchase from Nissan.

The switch to the Nissan battery was made possible by investments TransPower had made over the previous six months in testing and evaluating Nissan's NMC battery cells that are used for the Nissan Leaf battery-electric passenger car. TransPower had been in discussions with Nissan about the possibility of using Leaf batteries since before the start of the HDEYT project, but it was not until mid-2017 that Nissan finally agreed to supply batteries to TransPower for use in heavy-duty vehicles.

Adoption of the Nissan batteries at such a late stage in the HDEYT project presented challenges, but offered many potential benefits. The NMC battery chemistry has higher energy density than the $LiFePO_4$ chemistry used by CALB, meaning that more energy can be stored in smaller, lighter packs when using the Nissan batteries. Each Nissan battery module weighs about 9 kg and stores about 1.6 kWh of energy, whereas each 400 Ah CALB battery weighs about 13 kg and stores only about 1.2 kWh. By using 108 of the NMC battery modules used by Nissan in the Leaf, TransPower determined that the energy content provided by the NMC batteries in its Gen-3 design surpassed the energy content of the CALB batteries by about 12 percent. Additionally, the Nissan battery modules are about one-third less expensive on a cost-per-kWh basis than the CALB batteries. Furthermore, the Nissan batteries are made in the United States and can be acquired more quickly than the Chinese-made CALB batteries. Figure 24 shows the IKEA tractor built during HDEYT, showing the two Nissan battery enclosures mounted to the driver side of the tractor.

Figure 24: Tractor #4 Built for IKEA with Nissan Battery Enclosures

Photo Credit: Transportation Power, Inc.

Design-for-Manufacturing Improvements

Throughout the HDEYT project, TransPower made numerous design improvements to reduce drive system costs and to improve the ability of original equipment manufacturers (OEM) such as Kalmar to install drive systems on their own assembly lines. For example, TransPower integrated the radiator, condenser core, hydraulic tank, and charge cable box into a self-contained unit. By doing this, TransPower simplified the PCAS-to-vehicle interface to one low voltage connector. This interior design of the ICU enabled TransPower technicians to assemble the ICU in house, with just a few hours of work, and develop an improved ICU enclosure. The new ICU enclosure is visible in the Gen-3 PCAS shown installed into a tractor in Figure 25.

Figure 25: Gen 3 PCAS Installed Into a Tractor

Photo Credit: Transportation Power, Inc.

These changes enabled TransPower to pre-test with ease all tractor re-power kits on what it calls a "plywood tractor." The "plywood tractor" is test stand that imitates the drive systems prior to shipment (Figure 26). The test consists of filling the drive systems with fluids, powering them up, spinning the drive motor, operating all pumps, and shifting gears. Technicians will then recharge the drive system batteries to validate this function.

Figure 26: "Plywood Truck" for System Testing

Photo Credit: Transportation Power, Inc.

Only after successfully completing all these tests was the assembly packaged for shipment to Kalmar. By the end of the HDEYT project, technicians used the test stand to validate four commercially-purchased yard tractor drive system kits that Kalmar had ordered and had shipped to its manufacturing facility.

These advances enabled the conversion of a tractor at the vehicle manufacturer facility using a TransPower drive system kit delivered from its manufacturing facility. In early 2018, TransPower built a full battery-electric power and drivetrain in Escondido, shipped it to Kansas, and Kalmar installed it into one of the HDEYT tractors with support from visiting TransPower technicians. This process was carried out without any major difficulties and resulted in the first OEM-integrated Kalmar T2 battery-electric yard tractor. Kalmar shipped the tractor to Devine Intermodal in February 2018, for deployment at Blue Diamond Almond Growers in Sacramento. By March 2018, the Grimmway Farms and Harris Ranch tractors were both accumulating mileage at an impressive rate. Blue Diamond had only just had its charging infrastructure installed, so operational use and data collection from the tractor that was integrated in Kansas was in its infancy.

To address the persistent issue of project delays, TransPower initiated a scheduling and reorganization effort in October 2017. This took into account customer expectations, funding source desires, parts availability, and technology evolution. Meritor, a major Tier 1 automotive supplier, made a significant investment in TransPower in November 2017, which allowed the corporate reorganization. Initially, one person was responsible for all aspects of manufacturing, fabrication, and procurement. Under the revised organizational concept, one person was responsible for the ESS, one for integration and commissioning, one for fabrication, and one for PCAS. TransPower also initiated the recruitment of a new supply chain manager in early 2018. It established weekly reviews to compare the build schedule against procurement and other challenges, with an eye on finding ways to meet schedule. These organizational and process improvements resulted in continuous progress throughout 2018 and into the final three months of the HDEYT project in the first quarter of 2019. By the end of the project, all five tractors had been built and validated, with approximately five tractor-years of in-service operation had been accumulated. Operating results are discussed in more detail in the following chapter.

CHAPTER 4: Operational Testing and Evaluation

Tractor Deployment Sites

Four of the five HDEYT tractors deployed with the fleets that originally signaled interest to receive these tractors at the beginning of the project. Farmer's Rice Cooperative elected not to receive a tractor after initially expressing interest. Raley's Supermarkets agreed to operate the tractor in its stead. Table 2 lists the five participating fleets, indicates the type of tractor each fleet received, and the date each tractor was placed into operational service. Unfortunately, the first tractor deployed with Grimmway Farms was the only tractor completed in time to meet the original project goal of providing two years of operations and data collection by the time the HDEYT project concluded at the end of March 2019. The number of unplanned design changes discussed in Chapter 2 delayed the deployment of the other tractors. As a result, those tractors have less than two years of operation. As all five tractors operated intensively and demonstrated superior performance once they were deployed, the HDEYT project provided a wealth of valuable information on the operation of these tractors.

