# High-Power Electric Terminal Tractor (HPETT)

## Task #3: Vehicle Durability Testing Report

## for:

## New Technology Research and Development Program

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**Submitted by:**

**Transportation Power, Inc.**

**Principal Investigator:**
**Michael Simon**

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## Abstract/Executive Summary

This report highlights the results of *Task 3, Vehicle Durability Testing,* which was the third task assigned under the High-Power Electric Terminal Tractor (HPETT) project, being conducted by Transportation Power, Inc. (TransPower) under a grant from the Texas Commission on Environmental Quality (TCEQ). The vehicle durability testing task involved seven major subtasks relating to the testing of two prototype electric terminal tractors developed under this project.

1. Conduct at least three months of durability testing of Tractor #1 in simulated and/or actual service.
2. Monitor the performance of Tractor #1 and its components during this testing.
3. Update the electric drive system for the second tractor, if necessary, to reflect lessons learned during durability testing of Tractor #1.
4. Conduct at least two weeks of durability testing of Tractor #2 in simulated and/or actual service.
5. Optimize performance of both tractors to maximize their energy efficiency, while assuring adequate performance to meet operating requirements.
6. 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.
7. Prepare a report documenting results of durability testing and drive system changes made in response to testing results.

The overarching goal of Task 3 was to maximize the likelihood that the two tractors would perform adequately and reliably when delivered to San Antonio for the vehicle field demonstration, the last project task. Prior to durability testing, TransPower extended the duration of *Task 2, Vehicle Integration,* by several months to allow development of tractor technologies that were considerably more advanced than those envisioned at the start of the project. Pursuit of these more advanced technologies was made possible by the rapid growth of TransPower during the HPETT contract period of performance. As discussed in greater detail in the HPETT Task 2, report, unplanned technology advancements incorporated into the tractors included:

- development of a new “automated manual transmission” (AMT) with significantly superior capabilities to the 2-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 battery module design.

As Task 3 progressed, it became apparent that the durability testing phase 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 time allocated for testing of Tractor #1 was extended from an initial allocation of just a few weeks to the three-month duration cited above. In actuality, durability testing of Tractor #1 was performed on-and-off for a period of seven months, and Tractor #2 was tested on-and-off for four months. This protracted testing reduced the amount of time available during the HPETT contract period of performance for in-service field testing, but in TransPower's judgment was justified because it resulted in more improved tractors that stand a better chance of being operated successfully in the field testing phase of the project. Significant improvements were made to all major tractor subsystems during the durability testing period, such as making the design of the AMT more robust and increasing the number of speeds it can accommodate from two to four. These improvements enhanced 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 seem to have validated TransPower's decision to extend this phase of the project. In virtually all important categories of performance, the two tractors have exceeded original project expectations. Durability testing results indicate that the tractors will be capable of operating on a single battery charge for at least 8-12 hours in most applications, and potentially for longer periods in some environments. Durability testing also has provided confidence that the tractors will be highly energy efficient. Based on the UCR dynamometer testing and TransPower's own simulated operations, it is projected that each electric tractor will consume between 10 and 20 kilowatt-hours (kWh) of energy per hour, depending on duty cycle. When compared with the 2-3 gallons of diesel fuel consumption per hour that would be typical for a conventional tractor, the fuel energy cost of the electric tractors is projected to be 5-10 times lower than for a diesel tractor.

In summary, TransPower believes the advanced design of the HPETT tractors and the results of the durability testing suggest that the project has greatly exceeded its original objectives. The final proof of this premise will be provided over the next few months as the two tractors complete the in-service testing phase of the project at HEB's distribution center in San Antonio, Texas. TransPower remains on a pace to complete the remainder of project on schedule, albeit with an abbreviated field testing phase, and looks forward to receiving a tremendous market response to the new electric tractors. As evidence of the commercial interest already generated by these tractors, TransPower has received $1.5 million in additional funding 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 will 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 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 is 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 preparing to operate the two electric tractors at its main distribution facility in San Antonio, Texas,

following a brief period of training and orientation which is beginning as this report is being submitted. Key technical, economic, and business objectives 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 are 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.

Task 2 and Task 3 both 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 Task 3 progressed, it became apparent that the durability testing phase would also have to be extended to enable all of these improvements, which are discussed in the following section. Accordingly, durability testing of Tractor #1 was performed on-and-off for a period of seven months, and Tractor #2 was tested

on-and-off for four 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 in the course of building the two tractors under Task #2 and testing them under Task #3. Durability test results provide initial confirmation that, in actual tractor operation, these upgrades will improve tractor efficiency, operating range, performance, reliability, maintainability, and cost-effectiveness, resulting in end products far superior to the drive system and electric tractor concepts originally proposed to the TCEQ.

## Task 3: Vehicle Durability Testing

### *Task Overview*

The Vehicle Durability Testing task involved seven major subtasks relating to the testing of two prototype electric terminal tractors developed under this project:

1. Conduct at least three months of durability testing of Tractor #1 in simulated and/or actual service.
2. Monitor the performance of Tractor #1 and its components during this testing.
3. Update the electric drive system for the second tractor, if necessary, to reflect lessons learned during durability testing of Tractor #1.
4. Conduct at least two weeks of durability testing of Tractor #2 in simulated and/or actual service.
5. Optimize performance of both tractors to maximize their energy efficiency, while assuring adequate performance to meet operating requirements.
6. 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.
7. Prepare a report documenting results of durability testing and drive system changes made in response to testing results.

The overarching goal of Task 3 was to maximize the likelihood that the two tractors would perform adequately and reliably when delivered to San Antonio for the vehicle field demonstration, the last project task. Prior to durability testing, TransPower extended the duration of *Task 2, Vehicle Integration*, by several months to allow development of tractor technologies that were considerably more advanced than those envisioned at the start of the project. Pursuit of these more advanced technologies was made possible by the rapid growth of TransPower during the HPETT contract period of performance. Three of the drive system upgrades relate to major components and are particularly significant.

