High-Power Electric Terminal Tractor (HPETT)

Final Report

for:

New Technology Research and Development Program

582-11-13472-2019

Submitted by:

Transportation Power, Inc.

Principal Investigator:
Michael Simon
Technical Project Manager:
Frank Falcone

Submitted June 30, 2013
Revised July 19, 2013

The preparation of this report is based on work funded in part

by the State of Texas

through a Grant from the Texas Commission on Environmental Quality

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Abstract/Executive Summary

This report documents the results of the High-Power Electric Terminal Tractor (HPETT) project, conducted by Transportation Power, Inc. (TransPower) under a grant from the Texas Commission on Environmental Quality (TCEQ). The HPETT contract was signed on June 6, 2011, and work was formally completed on May 31, 2013. However, the two tractors built under this project remain in service as of the date of this report and TransPower plans to continue supporting the tractors until it is determined whether they are capable of being utilized permanently by HEB, the TransPower partner that has been using the tractors to move trailers at its San Antonio distribution center since mid-April 2013.

The HPETT project involved five major tasks relating to the design, assembly, and testing of two prototype electric terminal tractors developed under this project.

1. *Task 1, Drive System Design,* which was the first task completed under the HPETT project. The principal goals of this task were to select the components for a battery-electric drive system to be installed into two Kalmar terminal tractors supplied by Cargotec, develop plans for installation of the components into the tractors (including layout drawings and installation procedures), and develop and Integrated Test Plan (ITP) describing the tests to be performed to validate the functionality of the electric drive system in the HPETT tractors. Task 1 was completed on March 2, 2012.

2. *Task 2, Vehicle Integration,* which was the second task assigned under the HPETT project. By far the most intricate and extensive of the five assigned project tasks, the Vehicle Integration task involved nine major subtasks:

    a. Procure all components required for electric operation of the terminal tractors, including: drive motors, inverters, chargers, lithium batteries and/or integrated lithium battery packs, and electrically-driven accessory components.

    b. Procure two conventional diesel terminal tractor vehicles.

    c. Integrate the complete electric drive system into the first demonstration tractor, Tractor #1.

    d. Perform component-level testing as installation proceeds.

    e. Update the Integrated Test Plan (ITP) to describe drive testing to be performed following the first truck integration and prior to its delivery to for in-service test and evaluation.

    f. Update the electric drive system required components for the second tractor, if necessary, to reflect any changes in components or parts deemed necessary during initial road testing of Tractor #1.

    g. Update installation drawings and procedures as necessary to reflect new components/parts and lessons learned during integration and testing of Tractor #1.

h. Integrate the complete electric drive system into the second demonstration tractor, Tractor #2.

i. Perform component-level testing as installation proceeds.

Task 2, completed in September 2012, took longer to complete than expected, primarily because the TransPower team took on numerous additional research and development tasks that weren't part of the original proposal. Substantial upgrades were made to all four major subsystems comprising the TransPower electric drive system, as compared with the design concepts envisioned at the start of the project in June 2011.

3. *Task 3, Vehicle Durability Testing,* which was the third task assigned under the HPETT project, was completed in March 2103. The Vehicle Durability Testing task involved seven major subtasks relating to the testing of two prototype electric terminal tractors developed under this project:

    a. Conduct at least three months of durability testing of Tractor #1 in simulated and/or actual service.

    b. Monitor the performance of Tractor #1 and its components during this testing.

    c. Update the electric drive system for the second tractor, if necessary, to reflect lessons learned during durability testing of Tractor #1.

    d. Conduct at least two weeks of durability testing of Tractor #2 in simulated and/or actual service.

    e. Optimize performance of both tractors to maximize their energy efficiency, while assuring adequate performance to meet operating requirements.

    f. Identify actual and potential future problems with the tractor electric drive system and upgrade the system design and installation in the two tractors, as necessary, to mitigate these problems.

    g. Prepare a report documenting results of durability testing and drive system changes made in response to testing results.

    Durability testing was completed in March, 2013. Several reliability issues were identified, and both tractors were retrofitted with the modified designs prior to arriving in Texas.

4. *Task 4, Vehicle Field Demonstration,* which was the fourth task assigned under the HPETT project. The main goal of this task was to demonstrate the tractors' performance in a real world environment. The chosen location for this testing was HEB's main retail distribution center in San Antonio, Texas, where trailers are continuously transported over two daily shifts among several warehouses covering several city blocks. The original contract plan called for the tractors to be demonstrated at HEB for nearly a year, but due to the extended time required to complete the preceding tasks, only two months of field demonstration could be achieved within the contract period of performance. However, TransPower has been supporting continued operation of the two tractors at its own expense since the conclusion of the HPETT contract, and plans to do so for a total period of at least three months

following conclusion of the contract (i.e., until August 31, 2013). At that time, TransPower and HEB will make a determination as to the suitability of the two tractors to remain in service with HEB permanently.

5. *Task 5, Reporting*, which was the fifth task assigned under the HPETT project. This task included submission of monthly reports, task reports, and this final report.

As mentioned above, Tasks 1 through 3 were all extended to permit development and preliminary testing of a more advanced drive system design than TransPower originally intended to install into the two tractors. TransPower was enabled to pursue a more ambitious design by its receipt of several other research and development contracts during the HPETT period of performance. These other contracts, funded by sources such as the California Energy Commission and South Coast Air Quality Management District, enabled TransPower to invest substantially more resources in developing core electric vehicle technologies and new products not envisioned at the start of the HPETT project. These included:

- development of a new "automated manual transmission" with significantly superior capabilities to the two-speed manual transmission originally included in the tractor drive system design;
- utilization of a revolutionary new Inverter-Charger Unit (ICU) for motor control as well as battery charging, as opposed to its original plan of using a commercial off-the-shelf inverter for motor control; and
- incorporation of a new "Mile-Max™" battery module concept, which is expected to be significantly more robust and easier to manufacture than the original HPETT battery module design.