Table 2: Tractor ESS Design and Deployment Dates

Fleet	Tractor Type	Deployment Date
Grimmway Farms	Single rear axle, CALB battery	April 2017
Harris Ranch	Single rear axle, CALB battery	February 2018
Devine Blue Diamond	Single rear axle, CALB battery	March 2018
IKEA	Dual rear axle, Nissan battery	August 2018
Raley's	Single rear axle, CALB battery	February 2019

Source: Transportation Power, Inc.

Grimmway Farms

Grimmway Farms, one of the largest growers, producers, and shippers of carrots, received Tractor #1 (Figure 27). The tractor initially operated in Grimmway's shipping and receiving area, where it would accrue more mileage than it would have in the carrot wash cycle. This also kept the tractor free from the caustic carrot washing. The tractor continued its duties in shipping and receiving until Grimmway became familiar with the machine, while at the same time also installing splash guarding on the tractor in preparation for hauling carrots around the carrot wash.

Figure 27: Tractor #1 – Grimmway's Tractor

Photo Credit: Transportation Power, Inc.

The tractor performed better than planned. With the axle ratio set up for heavier loads, the tractor effortlessly pulled Grimmway's fully loaded 30,000 kg shipping and receiving trailers out of the recessed loading docks that have an eight percent grade. Additionally, the tractor was able to operate two shifts (21 hours) between charging. Below is a performance summary of the shipping/receiving area work:

- Average distance per day: 41 miles
- Maximum distance traveled on a single day: 90 miles
- Average speed: 4.7 miles per hour
- Average energy consumption: 2.3 kWh per mile

In April 2018, the tractor began to serve the carrot wash route while still operating in shipping and receiving. The carrot wash route has heavier loads, rougher road surfaces, shorter daily distances, and exposure to corrosive carrot juice and the tractor continued to operate above expectations:

- Average distance per day: 27 miles
- Maximum distance traveled on a single day: 137 miles
- Average speed: 4.9 miles per hour
- Average energy consumption: 2.5 kWh per mile

Cumulatively, the Grimmway tractor generated the following statistics:

- Average distance per day: 33 miles
- Maximum distance traveled on a single day: 137 miles
- Average speed: 4.8 miles per hour
- Average energy consumption: 2.3 kWh per mile
- Total distance traveled: 9,731 miles

Grimmway Lesson Learned

The Grimmway tractor inspired two design improvements from which all HDEYT tractors benefited: the hydraulic fluid tank and the ESS mounts referred to in Chapter 3.

After producing the Grimmway tractor, TransPower decided to manufacture the hydraulic tank out of steel (Figure 28) instead of aluminum because the steel construction can handle pressure changes better when hydraulic fluid is rapidly forced in and out of the tank when raising and lowering loads. TransPower also elected to mount the tank to the vehicle frame instead of the PCAS.

Figure 28: Hydraulic Fluid Tank Made from Steel

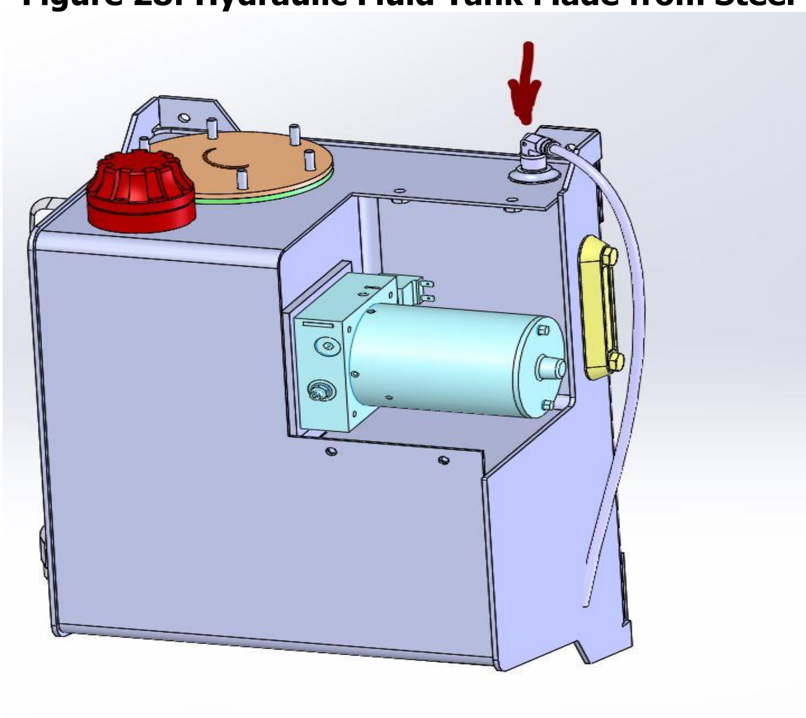


Photo Credit: Transportation Power, Inc.

As stated in Chapter 3, the ESS mounts on the Grimmway Farms tractor, while very strong in vertical loads, were inadequate to handle movements along the horizontal or diagonal axes, as when one side of the truck struck a bump or dip. The lower ESS boxes tried to swing side to side and that fatigued the mounts where the boxes neck down (Figures 29 and 30).