- TransPower elected to develop a new three-speed “AMT” with significantly superior capabilities to the two-speed manual transmission originally included in the tractor drive system design. During the durability testing phase of the project, numerous problems were encountered in the operation of the new transmission, which required replacement of nearly the entire system with

new hardware and software. However, the underlying theory of operation remained sound, and the upgraded AMT proved to be reliable and highly beneficial in improving tractor performance and energy efficiency. In fact, testing of the upgraded transmission proceeded so well that TransPower elected to further improve the product by enabling four-speed shifting, a feature that has resulted in greater performance improvements in both tractors.

- TransPower elected to utilize its revolutionary new 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. During durability testing, a few ICU components were replaced with parts that are expected to offer greater operating life, and the ability of the ICU to provide power to the drive motors and the battery pack was enhanced. The ICU is now capable of operating the tractor's main drive motors at power levels very close to their theoretical maximum of 150 kilowatts (kW), and can charge batteries at the ICU's maximum charge rate of 70 kW. Development of a single device that can perform both of these tasks is an unprecedented accomplishment in the electric vehicle industry.

- TransPower developed a new "Mile-Max™" battery module concept after testing its first generation battery enclosures on a Navistar on-road electric truck funded under a separate program. The Mile-Max™ module is expected to be significantly more robust and easier to manufacture than the original battery module design. During durability testing, TransPower learned that the lithium iron phosphate battery cells used in this subsystem remain at very constant temperatures even during fairly high power operation of the tractors. This learning enabled TransPower to seal openings in the battery modules that had previously been created to allow air flow for cooling. Elimination of these openings will help protect the cells from potential damage caused by exposure to water or debris, and is expected to improve the reliability and maintainability of the HPETT tractors.

As Task 3 progressed, it became apparent that the durability testing phase 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 time allocated for testing of Tractor #1 was extended from an initial allocation of just a few weeks to an actual test period of seven months, and Tractor #2 was tested on-and-off for four months. This testing was performed in two phases.

- *Phase 1, Basic Operational Testing (September 1 through December 31, 2012).* During this phase, testing activities focused on Subtasks 1-3 listed above. Its main results were achieving initial functionality with the AMT and reliable operation of both tractors under lightly loaded conditions. Subtask 6 was also partially achieved during Phase 1.

- *Phase 2, Intensive Operational Testing (January 1 through March 31, 2013).* During this phase, testing activities focused on Subtasks 4 and 5 listed above. Its main results were achieving further improvements in the functionality of the AMT, sealing of the Mile-Max™ battery modules, improving the design of the central control module, and achieving reliable operation of both tractors under higher power loads. Subtask 6 was also partially achieved during Phase 2.

This protracted seven months of durability testing required to achieve these goals reduced the amount of time available during the HPETT contract period of performance for in-service field testing, but in TransPower's judgment was justified because it resulted in more improved tractors that stand a better chance of being operated successfully in the field testing phase of the project. As summarized above, significant improvements were made to all major tractor subsystems during the durability testing period. 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 UCR, at no additional cost to the HPETT project. The cost of this testing was covered by a grant from the California Air Resources Board (CARB) to UCR, and TransPower's only expense was the cost of making two of its engineers available to help monitor testing during the two days of testing on March 20, 2013, through March 21, 2013. Based on the UCR dynamometer testing and TransPower's own simulated operations, it is projected that each electric tractor will consume between 10 and 20 kWh of energy per hour, depending on duty cycle. When compared with the 2-3 gallons of diesel fuel consumption per hour that would be typical for a conventional tractor, the fuel energy cost of the electric tractors is projected to be 5-10 times lower than for a diesel tractor. The UCR testing and TransPower's own durability tests indicate that the tractors will be capable of operating on a single battery charge for at least 8-12 hours in most applications, and potentially for longer periods in some environments.

In virtually all important categories of performance, the two tractors have exceeded original project expectations relating to performance and energy efficiency. Following is a more detailed discussion of the results of *Task 3: Vehicle Durability Testing.*

## *Phase 1: Basic Operational Testing*

From the Grant Activities (Scope of Work):

> *2.3.1. The PERFORMING PARTY will conduct at least 3 months of drive testing of Tractor #1 in simulated or actual service.*
>
> *2.3.1.1. During drive testing the PERFORMING PARTY will closely monitor all drive system components and functions using both data obtained by engineer's operating the vehicle and onboard data loggers.*
>
> *2.3.1.2. The PERFORMING PARTY will optimize the drive system to maximize energy efficiency while meeting performance requirements and maintaining driver comfort.*
>
> *2.3.1.3. The PERFORMING PARTY will identify problems likely to occur in operational service during durability testing of Tractor 1 and implement any changes to the electric drive system deemed necessary to assure reliable operation of the tractors once they are placed in actual field service.*

Basic operational testing was achieved by driving the tractors around the parking lot at TransPower's facility in Poway, California. This provided a loop with a distance of approximately a half mile that allowed TransPower to test the tractors without the risks or liabilities that would have been associated

with operating them on public roads. Testing of Tractor #1 was initiated on September 1, 2012, initially unloaded and subsequently with a partially loaded trailer attached to the tractor. Figure 1 is a photo of the tractor performing initial tests with the trailer attached in September 2012.

**Figure 1: Tractor #1 pulling a trailer during initial durability testing in September 2012.**

Throughout the Basic Operational Testing period, which extended through the end of 2012, testing was performed with both tractors locked into a single gear, because the AMT (AMT) was not yet functional. The AMT is an innovation that electronically shifts gears while transferring power from the electric motor to the drive axle. This approach was expected to offer superb pull-away torque at much higher efficiencies than would otherwise be achieved using a torque converter or conventional automatic transmission, by eliminating torque converter stall loses while utilizing most of the motor's revolutions per minute (RPM) range. However, during lab testing of the AMT during the summer and early fall of 2012, TransPower encountered numerous difficulties in achieving reliable operation of the device using software and controls provided by Mastershift, a small California company that developed an AMT for racing cars and other specialized automotive applications. This forced TransPower to redesign major portions of the AMT and write much of the control software on its own, which delayed testing of the AMT until the Intensive Operational Testing phase, discussed below.