As Tasks 1 through 3 progressed, it became apparent that the design, integration, and testing phases would also have to be extended to enable all of these new technologies and components to be perfected, or at least reduced to practice to the level required for reliable performance of the two electric tractors. Accordingly, the total time allocated for completion of these three tasks was extended from an initial allocation of one year to 21 months, which reduced the amount of time available during the HPETT contract period of performance for in-service field testing. In TransPower's judgment, this modification was justified because it resulted in more improved tractors that stand a better chance of being operated successfully beyond the time frame of the HPETT project. Significant improvements were made to all major tractor subsystems during the design, integration, and durability testing periods, such as making the design of the automated manual transmission more robust and increasing the number of speeds it can accommodate from two to four. These improvements improved the performance and efficiency of the tractors, while making their operation extremely smooth. Extending the durability testing also enabled TransPower to take advantage of a unique opportunity to test Tractor #1 for two full days on a chassis dynamometer operated by the University of California, Riverside (UCR), at no additional cost to the HPETT project.

Results of durability testing and in-service field testing to date seem to have validated TransPower's decision to pursue a more advanced tractor design. In virtually all important categories of performance, the two tractors have exceeded original project expectations. Durability and field testing results indicate that the tractors are capable of operating on a single battery charge for 12 hours even in HEB's

application, which is particularly demanding. Durability and field testing also have provided confidence that the tractors will be highly energy efficient. Based on the UCR dynamometer testing and operational testing at HEB, TransPower calculates that each electric tractor s approximately 2.2 kilowatt-hours (kWh) of energy per mile in very heavy service – carrying heavy loads at unusually high speeds and frequencies. When compared with the one-quarter to one-half a gallon of diesel fuel a conventional tractor would typically use per mile in this type of service, the fuel energy cost of the electric tractors is projected to be at least 3 to 5 times lower than for a diesel tractor.

As of the date of the final editing of this report (mid-July 2013), one of the two tractors delivered to HEB has been performing reliably for a period of approximately one month. The other tractor had intermittent problems throughout the contract period of performance and subsequently, in late June, experienced an unplanned and potentially damaging draw-down of the charge in its batteries while parked overnight. This will require a thorough examination of this tractor's battery pack and battery management system before it can be returned to operating service. Due to resource constraints, TransPower will require several weeks to complete this assessment and any corrective actions, delaying the earliest possible return of this tractor to service until sometime in August. The latter tractor is the second of the two tractors to be built, so its problems may be at least partly due to the fact that TransPower had less time to test this vehicle during the Durability Testing phase of the project in California, prior to delivery of both tractors to HEB in April 2013. In total, Tractor #1 was tested and upgraded by TransPower for a total of eight months prior to shipment of the tractors to HEB, whereas Tractor #2 had only about half as much time to be perfected. TransPower believes Tractor #2 can be made at least as reliable as Tractor #1 by systematically addressing the causes of its recent failures. However, there remains some uncertainty regarding the long-term reliability of some experimental components TransPower acquired from third parties and used in both tractors, particularly the battery management system (BMS).

While the two HPETT tractors are clearly experimental vehicles and will require continued evolution before they represent refined commercial products, TransPower believes that, based on the advanced design of the HPETT tractors and the results of testing to date, the project has greatly exceeded its original objectives. The success of the HPETT project has already resulted in generation of some commercial interest in electric tractors. In the first half of 2013, TransPower received $1.5 million in additional funding commitments from California agencies to build similar electric tractors and place them in service with two major users of terminal tractors – IKEA and Eagle Marine Terminals (a subsidiary of global giant APL Terminals). Thus, the NTRD Program has established a solid foundation for dissemination of a unique new electric propulsion system for terminal tractors, which appears likely to yield significant environmental and economic benefits as these technologies are deployed throughout the world.

Introduction/Background

While large automakers focus on developing electric propulsion technology in smaller vehicles, TransPower's technology is focused on the unique problems created by heavy-duty vehicles, including Class 8 trucks and large terminal tractors. These are among the least fuel-efficient, most polluting vehicles in use today. These problems are particularly acute in the case of locally-driven Class 8 trucks and terminal tractors, also known as "yard tractors", that spend large amounts of time idling and operating a low speeds in heavily-populated areas, such as port drayage and warehouse/distribution facility operations. When equipped with TransPower's electric drive systems, customized for each individual truck/tractor model, these trucks become zero-emission vehicles, operating cleanly and economically on electric power alone. The electric drive motors used to propel these vehicles obtain all their energy from onboard batteries. Such vehicles are simpler and more reliable than conventional internal combustion engine or hybrid vehicles.

TransPower's product offering is innovative because it's one of the first pure battery-electric drive systems targeted at the largest trucks and tractors. Most companies developing electric-based solutions for Class 7 and 8 trucks have focused on hybrid-electric drive systems, where electric motors drive the vehicle but onboard batteries supply only a small fraction of the energy used by the vehicle each day. TransPower's innovative approach is to move beyond hybrids to take advantage of recent advances in lithium battery technology, which make it possible for the first time to achieve sufficient operating range with a pure battery solution. Also, by eliminating the engine, transmission, and fuel system, the battery-electric system gets rid of several of the highest maintenance items on a typical conventional or hybrid truck.

The second, most important unique feature of the battery-electric system is that it eliminates fuel use entirely. Whereas hybrids typically reduce fuel use by only 10 to 20% and natural gas trucks actually use more fuel than diesel trucks, electric systems require no refueling, thereby saving a typical truck operator tens of thousands of dollars each year, even after accounting for the cost of electricity to recharge the system's batteries. A typical terminal tractor uses 5,000 to 10,000 gallons of fuel per year, and based on the results of TransPower's durability and in-service testing, it appears that converting such tractors to TransPower's electric drive technology could save $30,000 per year or more in fuel energy costs per tractor, when comparing the cost of electricity to recharge the tractor batteries to the current price of diesel fuel.

Project Objectives/Technical Approach

The High-Performance Electric Terminal Tractor (HPETT) project was a partnership between TransPower, HEB, and Cargotec with two overarching objectives: to demonstrate a superior electric drive technology for terminal tractors and to use this demonstration project as a springboard for rapid commercialization of TransPower's modular electric drive system. TransPower, an early-stage electric vehicle technology company based in California, purchased two Kalmar Ottawa tractors and retrofitted them with new battery-electric drive systems in 2012. HEB, a Texas-based, privately-owned retail

company, is presently operating the two HPETT electric tractors at its main distribution facility in San Antonio, Texas, where these tractors have shown the ability to move trailers weighing as much as 80,000 lb. at speeds in excess of 40 miles per hour. Key technical, economic, and business objectives of the HPETT project are summarized below.