Figure 29: Grimmway's Tractor with Upper ESS Box Removed

Photo Credit: Transportation Power, Inc.

Figure 30: Close-up of ESS Mount

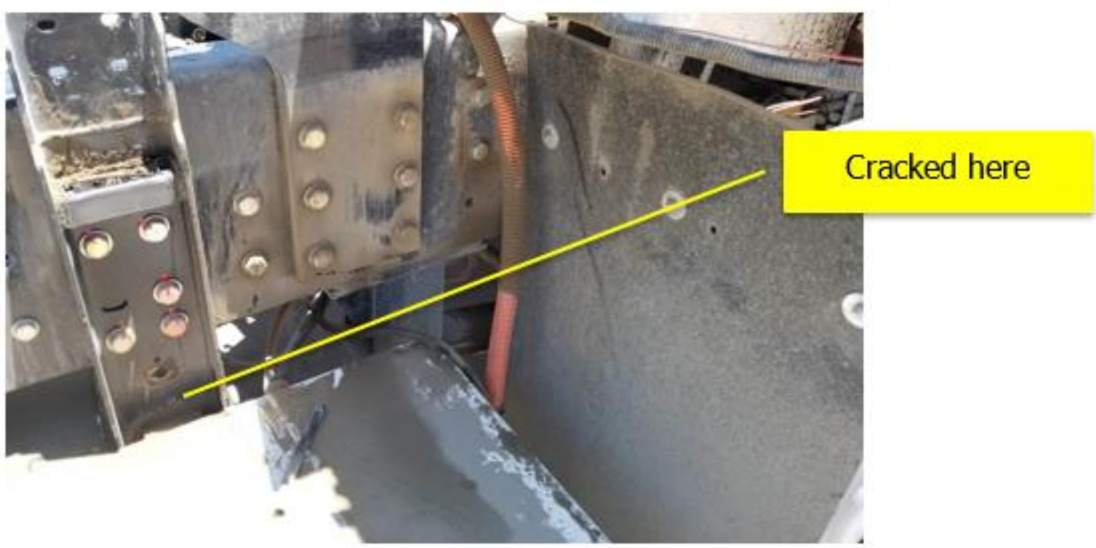


Photo Credit: Transportation Power, Inc.

The new mount design (Figure 31) is a bolt-on modification that adds material to the back of the mount to stiffen it, and does so in a way that if the mount bends backwards, it bends into the frame for added support. This solution and the steel hydraulic fluid tank will be part of all new tractor builds.

Figure 31: Old vs. New Iron Phosphate ESS Bracing Configuration

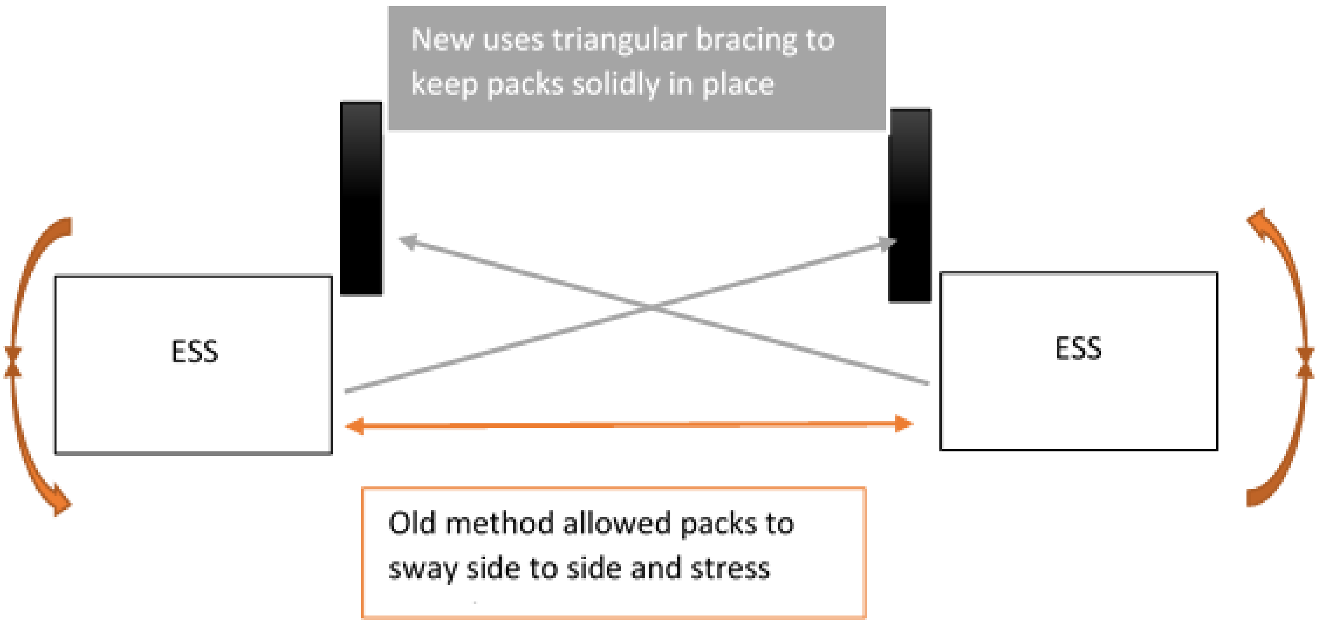


Photo Credit: Transportation Power, Inc.