Nonetheless, testing of the tractors in a single gear during the Basic Operational Testing phase enabled TransPower to make incremental improvements to numerous components and the tractors' control software. Gradually, the amount of power available to the drive motor was increased through fine-tuning of the software controlling the ICU, the innovative new device TransPower developed, in partnership with EPC Power Corp., to control the motor and recharge the batteries. During the Basic Operational Testing phase, TransPower and EPC demonstrated the ability of the ICU to recharge the tractor batteries from a standard 220 to 240 volt (V) outlet equipped a power cord and plug. This validated the concept of eliminating the need for a separate off-board battery charger, which reduce the cost of ownership while simplifying facility requirements and charging logistics.

During the Basic Operational Testing, TransPower also completely redesigned the interior of the central control module (CCM). During the assembly and initial testing of Tractor #2, the wiring of the CCM was modified numerous times, resulting in a jumble of wires that made it increasingly difficult to troubleshoot or repair tractor control problems. A much cleaner version of the CCM was designed and installed into Tractor #2, and during the later Intensive Operational Testing phase, the CCM from Tractor #2 was removed and replaced with the improved version as well.

While the tractors were only beginning to show their potential during the Basic Operational Testing phase, initial results were nonetheless encouraging. Tractor #1 showed that it could operate while towing a partially loaded container for at least seven hours on a single battery charge, and all drive system components functioned over a period of four months without major incident. Tractor #2, which was completed in November 2012, was tested minimally during the Basic Operational Testing period because it was determined to be of little value to operate this tractor until it could be equipped with the AMT, redesigned CCM, and other improvements that were determined to be necessary as a result of testing of Tractor #1.

### *Phase 2: Intensive Operational Testing*

From the Grant Activities (Scope of Work):

> *2.3.2. The PERFORMING PARTY will conduct at least 2 weeks of drive testing of Tractor #2 in simulated or actual service.*
>
> *2.3.2.1. The PERFORMING PARTY will upgrade the drive system in Tractor 2 to reflect any changes in the drive system design incorporated into Tractor 1 as a result of durability testing of the first tractor.*
>
> *2.3.2.2. During drive testing the PERFORMING PARTY will closely monitor all drive system components and functions using both data obtained by engineer's operating the vehicle and onboard data loggers.*
>
> *2.3.2.3. The PERFORMING PARTY will optimize the drive system to maximize energy efficiency while meeting vehicle performance requirements and maintaining driver comfort.*

A working version of the AMT was finally demonstrated reliably in TransPower's test labs by early January 2013, enabling the device to be installed onto both tractors and allowing the initiation of the Intensive Operational Testing phase of the project. After the AMT was installed onto Tractor #1, this vehicle was subjected to higher power testing. As part of this regimen, the tractor was delivered to

Pomona, California, for independent testing by Southern California Edison. During these tests, the tractor was driven on public roads for the first time at higher speeds and power levels than were ever achieved while operating in TransPower's parking lot. Under higher power levels, it was determined that the accessory inverters used for power steering and braking experienced faults and shut down, making it impossible to perform sustained high power testing of the tractors. This forced a curtailment of the testing by Southern California Edison and required TransPower to redesign the accessory subsystem to eliminate this problem. The selected resolution was to eliminate the soft starters that were utilized with the accessory inverters, separate the inverters used for continuous and intermittent loads, and utilize contactors to regulate the use of the inverters for the latter.

Another issue that was disclosed during the Intensive Operational Testing phase was contamination of the battery modules on Tractor #1. The original Mile-Max™ battery module design, as illustrated in Figure 2, incorporated numerous openings near the tops and bottoms of the module, to allow air flow for battery cooling. However, it was discovered after a few months of testing of Tractor #1 that a significant amount of dust and debris had entered the 14 modules installed into the tractor. One of TransPower's battery suppliers, after a visit to TransPower during the Intensive Operational Testing phase, recommended that these openings be sealed to prevent such contamination. Excessive buildup of dust on cells can eventually provide conductive paths for stray currents, leading to ground faults which can disable the vehicle and lead to electric shock hazards. This particular battery supplier advised that the cells used by TransPower were unlikely to overheat, even in fully sealed modules. Based on this advice, and TransPower's own testing which had shown little increases in cell temperature, TransPower elected to follow the supplier's advice and seal most of the openings in its Mile-Max™ modules.