HPETT Demonstration Project Objectives

- Technical: Demonstrate a robust, reliable electric drive system combining proven components with several key new technologies and products.
- Technical: Demonstrate sufficient operating range for terminal tractors using lithium battery energy storage.
- Economic: Demonstrate that electric tractors are more cost-effective to operate than diesel tractors.
- Business: Strengthen TransPower prototype and demonstration vehicle development capabilities.

HPETT Commercialization Objectives

- Technical: Develop a dependable supply chain for delivery of electric truck and tractor components cost-effectively and on a large scale.
- Technical: Develop facilities and methods for rapid and economical integration of electric drive components into "kits" that can be sold to Cargotec and other major tractor manufacturers.
- Economic: Create sufficient demand for vehicle batteries to drive production cost down and make energy storage systems more affordable.
- Business: Market electric drive systems successfully for short-haul truck and tractor applications, starting with terminal tractors and progressing to other markets such as refuse collection.

Technical Approach

TransPower's technical approach was designed to accomplish the objectives summarized above, while minimizing the risks and costs associated with product development. We were able to do so by modeling the yard tractor and duty cycle requirements before procuring components and beginning the vehicle integration process. In March 2012 we reported on the completion of our first task, *Task 1: Drive System Design,* discussing the selection of components, integration drawings that indicate where the components will be placed on the tractors, and providing an initial set of procedures for the integration and testing of the vehicles. In November 2013 we reported on the completion our second task, *Task 2: Vehicle Integration,* discussing the installation of components into the two tractors. In April 2013 we reported on the completion of our third task, *Task 3, Vehicle Durability Testing.*

Tasks 1 through 3 took longer to complete than expected, primarily because the TransPower team took on numerous additional research and development tasks that weren't part of the original proposal. Substantial upgrades were made to all four major subsystems comprising the TransPower electric drive system, as compared with the design concepts envisioned at the start of the project in June 2011. As each

of the first three tasks progressed, it became apparent that each of these phases would have to be extended to enable all of these improvements. Accordingly, the project design phase was extended from six to nine months, vehicle integration was extended from three to six months, and durability testing was extended from several weeks to a period of seven months. TransPower believes that the additional time invested in building and testing the two tractors was a wise choice, when consideration is given to all of the long-term benefits that are expected to result from the improvements TransPower has made to the drive system design. Durability and in-service test results provide initial confirmation that, in actual tractor operation, these upgrades greatly improve tractor efficiency, operating range, and performance.

Due to the complexity of some of the new technologies integrated into the tractors, the tractors have not yet matched the reliability, maintainability, and overall cost-effectiveness of conventional diesel tractors, even after ten months of continuous testing and product improvement dating back to completion of the first tractor in September 2012. However, we believe that many of the problems the tractors are encountering in service with HEB are the result of the particularly harsh operating environment prevalent at HEB, and that one by one, weaknesses in the design and construction of the tractors are being resolved by our engineers and technicians, working in concert with HEB's tractor drivers and mechanics. We therefore remain confident that with a few more months of testing and improvement, the HPETT tractors will result in end products far superior to competing Class 8 electric drive system and electric tractor products.

Tasks

Task 4: Vehicle Field Demonstration

Tractor Delivery

From the Grant Activities (Scope of Work):

> *"2.4.1. Task Statement: The PERFORMING PARTY will demonstrate the performance of the tractors in a real world environment while monitoring the tractors' performance.*
>
> *2.4.2. Field demonstration and testing*
>
> *2.4.2.1. The PERFORMING PARTY will deliver Tractors 1 and 2 to the field demonstration site, HEB's primary distribution facility in San Antonio, Texas.*

Both yard tractors completed durability testing and final inspections and were loaded onto flatbed trucks for delivery to HEB on April 12, 2013. Figure 1 shows the tractors in the process of being loaded onto the flatbed for shipment. The tractors were delivered to the main HEB distribution center in San Antonio on April 15, 2013.

Figure 1. Tractors loaded and ready for shipment from Poway to San Antonio on April 12, 2013.

Initial Tractor Operation

From the Grant Activities (Scope of Work):

> *2.4.2.2. The PERFORMING PARTY will ensure that Tractors 1 and 2 are operated in normal under real-world operating conditions by HEB tractor operators at HEB's primary distribution facility in San Antonio, Texas, for a period of at least three months.*
>
> *2.4.2.2.1. The PERFORMING PARTY will provide on-site service and support for the duration of the field testing to help maximize vehicle availability. The PERFORMING PARTY will closely monitor all drive system components and functions during the first month of testing, using both data obtained by engineers on the vehicle and data transmitted to the PERFORMING PARTY's facilities via wireless links.*

Supported by visiting TransPower technicians, HEB personnel test operated the two tractors for the remaining seven weeks of the contract period of performance (through May 31, 2013), periodically making modifications to the tractors to improve their functionality and to enable them to meet specific operational needs unique to HEB. Testing included monitoring the effects of operating the tractors at high speeds under load on the rough roads surrounding the HEB warehouses. The tractors were also run

through the HEB vehicle washing facility to verify that the tractors could endure these operations without suffering water damage.

Visiting TransPower technicians provided training to HEB personnel on the operation and maintenance of the electric yard tractors. The first three weeks the tractors were at HEB were extremely productive. HEB personnel quickly indicated that the tractors outperformed electric and hybrid tractors they had tested previously, and invested substantial efforts in working with visiting TransPower engineers to make a number of modifications to the tractors to customize them for unique HEB requirements. There was one small setback about a week after the tractors arrived when a device installed to protect the 12-volt battery on one of the tractors overheated and created a small fire near its wiring. The fire caused little damage and was quickly extinguished and this device was removed from the tractors, and HEB did not appear overly concerned. TransPower investigated the cause of the incident and prepared a detailed report documenting the fact that this was an isolated incident caused by a battery protector circuit which was subsequently removed from both tractors, eliminating the problem permanently. It should be emphasized this incident had nothing to do with the main high voltage battery packs on the tractors, which have performed without incident.