Harris Ranch

Tractor #2 (Figure 32) was deployed to Harris Ranch Beef Company, one of California's largest beef producers and one of the largest ranches on the west coast of the United States. Harris Ranch owns a fleet of trucks that ferry cattle from several ranches with which it deals to the processing plant where it does its own finishing, slaughtering, and packaging.

Figure 32: Tractor #2 – Harris Ranch's Tractor

Photo Credit: Transportation Power, Inc.

The Harris Ranch deployment went smoothly. TransPower technicians assisted in commissioning Harris Ranch's external charging infrastructure. After that, they placed the tractor on the charger to ensure a fully-charged battery and it went into service the next day. Harris Ranch's application is very typical of a distribution yard tractor and produces the following statistics:

- Average distance per day: 51 miles
- Maximum distance traveled on a single day: 150 miles
- Average speed: 6.5 miles per hour
- Average energy consumption: 2.6 kWh per mile
- Total distance traveled: 11,001 miles

Devine Intermodal at Blue Diamond Almond Growers

Tractor #3 (Figure 33) was delivered to Devine Intermodal at the Blue Diamond Almond Growers processing plant in Sacramento. Blue Diamond is a California agricultural cooperative that specializes in almonds and other tree nuts.

Figure 33: Tractor #3 – Devine Intermodal's Tractor at Blue Diamond

Photo Credit: Transportation Power, Inc.

The duty cycle for the Blue Diamond tractor differs from that of Grimmway and Harris Ranch in that Blue Diamond's tractor travels a lesser distance per day; however, the average speed of the Blue Diamond tractor is higher than Grimmway and Harris Ranch. This duty cycle, while producing a higher rate of average consumption, used only 60 percent to 75 percent of the ESS's usable energy, which allowed the tractor to function well within its operational parameters.

Blue Diamond's duty cycle was typical of a less-intense distribution yard tractor and produced the following statistics:

- Average distance per day: 22 miles
- Maximum distance traveled on a single day: 37 miles
- Average speed: 7.9 miles per hour
- Average energy consumption: 2.9 kWh per mile
- Total distance traveled: 3,684 miles

IKEA Tejon Distribution Center

IKEA received Tractor #4 (Figure 34). IKEA is one of the world's largest furniture retailer and it is committed to lowering its carbon footprint and to adopting new technologies to improve the company's environmental impact. Tractor #4 is the only on-road distribution tractor at IKEA's distribution center in Arvin, California. This tractor has a tandem rear axle that is similar to a typical semi-tractor, making it legal to carry up to 36,280 kg of combined weight loads on public roads and highways. IKEA used this tractor to take loads between warehouses that required driving on the street instead of simply within an enclosed yard; however, even though it was used fewer times than the previous HDEYT project tractors, it traveled more distance per day than did the Blue Diamond tractor, as the statistics show:

- Average distance per day: 27 miles
- Maximum distance traveled on a single day: 60 miles
- Average speed: 10.5 miles per hour
- Average energy consumption: 2.74 kWh per mile
- Total distance traveled: 4,425 miles

Figure 34: Tractor #4 – IKEA's Tractor

Photo Credit: Transportation Power, Inc.

Raley's

While four of the five demonstration companies still wanted to demonstrate the tractors, the Farmer's Rice Co-op was no longer interested. Fortunately, Raley's Supermarkets, a supermarket operator that employs around 12,000 people in northern California, was interested and accepted Tractor #5 (Figure 35). The tractor was delivered to the Raley's distribution center close to the end of the HDEYT project. Raley's, however, did not put the tractor into service immediately upon receiving it because the vehicle charger had not yet been installed. Once installed, Raley's personnel were taught all there is to know about driving the tractor, and all were given an opportunity to test-drive it under a load. The tractor had not been commissioned before the end of the HDEYT project, so it had not collected any data. TransPower is working with Raley's on a lease agreement to enable tractor operation well after the grant period of performance.

Figure 35: Tractor #5 – Raley's Tractor

Photo Credit: Transportation Power, Inc.

Operations Summary

Despite many challenges, the HDEYT project has produced exceptional accomplishments. The tractors continue to accrue mileage and hours at an excellent rate. TransPower is now focusing its efforts on the adoption and commercialization of battery-electric yard tractors. Table 3 summarizes the HDEYT project metric totals of tractor usage, including total miles, total hours of operation, total kilowatt hours, total NOx reductions, total PM reductions, total hydrocarbons reductions, and total CO_2 reductions.

Table 3: Tractor Usage Summary

Metrics Measured	Grimmway	Harris Ranch	Blue Diamond	IKEA	Raley's	Totals
Total Miles	9,731	11,001	3,684	4,425	0	**28,841 miles**
Total Hours of Operation	3,996	7,740	2,080	1,339	0	**15,155 hours**
Total kWh	56,245	68,866	43,987	85,579	0	**254,677 kWh**
Diesel Gallons Equivalent	15,987	30,960	8,320	5,356	0	**60,623 DGE**
Total NOx Reduction (kg)	448	867	233	150	0	**1,698 kg**
Total PM Reduction (kg)	16	31	8	5	0	**60 kg**
Total Hydrocarbons Reduction (kg)	24	46	12	8	0	**90 kg**
Total CO_2 Reduction (kg)	163,197	316,102	84,947	54,685	0	**618,931 kg**

Source: Transportation Power, Inc.