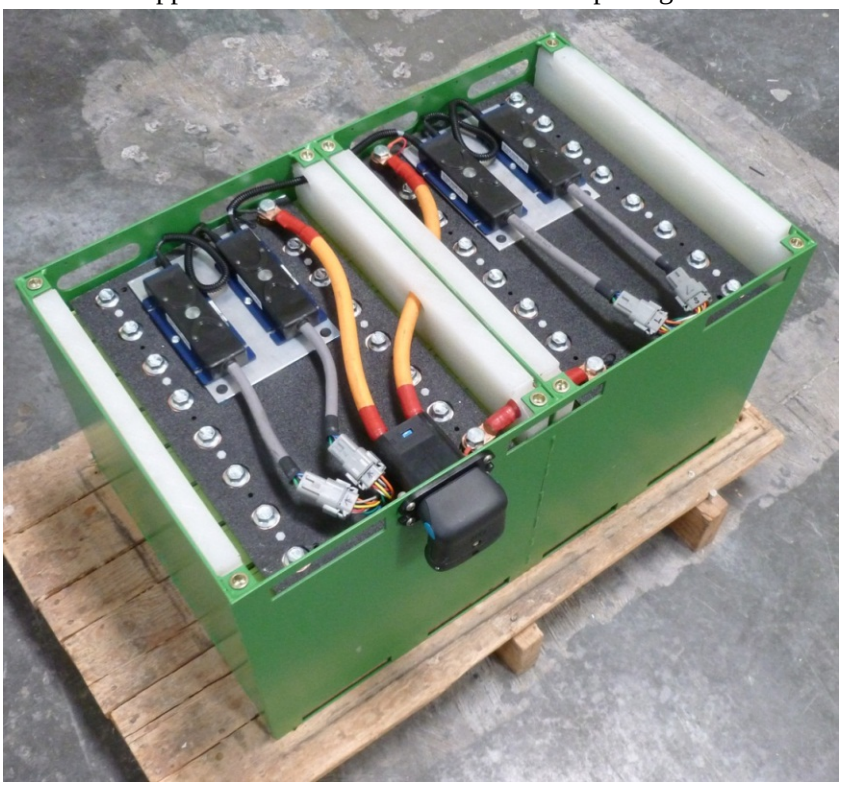

**Figure 2: Fully-assembled Mile-Max™ battery module.**

Figure 3 shows one of the Mile-Max™ modules installed on Tractor #1 following the sealing of its

openings.  An added benefit of sealing these openings is that moisture is less likely to enter the module, reducing the risk of problems relating to wet weather or water produced during washing of the tractors.

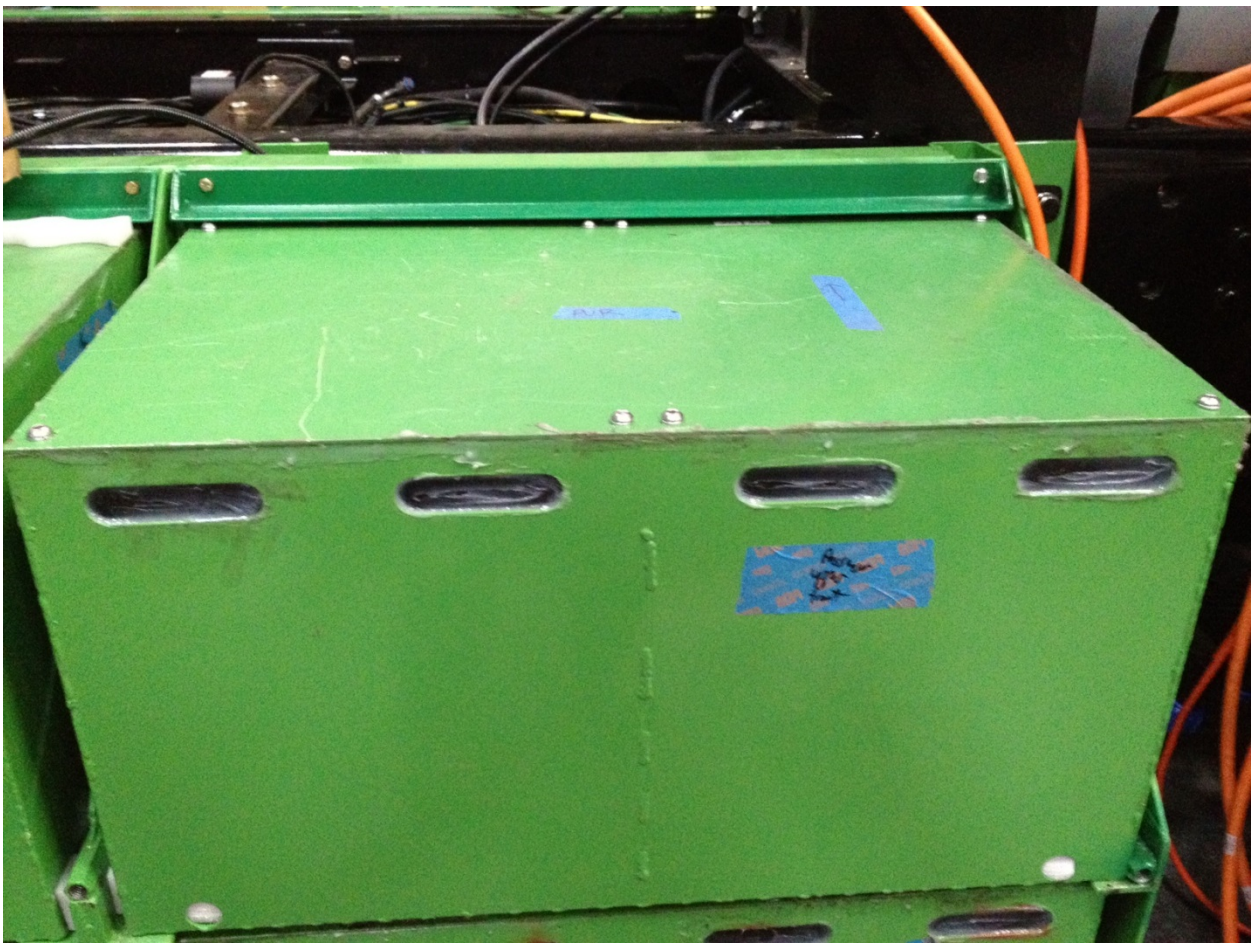

**Figure 3:** Mile-**Max™ battery module after sealing.**

Sealing of the 14 modules on each tractor proved to be a time-consuming activity, as each module weighs approximately 400 pounds and removing them required disconnection of numerous wires and cables. Following replacement of the modules on both tractors, it also took a significant amount of time to re-establish all connections with the battery management system (BMS).  This problem was traced to improper reconnection of some of the BMS cabling, pointing to a need for improved documentation and technician training in the installation of the battery modules.