Upgrades During Demonstration

From the Grant Activities (Scope of Work):

> *2.4.2.3. For the duration of field testing, the PERFORMING PARTY will collect data on key operational and performance parameters, accumulating a total of at least 3 months of in-service test data. Data collected will include vehicle availability percentage, mean time between failures or road calls, operating range on a single battery charge, energy efficiency, and hourly cost of operation.*
>
> *2.4.2.4. If necessary, the PERFORMING PARTY will continue to optimize the drive system to maximize energy efficiency while meeting performance requirements and maintaining driver comfort.*
>
> *2.4.2.5. The PERFORMING PARTY may prepare a preliminary test report documenting the results of the first month of field testing and evaluation. This report shall identify any additional changes to the drive system configuration or integration procedures recommended as a result of field testing and evaluation. This report should also include a preliminary evaluation of the readiness of the PERFORMING PARTY's electric drive system product for commercial deployment, based on test results.*

The initial upgrades and training of HEB personnel were largely completed by early May 2013. These upgrades included the following.

- Replacing springs to stiffen the suspension. The added weight of the batteries was found to be causing excess chassis movement, especially when driving at higher speeds on the surface streets connecting the various HEB facilities.
- Additional waterproofing of battery modules and other components to enable the tractors to be regularly washed in the pressure washer bays utilized at HEB.

- Adding a handle to the charger plugs to make it easier for HEB personnel to maneuver the plugs into position for battery charging.
- Strengthening the servo mechanism used to actuate shifting with the automated manual transmission. Fans and filters were later added to help keep the shift mechanisms from overheating.
- Improving the controller area network (CAN) messaging system to provide better data on vehicle operations and component performance.
- Correcting an improperly wired charging cable.

Following this initial set of upgrades, it was hoped that the tractors would be able to regularly haul containers, for complete 8 to 10 hour shifts per day. Efforts to operate the tractors in this manner commenced around the beginning of May 2013. By the end of the contract period of performance on May 31, 2013, the tractors were shown to be capable of operating for entire shifts which typically lasted 9 to 10 hours, typically accumulating 35 to 45 miles of operation per shift. In fact, the data on charge remaining in the vehicles at the end of these shifts implies that they have enough range to operate comfortably for at least 13 hours between charges.

However, it was determined that several additional issues needed to be addressed for the tractors to survive this level of use in the HEB operating environment, which is relatively harsh. The tractors pull heavy loads, operate at unusually high speeds, and travel on rough roads. These factors, along with the hot climate in San Antonio, pushed the tractors beyond their limits in several areas. By the end of the contract, the two tractors had accumulated a total use of only about 300 miles, of which approximately 100 miles was accumulated during operations at HEB during the month of May. If the tractors were fully reliable and capable of being used 5 to 6 days per week, then over the course of May the two tractors should have accumulated closer to 2,000 miles. So trailer availability during May was effectively only about 5%.

Fortunately, it was determined by TransPower engineers and technicians that all of the problems being experienced with the tractors could be solved, provided a concerted effort was made to resolve them. Even though the contract formally ended on May 31, 2013, and TransPower could no longer obtain reimbursements for any of our expenses, we made the decision to send a team of four engineers and technicians to HEB in early June 2013, for a period of two weeks, to perform a series of tractor upgrades at our own expense. We also hired a new field technician, David Ticonchuk, who was assigned to support the tractors on a full-time basis until the end of August or until such time that the tractors can function reliably without his support, whichever occurs first. During the first half of June 2013, a number of changes were made to the two tractors to improve their reliability and robustness, including the following.

- Improvements to shifting software to reduce intermittent shifting problems and make operation at low speeds smoother.
- Replaced and resoldered electrical connectors, enabling more reliably communication of control signals to the shift mechanism.
- Repaired faulty fifth wheel lift mechanism on one tractor.
- Modified fifth wheel inverter parameters to enable fifth wheel to be lifted five seconds faster. This was a key improvement because the speed with which the fifth wheel can be lifted determines how

quickly drivers can connect the tractor to trailers and affects operational throughput (containers moved per hour or per shift).

- Replaced numerous thermistors that were providing inaccurate battery temperature readings.
- Correction of an improperly installed radiator fan on one of the tractors.
- Installation of improved UniCAN systems and antennas to improve data collection.

These improvements had highly positive results on tractor operations. Within the first three weeks of June 2013, the tractors accumulated an additional 400 miles of use, four times the usage recorded for the entire month of May. During the last week of June, the tractors drove another 300 miles. One tractor is functioning well, with an availability of approximately 90% over the previous 10 days. The other tractor continues to need additional troubleshooting and maintenance, and as such has had lower availability.

Schedule

From the Grant Activities (Scope of Work):

> *2.4.3. Schedule: The PERFORMING PARTY shall complete this task within 24 months of the signed Notice to Proceed Date as issued by TCEQ.*
>
> *2.4.4. Deliverables: The PERFORMING PARTY shall submit a report to the TCEQ upon completion of this task. This report will include but is not limited to preliminary and final results of field testing including an analysis of the tractors' performance.*

Task 4 was officially completed on May 31, 2013, within 24 months of the signed Notice to Proceed which was received on June 6, 2011. This final report fulfills the requirement for submission of a report upon completion of Task 4. Preliminary and final results of field testing as of the contract end date of May 31, 2013 have been provided in the preceding sections, plus additional results of field testing performed in the one month since the contract formally ended. Figure 2 is a photo showing the mighty capabilities of the electric tractors built under this project. In this photo, one of the tractors, shortly after its arrival at HEB, is shown pulling a fully loaded refrigerated trailer weighing approximately 80,000 lb.

Figure 2. One of the HPETT tractors during initial tests, pulling a fully-loaded container at HEB in April 2013.