The kWh-diesel conversion in Table 3 is approximate and based on the ARB data that was presented in Table 1. It indicates that a typical diesel yard tractor uses approximately four gallons of fuel per hour. This data is consistent with TransPower's experience; for example, the first yard tractor demonstration with H-E-B in Texas (Chapter 2) revealed that H-E-B's diesel yard tractors used about 50 gallons of fuel per day, over a 12-13 hour shift.

Specific fuel consumption per hour can vary from fleet to fleet, depending on how heavily each tractor is used. Unfortunately, a key data analysis subcontractor was unable to accomplish its some key tasks, so TransPower did not have access to specific fuel consumption data for each of the battery-electric tractors in the HDEYT project, so it used the ARB formula.

CHAPTER 5: Commercialization and Outreach

TransPower's leadership in the battery-electric yard tractor sector has led to not only advancement of clean transportation but also towards a commercialization path for both manufacturing stakeholders and fleet early adopters. These initial electric yard tractors have led Kalmar to dedicate sales, marketing, and dealership efforts towards a branded T2E battery-electric yard tractor line. The demonstration of these units has simultaneously led to further clean transportation acquisitions including planned purchases of T2Es from IKEA and Raley's and interest from other fleets that were not participating in the HDEYT project, including Starbuck's and Everport Terminals.

In early 2016, TransPower representatives attended the Kalmar dealer meeting in Ottawa, Kansas. That gave TransPower a chance to get dealers into the tractor and get feedback, which was overwhelmingly positive. The dealers were looking forward to being able to demonstrate the tractors to customers and they wanted to get purchasing information, which was easily disseminated to Kalmar and its dealers. After that meeting, and while the HDEYT project was still in its design and build phase, TransPower shipped one of its earlier Gen-2 battery-electric tractors to the Ottawa facility for testing by Kalmar. Kalmar tests their tractors at a local Walmart distributor. Walmart drove the Gen-2 tractor approximately 100 miles over 3 test days averaging over 30 miles a day. The tractor was able to do 22-24 pulls (connecting to a trailer and moving it) per hour, which is on par with a diesel T2. The battery-electric tractor was even able to move trailers that had seized brakes when even the diesel T2 could not move them.

The Walmart drivers liked the TransPower tractor's torque, ease of operation, and heater and air conditioning capabilities. There were, however, some concerns expressed by the drivers regarding the difficulty of climbing into the tractor cab without the benefit of steps, which were not available in earlier TransPower tractor designs due to the large battery packs. As discussed in Chapter 2, this issue was resolved with the new battery pack designs used in the HDEYT Gen-3 tractors.

To help speed up TransPower's drive system manufacturing throughput and move closer to Kalmar's Ottawa-based integration, Kalmar manufacturing experts made a series of production planning visits to TransPower starting in August 2017. A month later, Kalmar manufacturing personnel visited TransPower to help integrate components into the second HDEYT tractor, which served as a training exercise in preparation for assembly of future tractors at Kalmar's Ottawa manufacturing facilities.

In September 2017, following the replacement of ESS mounts, the Grimmway tractor was shipped to Kalmar's Ottawa facility where Kalmar employees trained on the new equipment and where the tractor was tested on Ottawa's new tractor test track.

In conjunction with the transportation of the tractor to Kansas, Harry Meyer, TransPower's vice president of manufacturing, visited Kalmar for a week of meetings to discuss the electric yard tractor bill of materials and manufacturing processes. These meetings were part of Kalmar and TransPower preparations for installing TransPower drive systems into Kalmar tractors at the Ottawa facility, a critical transition on the path to full-scale commercialization. Figure 36 is a photo of the Grimmway tractor on Kalmar's Ottawa test track.

Figure 36: Grimmway Tractor on Kalmar Ottawa Test Track

Photo Credit: Transportation Power, Inc.