Yet another technical issue that emerged during Intensive Operational Testing was the inability of certain components of the AMT to endure the wear and tear of use on a heavy-duty tractor.  The AMT hardware installed on Tractor #1 at the beginning of the test phase had been adapted from much lighter racing cars and, as it turned out, was unable to handle the greater forces associated with shifting gears on a Class 8 tractor.  This required TransPower to replace numerous elements of the AMT on both tractors with more rugged parts.  While doing this, TransPower engineers took advantage of the extra time and improved the AMT software and controls, achieving the ability to operate the transmission in four speeds.  This improvement enabled the tractors to operate at higher speeds than with the 3-speed AMT that was

originally planned.  In fact, with the improved AMT, TransPower was eventually able to operate the tractors, with loaded trailers, at speeds up to 43 miles per hour.

During the Intensive Operational Testing phase, TransPower was provided with the unique opportunity to test one of the tractors at the UCR, at no additional cost to the HPETT project.  The cost of this testing was covered by a grant from CARB to UCR, and TransPower's only expense was the cost of making two of its engineers available to help monitor testing.  Figure 4 shows Tractor #1 on the chassis dynamometer at UCR, where it was tested for two full days on March 20, 2013 through March 21, 2013.

**Figure 4:  Tractor #1 being tested on the chassis dynamometer at UC Riverside.**

The dynamometer testing at UCR provided the final validation of the TransPower electric drive system's readiness to be field tested by placing the tow electric tractors into regular service with HEB.  A few minor additions and improvements were made to both tractors during the two to three weeks following the UCR testing, and Tractor #1 was subsequently showcased at a zero emission transportation symposium hosted by the South Coast Air Quality Management District on April 10, 2013, through April 11, 2013.  The day after the end of the symposium, on April 12, 2013, both tractors were loaded onto trucks to be transported to San Antonio, where they were scheduled to be received on April 15, 2013, and to enter service shortly thereafter.

## Discussion/Observations

### *Objectives vs. Results*

#### Shift Algorithm Development

#### *Output Shaft Sensor*

Occasionally rough grinding shifts were observed when shifting from second to first gear at low speeds while decelerating quickly. Analysis showed that the transmission output shaft sensor would drop out at around 65 RPM (Figure 5). Furthermore there was some instability 100 and 175 RPM. The output shaft sensor is the main source of transmission output shaft speed and is generally the most accurate. Another method is to use high resolution wheel speeds to predict output shaft speed which is stable to less than 1 km/hr or about 30 output shaft RPM. This speed measurement is very stable but it also is an average of wheel speeds and not necessarily indicative of true output shaft speed. By creating a rule set that reads output shaft speed when speed is over 150 RPM and wheel based output shaft speed below 150 RPM a reliable speed request can then be sent to the motor ensuring speed matching down to the threshold where speed matching is required (at greater than 60 RPM). This has resulted in smooth shifts over the entire vehicle speed range.

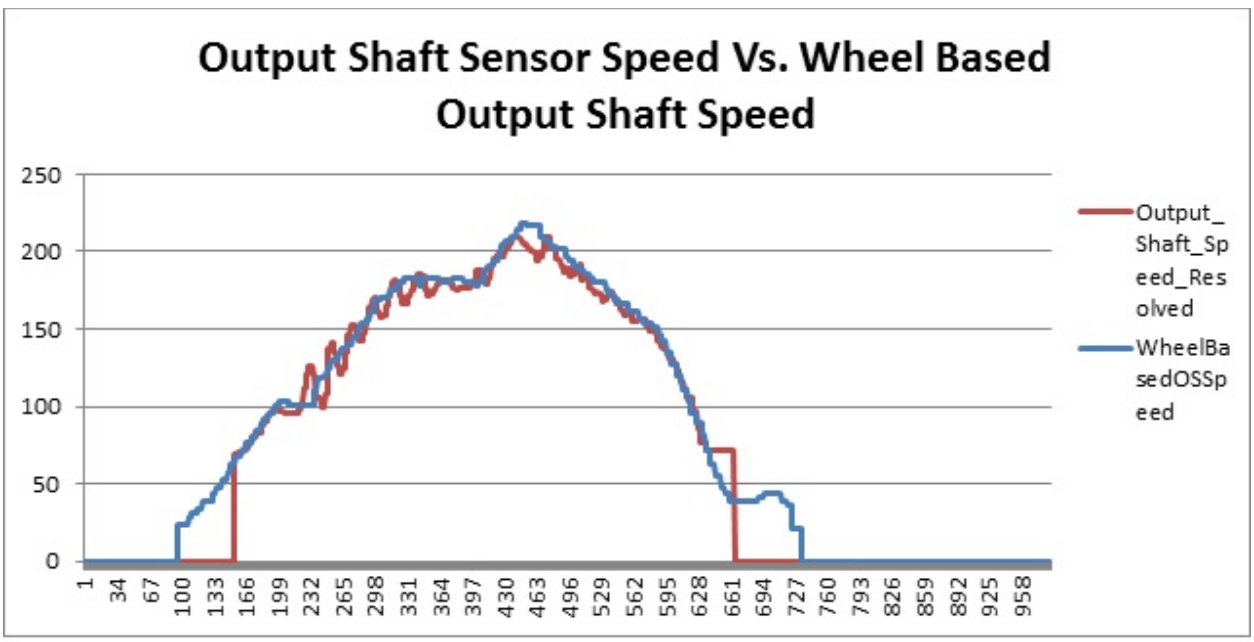


**Figure 5:** Output **shaft sensor speed versus wheel-based output shaft speed.**

#### *Acceleration in Gear*

The charts below are an excerpt from a testing run of an unladen truck accelerating in gear. Table 1 depicts the gear commanded to the transmission. Column 1 is absolute time of run in seconds (s). Column 2 is the total delay time in seconds for this excerpt. Column 3 is speed in kilometers per hour

(km/h) while Column 4 is in miles per hour (mph). Column 5 is the gear and Column 6 the time in seconds spent in gear.