Discussion/Observations

Objectives vs. Results

Task 4: Vehicle Field Demonstration provided TransPower with the opportunity to evaluate and demonstrate the performance and reliability of the two tractors. "Performance" is a measure of how well tractors perform at any given moment, and is measured in such terms as towing capacity, acceleration, top speed, operating range, quickness in capturing containers, and overall ease of operation. "Reliability" is a measure of how dependably the tractors can be relied upon to perform its basic functions, and is generally measured by evaluating hours of operation and/or miles driven, and using these quantities to determine the percentage of time the tractors are available for use. Mean time between failures (MTBF) is another key reliability metric, but the abbreviated duration of the HPETT demonstration phase did not offer sufficient time to produce meaningful MTBF statistics.

Performance and reliability are both essential to the ultimate goal of each tractor – maximizing container throughput. The following paragraphs briefly summarize how performance and reliability results compared with the objectives established, formally or informally, prior to deployment of the tractors.

Performance Objectives

Towing Capacity

One of the most basic questions to be answered by any new vehicle is the extent to which it can meet its basic operating function – in the case of the HPETT tractors, moving containers that can weigh as much as 80,000 lb. when fully loaded. The two HPETT tractors exhibited strong performance in this regard from the beginning of their deployment at HEB. This success was in part due to the inherent strengths of the HPETT tractor design, employing high torque electric motors, 4-speed transmissions to optimize driveline speed and torque over a wide variety of operating conditions, and employment of an extremely large bank of high-power batteries, among other features. This success can also be attributed in part to the extended durability testing performed prior to delivery of the tractors to HEB. One result of this durability testing was the discovery that accessory inverters had a tendency to fault when subjected to high power. By addressing these and other power-related issues prior to sending the tractors to HEB, TransPower was able to deliver tractors which, from the beginning of their deployment at HEB, could move the heaviest containers with ease. This success is further evidence that, contrary to long-held beliefs, electric vehicles can meet and often exceed the performance characteristics of conventional internal combustion engine vehicles.

Top speed

The tractors delivered to HEB achieved top speeds as high as 43 miles per hour in initial testing in San Antonio. This exceeded the maximum speed HEB wants its drivers to reach while operating its tractors, so TransPower's control software was subsequently modified to limit the speed of each tractor to 35 mph. Most yard tractors are used at speeds of 25 mph or less, so the HPETT tractors clearly exceed performance requirements with respect to operating speed. The high speed of these tractors is enabled by some of the same factors that give these tractors strong towing capacity, i.e., powerful drive motors, an excellent transmission, and abundant battery energy.

Operating range

The key challenge facing all battery-electric vehicles is achieving sufficient operating range with the limitations imposed by the energy content of vehicle batteries. HEB is like most yard tractor operators in that its tractors must operate continuously for 8-10 hours to complete a single shift. Due to the comparatively high speeds achieved by tractors operating at HEB's San Antonio's facilities, which span numerous city blocks, each tractor must effectively be able to operate for at least 40-50 miles on a single battery charge to meet HEB's operating requirements.

This requirement would have stressed the limits of most electric tractors built and tested over the past several years, but the HPETT tractors handled this requirement with comparative ease. Throughout the demonstration period, the battery packs in the tractors never dropped below a 25% state of charge, even during ten hour shifts (the maximum duration of an HEB shift) with a high number of containers per hour. Extrapolating from these data, we estimate that these tractors could operate for as many as 13 hours in HEB's demanding operating mode before they would need to be recharged.

The high operating range of the HPETT tractors results from two attributes of its drive system design – the large battery packs installed into the tractors and the high efficiency of the tractors' electric drive

systems. As discussed extensively in this and previous reports, innovations such as TransPower's automated manual transmission and electrically driven accessories help boost efficiency and enable the tractors to make the most of the 215 kilowatt-hours (kWh) of energy stored in each tractor's battery pack. The HPETT tractors have the added advantage of employing high-power onboard inverter-charger units (ICUs) that can recharge the tractors' batteries comparatively rapidly. A fully discharged pack can be recharged in less than 3 hours by using the onboard ICU at its maximum charge rate of 70 kW. With a 1-2 hour break between shifts, HEB could use the ICU to obtain enough of a charge after one shift to complete a second shift. HEB has not elected to operate the tractors in this manner, but the option will be available to other users of tractors employing the HPETT design. In evaluating the utility of the HPETT design to other potential customers, it is also important to consider the intensity of the user's duty cycle. As HEB's duty cycle is relatively severe for a yard tractor, due to the tractors' high operating speeds and the fact that they are used to move containers more or less continuously throughout each duty cycle, tractors of the HPETT design could operate for substantially more than 13 hours in less demanding applications. In summary, all operating range expectations for these tractors have been met and surpassed.

Quickness in capturing containers

As discussed previously, an early complaint about the HPETT tractors that was commonly heard during the first few weeks of testing was that the fifth wheel mechanism used to connect to trailers was too slow. By subsequently adjusting the control parameters programmed into the variable frequency drives that power the electric fifth wheel lift accessories, TransPower engineers were able to speed up the operation off the fifth wheel lifts by several seconds, helping to alleviate this concern. At this point, we believe the HPETT tractors' quickness in capturing containers is comparable to that of conventional yard tractors.

Reliability Objectives

The number of miles that the two tractors have collectively driven is an effective proxy for reliability because the tractors are stationary during repairs and retrofits. At the beginning of the vehicle field demonstration, the two tractors had collectively accumulated a total of 200 miles. These miles were accumulated during Task 3 which occurred between September, 2012 and mid-April 2013, for an average of only 6.66 miles per week. This is largely due to downtime caused by implementing fixes to some of the issues that were uncovered during Task 3. During the second half of April, 2013 and the month of May, 2013, the tractors drove for an additional 100 miles. The first three weeks of June saw an additional 400 miles driven, with the last week of June alone adding 300 miles to the total. The chart below shows the improvement of the Tractors' collective miles per week over time.