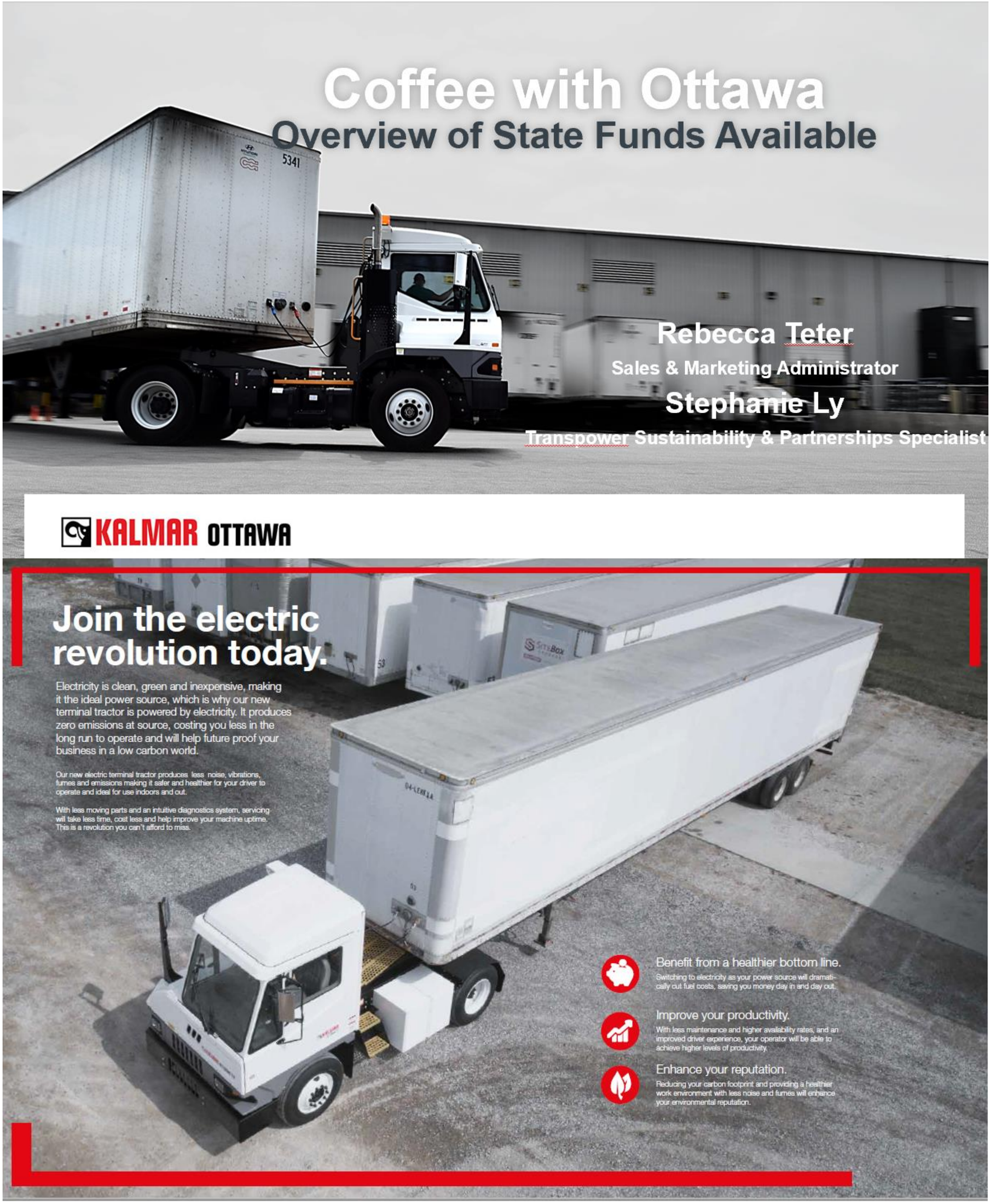
To advance preparations for large-scale manufacturing, TransPower staff held meetings with Kalmar's sales, marketing, and service staff to discuss the market and commercialization plans. After testing the Grimmway tractor in Kansas, it was transported to Atlanta, Georgia for the North American Commercial Vehicle show, where it was the centerpiece of Kalmar's exhibit (Figure 37). While participating in the show, Kalmar and TransPower representatives received many customer inquiries for purchasing a battery-electric T2E.

Figure 37: Kalmar Tractor at the North American Commercial Vehicle Show

Photo Credit: Transportation Power, Inc.

In March 2018, TransPower completed delivery of two complete drive system kits to Kalmar. These kits use Nissan battery modules and are nearly identical to the drive system configuration developed for the IKEA tractor. In April 2018, these kits were installed into two additional tractors being funded by Kalmar and TransPower as cost sharing under the Commercialization and Outreach task. In late-April and early-May of 2018, Kalmar showcased these tractors at its annual dealer meeting. At the same time, TransPower assisted Kalmar dealers in identifying potential clean vehicle funds across different states by holding webinars for grant funding (Figure 38, top), and later assisted dealerships with different grant applications. While that was happening, Kalmar developed a multi-page marketing brochure of the battery-electric T2E yard tractor, which touts the tractor's environmental, health, and reliability and productivity benefits (Figure 38, bottom). These activities significantly advanced the commercialization objectives of this project.