**Table 1: Tractor speeds at each of the four gear settings.**

| Time Absolute (s) | Delta T Total (s) | Speed (km/h) | Speed (mph) | Gear | Delat T per gear(s) |
|---|---|---|---|---|---|
| **505.1** | 0 | 0 | 0 | 1 | |
| **507.6** | 2.5 | 11.94 | 7.4 | 1 | 2.5 |
| **513.2** | 8.1 | 26.88 | 16.7 | 2 | 5.6 |
| **522.7** | 17.6 | 42.13 | 26.2 | 3 | 9.5 |

Figure 6 depicts accelerator pedal percent and vehicle speed in km/h.

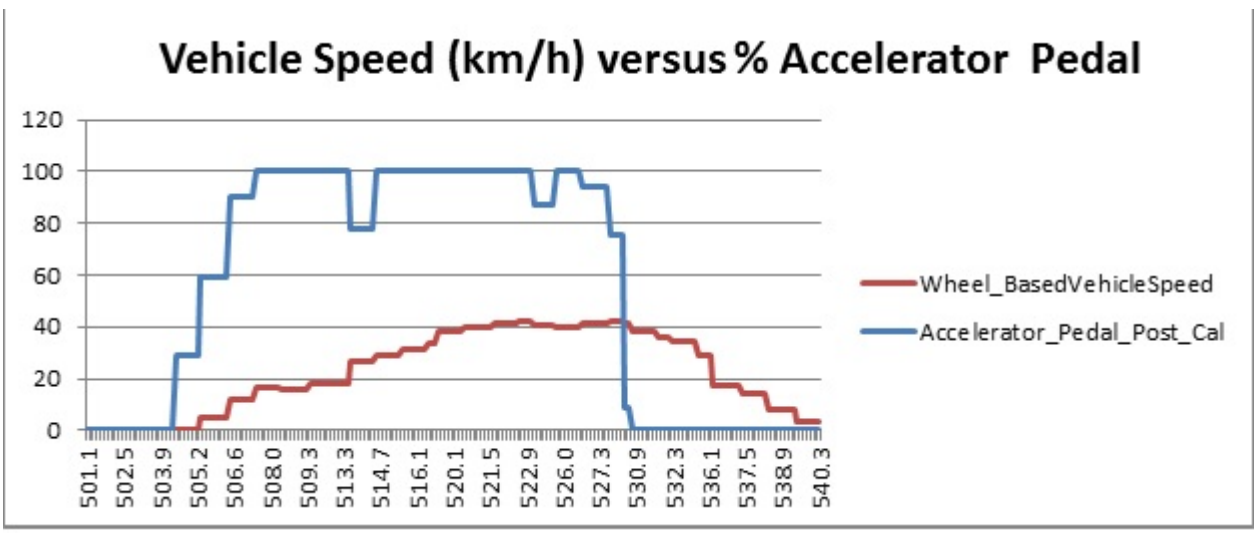


**Figure 6: Vehicle speed at each pedal position.**

Figure 7 summarizes key points from each chart. In this figure, "5" on the vertical axis refers to 'Neutral." The tractor accelerates to 11.94 km/h (7.4 mph) in about 2.5 seconds, and to 26.88 km/h (16.7 mph) in another 5.6 seconds, or 8.2 seconds total.

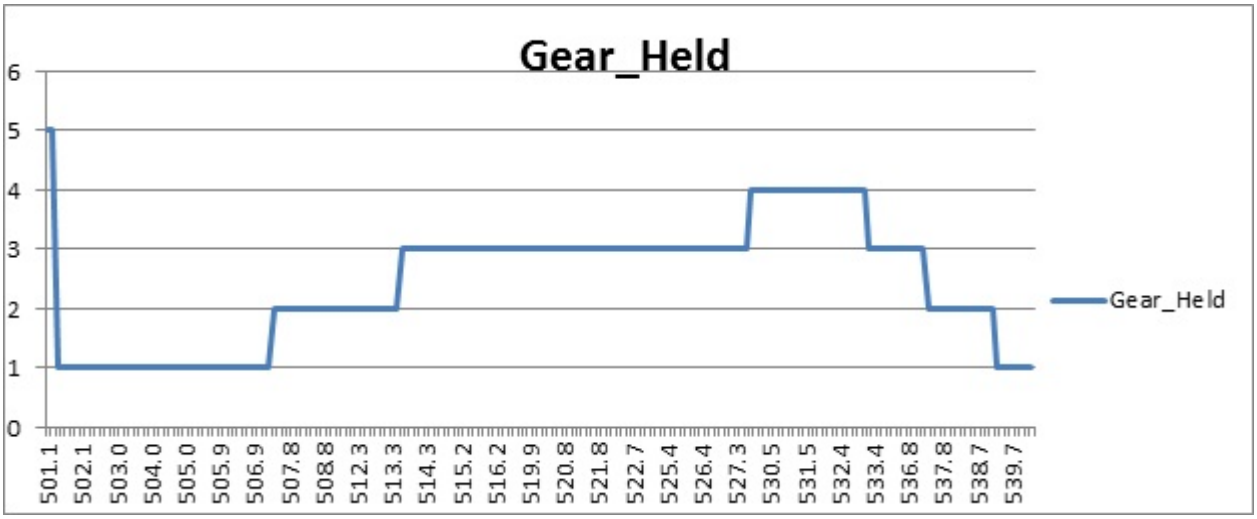


**Figure 7: Summary of gear data.**

### Charging

Figure 8 shows the result of the system control unit measuring critical charge parameters and tapering off current as the highest cells reach target voltages. Charging amperages (a) have ranged from the max of 200 A to 0 A ensuring the charge current is controlled over the entire spectrum and the cooling system is able to maintain table temperatures at high rates.