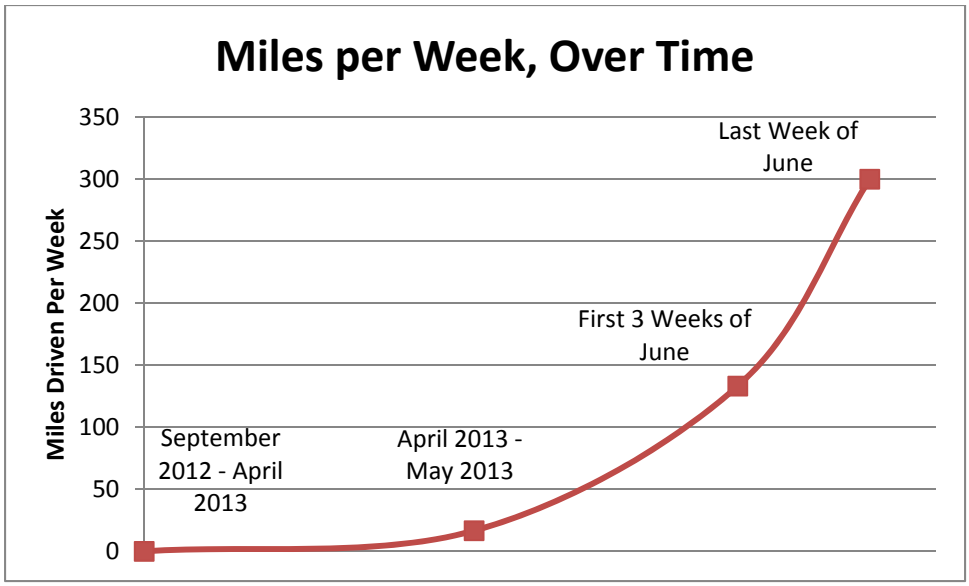

Figure 3: Miles per Week, Over Time

The chart shows the magnitude of improvement that the tractors have seen in terms of miles driven since the beginning of Task 4. Higher mileage per week can either be a result of fewer service calls or alternatively less downtime per service call. The improvement in the tractors' mileage is a result of both effects. The tractors are experiencing fewer service calls, and the required interventions are taking the tractors out of service for shorter periods of time.

Container Throughput

Since the primary function of a yard tractor is to move containers, container throughput is the key metric of tractor performance. TransPower's objective for Task 4 was to demonstrate that the two tractors could match diesel tractors in terms of container throughput. The container throughput metric is very sensitive to the specific details of any given shift, such as where the containers are physically located within the facility, so it can be difficult to have a true apples to apples comparison. HEB has indicated that a successful 10 hour shift will typically involve between 25 and 40 container trips, or about 2.5 to 4 containers per hour.

Initial reports from the HEB drivers indicated that the HPETT tractors were achieving an average throughput of approximately 2.1 containers per hour. The drivers also identified specific issues that were slowing down the overall container moving operation. These included shifting issues that were preventing the truck from accelerating quickly, as well as the tractors taking too long to raise and lower containers using the fifth wheel lift (as discussed above). Additionally, TransPower technicians discovered that one of the tractors had energy storage system thermistors that were reporting unusually high values, even though the batteries were not particularly hot. This was causing the system controller to derate the system because it thought it was experiencing thermal stress, yielding unimpressive performance. Once TransPower's technicians had an opportunity to fix some of these issues, container throughput ranged from 1.9 to 2.9 containers per hour, with several hours seeing as many as 4 containers per hour.

Critical issues

As might be expected with any experimental vehicle, the HPETT tractors have encountered numerous performance or reliability issues that have had to be addressed during the field demonstration at HEB. Table 1 summarizes these issues and the solutions implemented by TransPower in response. Also included in the table are comments on how experience with these issues will influence the design of future yard tractors and, in some cases, other heavy-duty electric vehicles being designed and developed by TransPower. The latter observations are significant because TransPower has attempted, to the greatest extent possible, to use similar components in a broad variety of heavy-duty electric vehicles, including the HPETT tractors, on-road drayage trucks, and even a prototype electric school bus. Experience gained on the HPETT project is having a profound effect on all of TransPower's vehicle projects, and most of the innovations developed and demonstrated during the HPETT project will be utilized in other vehicles, operated in a broad variety of circumstances, for years to come.

Table 1. Summary of tractors' performance and assessment of future drive system improvements required for successful commercialization

Subsystem	Problem Observed	Immediate Solution Applied to HPETT/HEB Tractors	How Problem will be Addressed in Design of Future Electric Tractors	Impact on Design of Other TransPower Vehicles
Main Propulsion	Temperature sensors provided faulty motor temperature readings	Temperature sensors were recalibrated to provide more accurate readings	Improved calibration procedures will be applied to future tractors	Improved calibration procedures will be applied to other future vehicles
Main Propulsion	Transmissions were experiencing sloppy or failed shifts intermittently	These issues were addressed by a combination of software and hardware fixes. The shift hardware geometry was modified to prevent binding and ensure that the shift flag remains in alignment, even when the transmission shift rails are hot. A fan was also added to the enclosure that contains the shift actuator motors, as they were overheating and derating. The hardware changes were complemented by software changes that improved the calibration of the system.	The software code changes that support improved calibration will be applied to future vehicles. The hardware fixes will not apply to future vehicles because future vehicles will use the much more robust Eaton shifter design instead of the Mastershift shifter that is on the current tractors.	The software code changes that support improved calibration will be applied to future vehicles. The hardware fixes will not apply to future vehicles because future vehicles will use the much more robust Eaton shifter design instead of the Mastershift shifter that is on the current tractors.
Main Propulsion	Transmission shift mechanisms	Actuator mechanisms were strengthened	The hardware fixes will not apply to future vehicles because future vehicles will use the much more robust Eaton shifter design instead	The hardware fixes will not apply to future vehicles because future vehicles will use the much more robust Eaton shifter design instead

	broke repeatedly		of the Mastershift shifter that is on the current tractors.	of the Mastershift shifter that is on the current tractors.
Inverter-Charger	One tractor failed to charge initially because he charge plug was wired incorrectly	Wiring was corrected	No design change required – better quality control in wiring to be exercised	No design change required – better quality control in wiring to be exercised
Inverter-Charger	Charger plug is heavy and difficult to maneuver into place to charge tractors	Handle was welded to charger plug to ease handling	Handles will be added to all future charger plugs	Handles will be added to all future charger plugs
Inverter-Charger	Inverter-charger units (ICUs) deliver only 90% of rated torque	Solution pending – tractors perform adequately at 90%	Additional dynamometer testing will enable ICU software changes to achieve 100% torque	School bus torque may be temporarily limited to 90%, but this will eventually be increased to 100%
Energy Storage	The BMS was reporting inaccurate battery temperatures to the vehicle controller in several instances, causing the	The inaccurate temperatures were caused by thermistors that were failing prematurely, and in one case a BMS module that was not functioning properly. As a short term solution, the failing thermistors were replaced. A revised thermistor design is being developed that will give the thermistors more robustness. The	Future tractors will use a different BMS solution.	While most future vehicles will use a different BMS solution, the School Bus uses the same BMS. The revised thermistor design and the procedures for recalibrating BMS modules will support the operation of the School Bus.