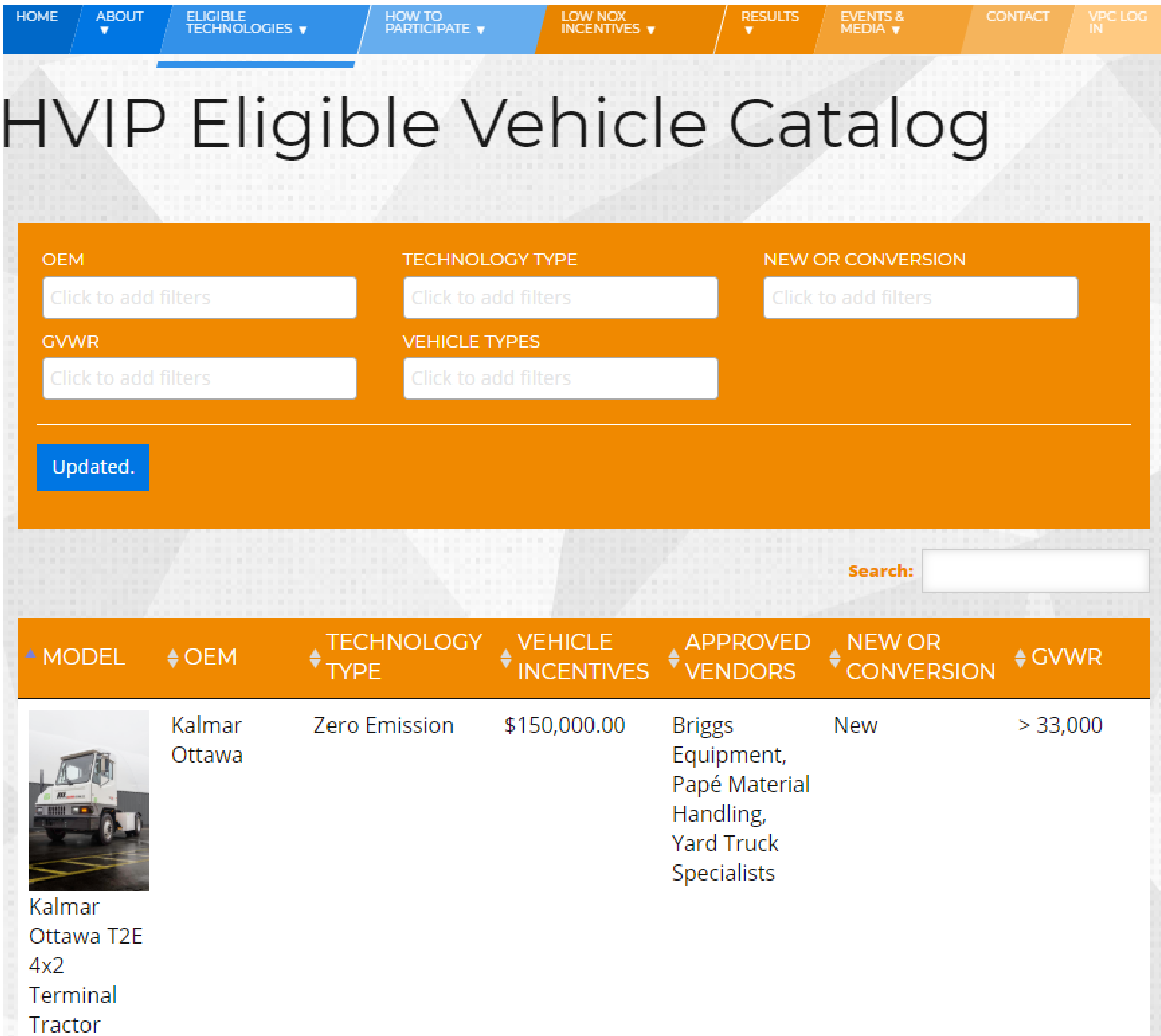
Figure 38: Marketing Materials from TransPower and Kalmar



Source: Kalmar Global

A major milestone that was achieved after the successful shows and demonstrations of these tractors was ARB making the Kalmar T2E eligible for California's Hybrid and Zero-Emission Truck and Bus Voucher Incentive Project (HVIP). The vehicle approval for HVIP required joint engineering and marketing efforts from both TransPower and Kalmar. TransPower also supported three Kalmar dealerships to secure vendor status approval to process the vouchers for Kalmar's fleet customers (Figure 39). Additionally, the T2E tractor was listed as an eligible vehicle for the state of New York's Truck Voucher Incentive Program.

Figure 39: Kalmar T2E Listed as HVIP-Eligible



Source: California Air Resources Board

The battery-electric yard tractors of the HDEYT project have positively engaged and influenced fleet operators. The uptime and consistent use of the units helped forge relationships with end users. Fleet investment in electric vehicle infrastructure and becoming familiar with heavy-duty battery-electric vehicle performance has advanced the early adoption of these technologies. In the fall of 2018, IKEA announced its zero-emissions vehicle (ZEV) goals. IKEA is committed to purchasing more T2E units that will span across major cities. Other fleets, such as Grimmway Farms, have been actively following regulations like the ARB's proposed Advanced Clean Trucks regulation, which may require fleets to own zero-emission (ZE) equipment in the future.

Future Plans

TransPower continues to work with Kalmar's dealership networks such as Cal-Lift and Papé Material Handling in order to drive commercialization. Meanwhile, Kalmar and TransPower continue to work on manufacturing processes at Kalmar's Ottawa facility.

The success of the T2E has garnered national attention across other freight facilities and major fleet operators. Kalmar and TransPower have been in discussions with at least 16 different fleet operators that have expressed interest in electrification (Table 4).

Table 4: Potential Fleet Purchases of the Electric T2E

Fleet operator	Location	Number of Units
Albertsons	Nationwide	TBD
Beltway	Maryland	TBD
Blue Diamond	Sacramento, California	1
Dole	Port of San Diego, California	2
Estes	Nationwide	TBD
Everport Terminals	Port of Los Angeles, California	2
FedEx	Nationwide	TBD
Grimmway Farms	Bakersfield, California	1
Harris Ranch	Central Valley, California	1
H-E-B	Texas	TBD
IKEA	Arvin, California	2
NFI	Port of Los Angeles, California	TBD
Penske	Nationwide	TBD
Raley's	Sacramento, California	1

<u>**Fleet operator**</u>	<u>**Location**</u>	<u>**Number of Units**</u>
Starbucks	Nevada	2
TTI	Port of Long Beach, California	TBD

Source: Transportation Power, Inc.

CHAPTER 6: Conclusion

The CEC funded the HDEYT project to demonstrate the feasibility of utilizing battery-electric power to achieve routine operation of class-8 yard tractors, many of which haul loads of up to 58,900 kg in a variety of applications in California and around the world. TransPower encountered numerous challenges during the HDEYT project, and it had to adapt its electric drive concept continuously to changing technologies while also redesigning its entire system for Kalmar's new T2E model yard tractor. In spite of the delays, TransPower fulfilled the overarching goal of the HDEYT project, which was to manufacture and demonstrate five state-of-the-art battery-electric tractors. Four of the five tractors operated for extended periods, each by a prominent fleet operator: Grimmway Farms, Harris Ranch, Blue Diamond Almond Growers, and IKEA. The fifth tractor was deployed at Raley's Supermarkets distribution center and it was just entering service when the project concluded.