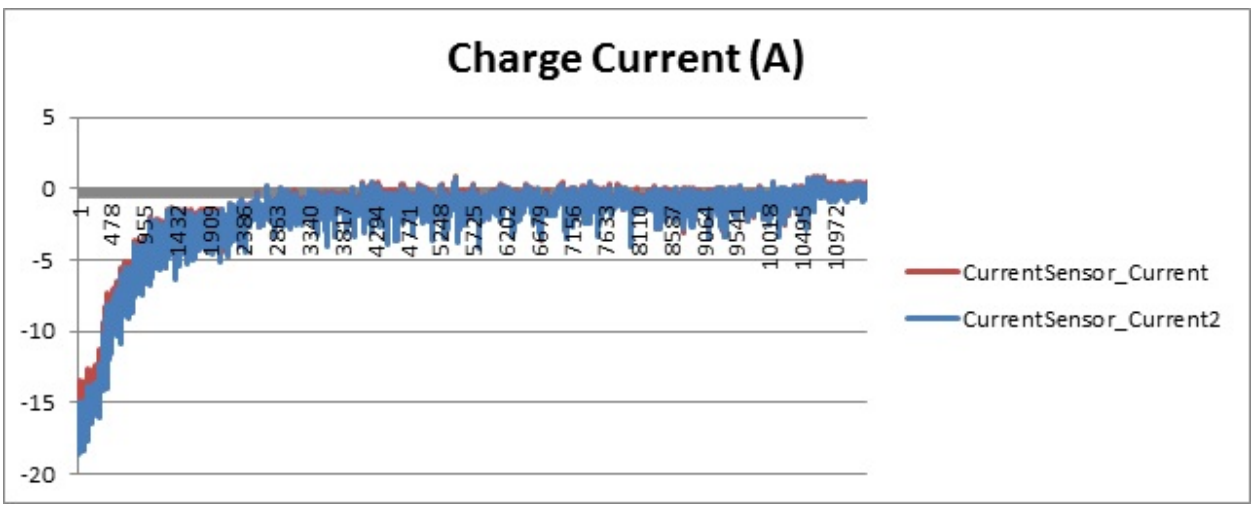


**Figure 8: Charge current analysis in amperes.**

### Chassis Dynamometer Testing

Vehicle drive testing was performed on March 20, 2013, and March 21, 2013, at UCR's heavy-duty chassis dynamometer facility. Day 1 test activities included general instrumentation and calibration tasks in support of two variants of a drayage cycle used to characterize competing yard tractor prototypes and baseline stock diesel vehicles. A total of six complete drive cycles were completed on the dynamometer; these included three replicates of each of two variants. The two variants are shown in Figure 9, and represent a "best" case and a "worst" case for energy consumption. The first variant is shorter in length,

performed at a lower average speed, and performed at a lower implied total vehicle mass than is the second variant.

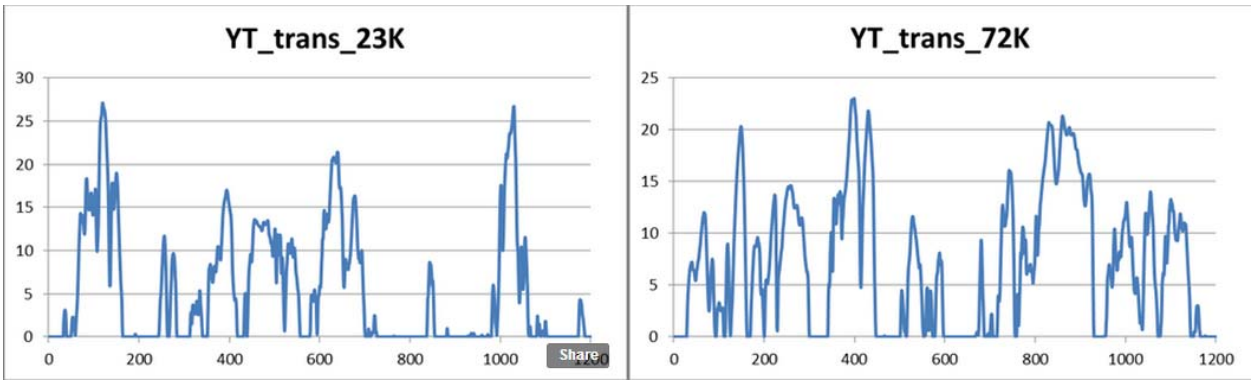


**Figure 9. Two chassis dynamometer cycle variants used to validate vehicle performance estimates.**

Statistics and energy results are reported in Table 2. These results are very encouraging, with an expected energy usage in operation of slightly more than 2 kWh/mile. At these consumption rates, a full charge is expected to last for more than a full shift in operation.

Key outcomes of the testing were, of course, verification of performance predictions for the vehicle in use, expansion of control limits to reflect a wider range of permissible operation, and data on performance of the vehicle cooling loops that led to improvements that will likely be crucial to success in their deployment in Central Texas.

**Table 2. CCERT dynamometer data.**

| Units | Light Cycle | Heavy Cycle |
|---|---|---|
| x1000 lb | 23 | 72 |
| Ah | 8.34 | 17.31 |
| kWh | 3.06 | 6.44 |
| Average km/h | 8.7 | 12.7 |
| Max km/h | 45.5 | 37.8 |
| Miles | 1.82 | 2.53 |
| kWh/mile | 1.69 | 2.55 |

### *Critical issues*

When our Task 1 report was submitted in March 2012, the most critical issue facing the HPETT project was the development risk associated with the ICU.  This report stated:

*"This is a completely new, clean-sheet design product that is required to meet two vital functions – motor control and battery charging. ICU development is being funded separately by TransPower and its ICU manufacturing partner EPC on a separate project, but the HPETT project is nonetheless dependent on availability of a reliable ICU in a timely manner. We have backup solutions in the event of a protracted delay in development of the ICU, but these backup plans have issues themselves. The Quantum inverter which is our backup device for motor control has performed poorly in initial testing with our on-road Navistar truck. This may be due to the fact that the two Quantum inverters we purchased for the Navistar program in 2011 were reconditioned units, but we won't know for sure until the first new Quantum inverters are delivered to us in April 2012. There are no attractive backup options for battery charging, as the only other commercially available solutions are off-board chargers that would cost significantly more than the ICU and not charge as fast, while also taking up space in the vehicle operator's facility. To avoid the necessity of falling back on these or other backup options, we are doing our best to keep ICU development on track. Initial tests of our first prototype ICU have proceeded favorably, and we remain hopeful that fully functional ICUs capable of controlling tractor motors and recharging tractor batteries will be available by this summer."*

The additional effort expended over the past year in accelerating development of ICU motor control functionality, and in validating the ICU through extensive bench, dynamometer, and vehicle durability testing, have greatly mitigated the risks surrounding this critical component. The ICU has demonstrated full-power battery charging at the targeted in rate of 70 kW (far in excess of the power levels at which it is expected the two HPETT tractors will be charged), and has demonstrated smooth and reliable motor control throughout the recently-concluded durability testing phase of the project. Based on these results, the ICU has greatly exceeded our expectations and we remain highly optimistic that we can depend on this product for reliable motor control and battery charging in the two HPETT tractors.

Other critical issues identified in our Task 1 report related to the reliability of the battery energy storage subsystem (ESS); the functionality and reliability of the new automated-manual transmission; and "our overall success in integrating the many new components that will have to work together seamlessly for the tractors to be useful." We believe that the extension of our durability testing helped address all of these issues by enabling numerous improvements in the ESS design (e.g., sealing of the modules to prevent debris or water contamination), ruggedizing and extension of the capabilities of our automated-manual transmission, and improvements in the design of our central control module and electrically-driven accessories. Progress with the AMT has been particularly encouraging.

As of the date of our Task 2 report in November 2012, vehicle durability testing had been performed only in one gear, due to a lengthy initial delay in perfecting the software and communications required for reliable shifting of the AMT while the vehicle is in motion. As of last November, it was even considered possible that the tractors would need to be delivered to HEB for the in-service test phase of the project locked into one gear, due to all the difficulties mastering the nuances of the AMT. Durability testing of the tractors using all three gears and the full capability of the AMT did not begin until early 2013, when we entered the Intensive Operational Testing phase of the durability testing task. However, over the past few months, we have not only mastered shifting in three gears using this game-changing technology, but have successfully added a fourth gear, which has allowed us to increase the top speed of the tractors to 43 mph. These achievements have largely resolved uncertainties over how robust and reliable the AMT will

be. The higher speeds enabled by the AMT are expected to be especially useful to HEB, as their tractors frequently travel on public roads and will be less likely to hold up traffic when operating at these higher speeds.

The delay in completing the two tractors under Task 2 and the subsequent extension of durability testing under Task 3 has reduced the time available for field testing the tractors under Task 4. However, with Tractor #1 already having completed seven months of durability testing, and Tractor #2 having completed four months of such testing, these two tractors will enter service with far more capability and many more hours of experience than originally planned. In our view, this makes it far more likely that the two tractors will remain in useful service with HEB for an extended period – well beyond the time frame of the HPETT project.

### *Technical and commercial viability of the proposed approach*

TransPower is more confident than ever 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; and
- numerous major improvements made to the design of the electric drive system used in these tractors over the course of all three project tasks completed to date.

The only remaining concern is the cost of the system, as we continue to forecast a drive system cost in excess of $150,000 for the foreseeable future. In addition, TransPower estimates that it still requires 2,500 labor hours to install its drive system into a 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. In addition, we are continuing to update our estimates of fuel and maintenance cost savings, and continue to explore vehicle-to-grid ("V2G") connectivity opportunities as ways of recovering the higher cost of the electric tractor. Once we complete a few months of in-service testing and have a more definitive idea of how efficiently these tractors operate, we'll have a better idea as to whether the operational savings of these vehicles will offset their higher capital cost. We remain optimistic that this will turn out to be the case.

One major source of encouragement is that, during the durability testing phase of the project, TransPower was awarded contracts to build three additional electric tractors using the same basic design of the tractors built under 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, California. 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*

The next task of the HPETT project is to complete *Task, 4, Vehicle Field Demonstration*. To accomplish this, both tractors have already been delivered to the HEB distribution facility in San Antonio, Texas. A Final Report (Task 5) will be submitted by the end of the contract. Figure 10 shows one of the two tractors loaded onto a flatbed truck, in preparation for transportation from TransPower's Poway, California, headquarters to San Antonio, Texas. Members of the TransPower team who helped build the two HPETT tractors are shown assembled in front of and on board the tractor.

**Figure 10. One of the two HPETT tractors, loaded onto a truck for delivery to HEB.**

## Intellectual Properties (IP)/Publications/Presentations

TransPower has not applied for any patents nor developed any IP specific to this project. Our work in development of the ICU, AMT, 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, CA, 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

TransPower has designed an advanced high-power electric drive system and has successfully integrated the system into the terminal tractors. 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. Updated design work completed since our last report includes extension of the capabilities of the AMT, improvements in the design of the "Mile-Max™" battery modules, upgrading of the central control module, and improvements in the electrically-driven accessories. While the design, integration, and durability testing of the two tractors took, in total, nearly a year longer than originally anticipated, we believe the many unplanned improvements we have been able to make to our drive system design justify the added time we spent on these tasks, and that the accruing benefits will far outweigh any difficulties created by these delays. The next step is to place both tractors into service with HEB in Texas and to monitor their performance while used under real-world operating conditions. Leveraging the resources of other electric vehicle projects that have made many of our technology advances possible, we believe the results of the HPETT project thus far have far exceeded all the major goals and expectations established for this project at the outset.

## Contact Information

For further information about this project please contact:

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