	vehicle to de-rate performance because it perceived a hot battery pack	BMS module that was not functioning properly was successfully recalibrated and is now reported accurate temperatures.		
Energy Storage	Tractor lost communication with one of its battery strings	The failure was traced to a BMS control module that had failed. A new BMS control module was installed.	Future tractors will use a different BMS solution	Future vehicles will use a different BMS solution. The School Bus, however, has the same BMS as the current tractors. Since this was an isolated incident, the only impact to date on the School Bus project will be for TransPower's engineers to keep a close eye on the BMS control module.
Energy Storage	Wash bay testing revealed that ESS waterproofing was inadequate	Plastic was added to the battery modules to protect them from water intrusion from the truck wash	Future tractors will potentially be operated in similar conditions and will thus incorporate the waterproofing lessons learned in Texas	The School Bus battery modules are inside the luggage compartment underneath the bus, and are thus not vulnerable to water intrusion. Other vehicles, however, will have battery packs outside of the chassis and will need similar levels of waterproofing.
Electrically-Driven Accessory	5th wheel lift malfunctioned	Actuator motor was replaced	The motor was found to have been wound improperly at the factory. The only impact on future tractors will be for TransPower to test this functionality upon receipt of the base vehicles.	Other vehicles do not have a 5th wheel lift.

Electrically-Driven Accessory	5th wheel lift too slow	Parameters in 5th wheel variable frequency drive were modified, decreasing the time it takes for the 5th wheel lift to engage.	Future tractors will be set with the modified variable frequency drive parameters.	Other vehicles do not have a 5th wheel lift, so this does not apply to them.
Electrically-Driven Accessory	The variable frequency drive that controls power steering and cooling failed.	The drive was replaced and will be brought back to TransPower's facility for analysis.	The variable frequency drive will be used in future tractors. If the analysis yields some steps that can be taken to improve the longevity of this part, the steps will be incorporated into future tractors.	The variable frequency drive will be used in other vehicles. If the analysis yields some steps that can be taken to improve the longevity of this part, the steps will be incorporated into other vehicles.
Vehicle Control	A cooling fan was found to be spinning backwards	The positive and negative leads were reversed.	Verification of cooling system functionality, and specifically fan direction, has been added to TransPower's general test and verification procedures.	Verification of cooling system functionality, and specifically fan direction, has been added to TransPower's general test and verification procedures.
Vehicle Control	The tractors were taking too long to shift from forward to reverse, impacting container throughput	A change was made to the shift control software, allowing the transmission to stay in first gear and utilizing electric neutral when the vehicle is not moving. This allows the tractor to quickly transition from forward to reverse, since the transmission's first gear is used for both. An added benefit is reduced wear and tear on the shift hardware.	This software code is directly applicable to subsequent tractors, even though they will be using different shift hardware.	This software code is directly applicable to subsequent vehicles, even though they will be using different shift hardware.

To summarize the results of the HPETT field demonstration at HEB, TransPower believes the HPETT tractors have met or exceeded all basic performance objectives. As discussed earlier, the tractors have shown, both in TransPower's own testing and in actual service in a very demanding environment, towing capacity and other performance characteristics comparable to or even superior to those of conventional tractors. The battery packs in the HPETT tractors appear to store sufficient energy to meet the operating range requirements of many, if not all yard tractor users. From the standpoint of reliability, results are more mixed, although this is not totally unexpected for a first-time deployment of vehicles as advanced as the HPETT tractors. As of the final editing of this report in mid-July 2013, one of the two tractors has been operating reliably for nearly a month without any significant malfunctions. Unfortunately, just as we appeared ready to achieve similar results with the other tractor, an incident occurred while this tractor was parked overnight at the end of June which caused this tractor's batteries to discharge nearly completely. It will take several weeks to individually test each of the 224 batteries installed into this tractor and to determine what steps will need to be taken to restore a fully working battery pack. This experience has reinforced TransPower's recognition that the performance of the battery management system is one of the most critical issues, and possibly the single most critical issue, remaining to be addressed in the course of perfecting the drive system products developed and demonstrated during the HPETT project.

Technical and commercial viability of the proposed approach

From a performance standpoint, TransPower believes the results of the HPETT project show that the HPETT tractor design has a high level of technical and commercial viability. As discussed above, the tractors have shown towing power, energy storage capacity, and other performance characteristics required to achieve adequate levels of container throughput in demanding commercial duty cycles. While reliability results are indeed mixed, nearly all of the core, high-value components on the tractors have been performing with exceptional reliability, including the main drive motors, automated manual transmissions, and inverter-charger units. The battery cells themselves seem capable and resilient, despite the unfortunate over-discharging of Tractor #2's batteries in late June. While the time spent developing all these advanced components reduced the amount of time that the tractors spent in service during the HPETT period of performance, TransPower will be able to incorporate all of the lessons learned from the HPETT project into future tractors as well as other future vehicles, resulting in a significantly more reliable and higher performing drive system.

Apart from technical issues, one additional requirement for successful commercialization will be reducing the cost of the HPETT drive system. We forecast a drive system cost in excess of $150,000 for the foreseeable future. In addition, we estimate that it required at least 2,500 hours of recurring integration labor to install the HPETT drive system into each tractor. As discussed in our Task 1 report, for this drive system product to be commercially viable, TransPower will have to learn how to install it with expenditure of about half as many labor hours, and the system will have to offer significant operational cost savings. As a result, we are continuing to study possible ways of reducing the number of hours required to install the system. Fortunately, experience gained during tractor testing at HEB supports our early predictions of operational cost savings. With average energy use estimated at 2.2 kWh per mile, the HPETT tractors have an equivalent fuel energy cost of about 25 cents per mile. A conventional tractor

with a fuel economy of 3 mpg has a fuel energy cost of more than $1.00 per mile, and this cost is likely to increase as fuel prices escalate. As we gain more experience with these tractors, we will continue to update our estimates of fuel and maintenance cost savings, and will explore vehicle-to-grid ("V2G") connectivity opportunities as ways of recovering the higher cost of the electric tractor.