The five tractors of the HDEYT project accumulated a total of nearly 29,000 miles of battery-electric operation displacing more than 60,000 gallons of diesel fuel, and reduced tailpipe carbon emissions by more than 618 metric tons.

The HDEYT project showed that battery-electric power is an ideal solution for yard tractors, using TransPower innovations such as an automated manual transmission, active battery cell balancing, and advanced models-based electric vehicle controls. The HDEYT tractor delivered to IKEA was the first heavy-duty vehicle to use batteries originally designed for light-duty vehicles like battery-electric passenger cars. All five HDEYT tractors operated with a high degree of reliability and gained the confidence of the participating fleet operators, all of which elected to continue operating their tractors beyond the project period of performance. Of even greater significance, the success of the HDEYT project motivated Kalmar to commit to the electrification of its yard tractors on a commercial scale. Within a few weeks of the conclusion of the HDEYT project, Kalmar purchased 27 TransPower electric drive systems on a commercial basis. These drive systems will be installed into tractors that will be manufactured by Kalmar during the second half of 2019. Kalmar also requested that TransPower increase its yard tractor drive system production rate to 150 kits per year by the beginning of 2020, as Kalmar is anticipating huge commercial demand for this trail-blazing product.

GLOSSARY

ADVANCED BATTERY ELECTRIC PORT VEHICLE (ABEPV) – A parallel TransPower demonstration project that is funded under a separate Energy Commission grant. It manufactured two additional electric yard tractors using the same technology as this HDEYT project.

ADVANCED CLEAN TRANSPORTATION EXPO (ACT) – A conference and exposition that brings the transportation industry together to highlight existing and new technologies, fuels, policies, and organizations that are driving innovation and sustainability.

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.

AUTOMATED MANUAL TRANSMISSION (AMT) – A transmission that is a combination of an automatic transmission and a manual transmission. The AMT requires the shifting of gears like a manual transmission, but it does not require a clutch like an automatic transmission.

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 (ARB) – The state agency that is responsible for 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 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:

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

CARBON DIOXIDE (CO2) – A colorless, odorless, non-poisonous 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. CO2 is the greenhouse gas whose concentration is being most affected directly by human activities. CO2 also serves as the reference to compare all other greenhouse gases.

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 Controller Area Network is a communication system made for vehicles that allows many microcontrollers and different types of devices in a vehicle to communicate with each other in real time and also without a host computer.

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

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

DISADVANTAGED COMMUNITY (DAC) – Areas throughout California, predominantly communities of people of color, which most suffer from a combination of social, economic, health, and environmental burdens that include poverty, high unemployment, air and water pollution, presence of hazardous wastes.

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

ENERGY STORAGE SUBSYSTEM (ESS) – One of TransPower's systems that employ many technological advances to safely accommodate the large quantities of batteries required for large electric vehicles. Each ESS is custom-designed for its intended vehicle application, utilizing battery cells and packaging concepts tailored to vehicle operating needs and space constraints.

GREENHOUSE GASES (GHG) – Any gas that absorbs infra-red radiation in the atmosphere. Greenhouse gases include water vapor, carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), halogenated fluorocarbons (HCFCs), ozone (O_3), perfluorinated carbons (PFCs), and hydrofluorocarbons (HFCs).

INVERTER-CHARGER UNIT (ICU) – One of TransPower's systems that automatically regulates the recharging of the vehicle's batteries and safely terminates the charging process when the batteries are brought up to a full charge.

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.

KILOWATT-HOUR (kWh) – The most commonly-used unit of measure telling the amount of electricity consumed over time. It means one kilowatt of electricity supplied for one hour.

LITHIUM-IRON-PHOSPHATE BATTERY ($LiFePO_4$) – A type of lithium-ion rechargeable battery. In the batteries lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. $LiFePO_4$ batteries are finding a number of roles in vehicle use, utility scale stationary applications, and backup power.

MOTIVE DRIVE SYSTEM (MDS) – One of TransPower's systems that is used for vehicle propulsion. It consists of the main electric drive motors and the transmission.

NICKEL-MANGANESE-COBALT BATTERY (NMC) – A type of lithium-ion rechargeable battery. In the batteries lithium ions move from the negative electrode to the positive electrode during discharge and back when charging. NMC batteries are finding a number of roles in vehicle use, medical devices, and industrial equipment.

NOx – Oxides of nitrogen that are a chief component of air pollution that can be produced by the burning of fossil fuels. Also called nitrogen oxides.

ORIGINAL EQUIPMENT MANUFACTURER (OEM) – A company that makes equipment or components that are then marketed by its clients, other manufacturers, or resellers, usually under the resellers' own name.

PARTICULATE MATTER ($PM_{2.5}$) – A mixture of solid particles and liquid droplets found in the air, such as dust, dirt, soot, or smoke. $PM_{2.5}$ are fine, inhalable particles, with diameters that are generally 2.5 micrometers and smaller. The average human hair is about 70 micrometers in diameter.

POWER CONTROL AND ACCESSORY SUBSYSTEM (PCAS) – One of TransPower's systems 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.

HYDROCARBON EMISSIONS – The unburned and partially-burned petroleum combustion emissions. Many have been identified as hazardous to humans and are commonly targeted for abatement or regulatory control.

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 energy source that emits no airborne waste products that pollute the environment or disrupt the climate.

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