In conclusion, TransPower is highly confident of the technical and commercial viability of the proposed approach, based on:

- successful completion of extensive dynamometer testing of key components under Task 2;
- completion of the two HPETT tractors under Task 2;
- completion of seven months of durability and validation testing under Task 3;
- numerous major improvements made to the design of the electric drive system through Task 4;
- achievement of reliable operation of one of the two tractors deployed at HEB, with the expectation that with improved battery management, the second tractor can achieve similar results; and
- excellent performance results with both tractors, including superior towing capacity, higher top speeds than required in virtually any yard tractor application, and sufficient operating range for most yard tractor duty cycles.

Providing concrete evidence of commercial interest in the HPETT concept, TransPower was awarded contracts to build three additional electric tractors during the final few months of the HPETT project. One of the three new tractors will be operated by IKEA, the world's largest furniture retailer, at a major distribution center it operates in Tejon, California. The other two tractors will be operated by Eagle Marine Terminals, a subsidiary of APL Terminals, at its main terminal at the Port of Los Angeles. These tractors will use the same basic design of the tractors built under the HPETT project, with a few key improvements such as use of a new battery management system. All three of these tractors are scheduled to enter service during the first half of 2014, providing the first concrete evidence that the HPETT project is succeeding in its primary objective of encouraging commercial adoption of the new technologies developed under this project.

Scope for future work

Even though this report marks the end of the HPETT contract, TransPower will continue to support the HPETT tractors at least through the end of August 2013. It is hoped that Tractor #1, which has accumulated nearly 1,000 miles of in-service use, will continue to operate as reliably as it has during June and July, and that Tractor #2 can be restored to service by August 2013. Additionally, the overall electric tractor design will be improved in preparation for integration of the three additional tractors to include recent advances in TransPower's core technology as well as to reflect the lessons that have been learned through the operation of the tractors in Texas.

Figure 4: One of the two HPETT tractors, loaded onto a truck for delivery to HEB.

Intellectual Properties/Publications/Presentations

TransPower has not applied for any patents nor developed any IP specific to this project. Our work in development of the ICU, Automated Manual Transmission, and other innovations has been funded from multiple sources and supports multiple vehicle platforms. We successfully made the first public presentation of an HPETT vehicle and related technical data at the PortTech Expo in San Pedro, California, on September 6, 2012. The first HPETT tractor was subsequently test operated by Southern California Edison in Pomona, California, and by UCR in Riverside, California, then demonstrated for two days at a symposium hosted by the South Coast Air Quality Management District in Diamond Bar, California,. Funding for three additional tractors has been received from the San Joaquin Valley Air Pollution Control District and the California Air Resources Board. We continue to share technical data from the project with prospective customers around the world.

Summary/Conclusions

The first technical objective for this project was to demonstrate a robust, reliable electric drive system combining proven components with several key new technologies and products. TransPower has designed an advanced high-power electric drive system and has successfully operated the system as HEB's distribution center in Texas. Along the way, TransPower has performed numerous upgrades to the drive system design and has validated key aspects of the design through component-level testing, including testing with two dynamometers, followed by durability testing of two prototype tractors over a seven-month period. The tractors entered the field service testing phase of the project as technically proficient machines but, as should be expected with any vehicles this new, they have each experienced various reliability issues during their first three months of in-service use. As of mid-July 2013, about six weeks beyond the end of the project, one of the two HPETT tractors has achieved about a month of fairly continuous, reliable operation, while the second will require a thorough assessment of its battery subsystem and possible replacement of numerous cells and/or its battery management system before it can be utilize reliably. Other than the specific battery management-related problem experienced by this particular tractor, the major components on both tractors appear fundamentally capable of operating reliably, even under particularly harsh operating conditions such as those that are prevalent at HEB's sprawling facility in San Antonio, Texas.

The second technical objective was to demonstrate sufficient operating range for yard tractors using lithium battery energy storage. Initial expectations were that the tractors should be capable of completing an 8 to 10 hour shift at HEB's distribution center. TransPower has subsequently determined that, given HEB's duty cycle and performance requirements, the tractors meet and exceed this requirement, and that they could in fact be operated continuously in the HEB duty cycle for approximately 13 hours between battery charges. TransPower has also determined through additional commercialization research that HEB is a relatively heavy user compared to other entities that use these vehicles. TransPower is thus confident that this technical objective was not only reached but exceeded.

In the process of accomplishing these two technical objectives, TransPower also achieved a key business objective, which was to strengthen TransPower's prototype and demonstration vehicle development capabilities. TransPower as an organization has grown in size significantly since the start of this project, both in terms of employees, facilities, and number of projects. When the HPETT project was awarded to TransPower in March 2011, TransPower had only three employees. By the conclusion of the HPETT project in June 2013, TransPower had grown to 30 employees, most of whom are full time. The HPETT project helped provide TransPower with a solid foundation that the company has built on. The subsequent tractor projects that TransPower recently initiated are further evidence that TransPower has achieved this business objective.

The final demonstration project objective was to demonstrate that electric tractors are more cost-effective to operate than diesel tractors. The efficiency data from the dynamometer testing at UC Riverside and measurements taken during several hundred miles of tractor operation at HEB confirm that, mile-per-mile, these tractors have a significantly lower fuel energy cost than diesel tractors. Improvements in tractor reliability will help reduce other operating costs, and TransPower believes an electric tractor of this type will eventually cost a typical user about $25,000 per year less to operate than a conventional diesel tractor. TransPower is confident that, within a few years, electric yard tractors can be built at costs

low enough to enable users to recover their incremental costs through these cost savings over the life of each tractor, making the goal of zero-emission tractor operation economically realistic for the first time.

Contact Information

For further information about this project please contact:

Frank Falcone
TransPower
(630) 327-9779
frank@transpowerusa.com