California Energy Commission

Clean Transportation Program

FINAL PROJECT REPORT

Vertically Integrated Facility for Electric Truck Manufacturing (VIFET)

Prepared for: California Energy Commission

Prepared by: Transportation Power, Inc.

Gavin Newsom, Governor

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PREFACE

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

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

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

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-09-605 to provide funding opportunities under the Alternative and Renewable Fuel and Vehicle Technology Program for the development and expansion of manufacturing and assembly plants in California that produce electric vehicles, batteries, and component parts for alternative fuel vehicles. In response to PON-09-605, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards July 30, 2010, and the agreement was executed as ARV-10-020 on February 17, 2011.

ABSTRACT

This Vertically Integrated Facility for Electric Truck Manufacturing (VIFET) final report documents Transportation Power, Inc.'s research and development under this project, funded by CEC ARV-10-020 in the amount of $1,000,000. The goal of this agreement was to conduct feasibility studies to establish the economic viability of Transportation Power, Inc.'s concept of a three-stage vertically integrated facility for manufacturing electric Class 8 trucks, and to conduct performance tests to validate that certain key components are ready for commercial manufacturing. The components addressed by the latter activity include an advanced power converter and a high-capacity energy storage module using lithium batteries and an advanced battery management system. The specific objectives of this agreement were to produce the quantitative data necessary to achieve the above goals.

The VIFET project sought to achieve major technology advances in to key areas: vehicle control and integration, and advanced energy storage. The VIFET project not only made major advances in these two areas, but also achieved significant advances in the area of electric vehicle propulsion, and moderate advances in several other technology areas. The combined effect of VIFET technology advances is expected to have a transformative effect on the heavy-duty vehicle industry.

Keywords: California Energy Commission, electric vehicle, battery, inverter, electric motor, vehicle manufacturing, battery charger, vehicle control, lithium-ion, prototype integration.

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EXECUTIVE SUMMARY

This Vertically Integrated Facility for Electric Truck Manufacturing (VIFET) final report documents Transportation Power, Inc.'s research and development under this project, funded by CEC ARV-10-020. The goal of this Agreement was to conduct feasibility studies to establish the economic viability of Transportation Power, Inc.'s concept of a three-stage vertically integrated facility for manufacturing electric Class 8 trucks, and to conduct performance tests to validate that certain key components are ready for commercial manufacturing. The components addressed by the latter activity include an advanced power converter and a high-capacity energy storage module using lithium batteries and an advanced battery management system. The specific objectives of this Agreement were to produce the quantitative data necessary to achieve the above goals. Primary objectives of the VIFET project included:

- Quantify economic benefits of colocating three stages of manufacturing in one facility, such as reducing shipping costs and efficiencies related to enhanced just-in-time manufacturing.
- Quantify economic benefits of locating the vertically integrated facility in various Southern California municipalities, including macroeconomic benefits such as job creation and enhanced tax revenues, and microeconomic benefits such as accessibility, availability of skilled labor, and reduced facility costs.
- Measure the efficiency of an advanced converter based on performance testing and quantify the economic advantage of efficiency improvements observed.
- Measure the responses of large battery modules to repeated charge and discharge cycles under various operating conditions.
- Measure the time required to recharge a large battery pack using an advanced converter, and the ability of the converter to bring the battery pack to a full state of charge (SOC).
- Generate cost and schedule data required to establish a comprehensive plan for construction of a vertically integrated facility, with the objective of initiating construction within one month of VIFET project completion.

The VIFET period of performance began on February 17, 2011 and was originally scheduled to end on March 31, 2013, but was extended to September 30, 2013 to allow more time for manufacturing and testing of a second electric Class 8 truck, which was not part of the original contract scope of work. The original scope of work involved utilization of a used Navistar International truck as a "rolling test bed" to help validate the components and technologies described above, but did not entail manufacturing of a fully functional Class 8 electric truck. The expansion of the scope of work to include the second truck, which is designed for full operational capability, was made possible by a grant from the South Coast Air Quality Management District, which commenced on June 8, 2011 and is scheduled to continue until November 7, 2013.

The VIFET project sought to achieve major technology advances in two key areas: vehicle control and integration, and advanced energy storage. As discussed in more detail in Chapter

1 of this report, the VIFET project not only made major advances in these two areas, but also achieved significant advances in the area of electric vehicle propulsion, and moderate advances in several other technology areas. The combined effect of VIFET technology advances, as discussed in Chapter 1, is expected to have a transformative effect on the heavy-duty vehicle industry.

CHAPTER 1: Major Technology Advances Enabled by VIFET

Vehicle Control and Integration

The term "vehicle control and integration" refers to the functions of achieving smooth, reliable control of an electric vehicle (EV) and assuring that the integrated electric drive system works seamlessly with the vehicle's power system, controls, and displays. As shown by recent experience with the Toyota Prius, achieving reliable electric drive control is a challenge even when the drive system is designed to work with just one vehicle model. Transportation Power, Inc.'s (TransPower's) challenge was intensified by the fact that its system must work in many different vehicle models to achieve commercial viability and transportation transformation. To be implemented across multiple vehicle models cost-effectively, the drive system must have a flexible architecture and programmable functions so the system layout and functionality can be quickly and easily customized to meet differing design and operating requirements

TransPower's approach to solving the control and integration problem was to develop a proprietary power control and conversion system based on two key technologies: 1) An advanced network control architecture, which provides a fine degree of vehicle control and accommodates a multitude of vehicle components; and 2) An advanced inverter-charger unit (ICU), developed jointly with partner EPC Power Corp. (EPC), to improve on the efficiency and weight of existing inverters, and to eliminate the need for a separate battery charger.

The selected network control architecture uses controller area network (CAN) protocols that are standard throughout the automotive industry. This enables the network to communicate with most standard devices on commercial buses and trucks, such as dashboard displays, accelerator and brake pedals, and gearshift mechanisms. In testing and validation during the VIFET project, this control architecture demonstrated high reliability and unparalleled flexibility. Inexpensive, standardized microprocessor platforms interface each drive system component with the control network, similar to how PCs and peripherals can be linked in an office IT network using Ethernet connections. Over the course of the VIFET project, TransPower has already shown how this control network can be applied to multiple types of vehicles, employing modules that also enable new components to interact with the network.

The second major innovation of the TransPower power control and conversion system is the new ICU developed with partner EPC (Figure 1). The ICU converts direct current (DC) power from the vehicle battery packs to alternating current (AC) power for the vehicle drive motors, and regulates drive motor speed and other operating characteristics to assure smooth acceleration, hill-climbing, regenerative braking, and other control aspects. The most unique and valuable attribute of the advanced TransPower-EPC ICU is its ability to mimic the functions of a battery charger. To achieve this, the ICU regulates the flow of energy into vehicle battery packs as they are recharged using power from the grid, accounting for the rising internal resistance of the batteries as their SOC increases. Eliminating the need for external battery chargers will save tens of thousands of dollars per vehicle in infrastructure costs and simplify the logistics of recharging, helping to accelerate market acceptance.

Figure 1: Interior of ICU

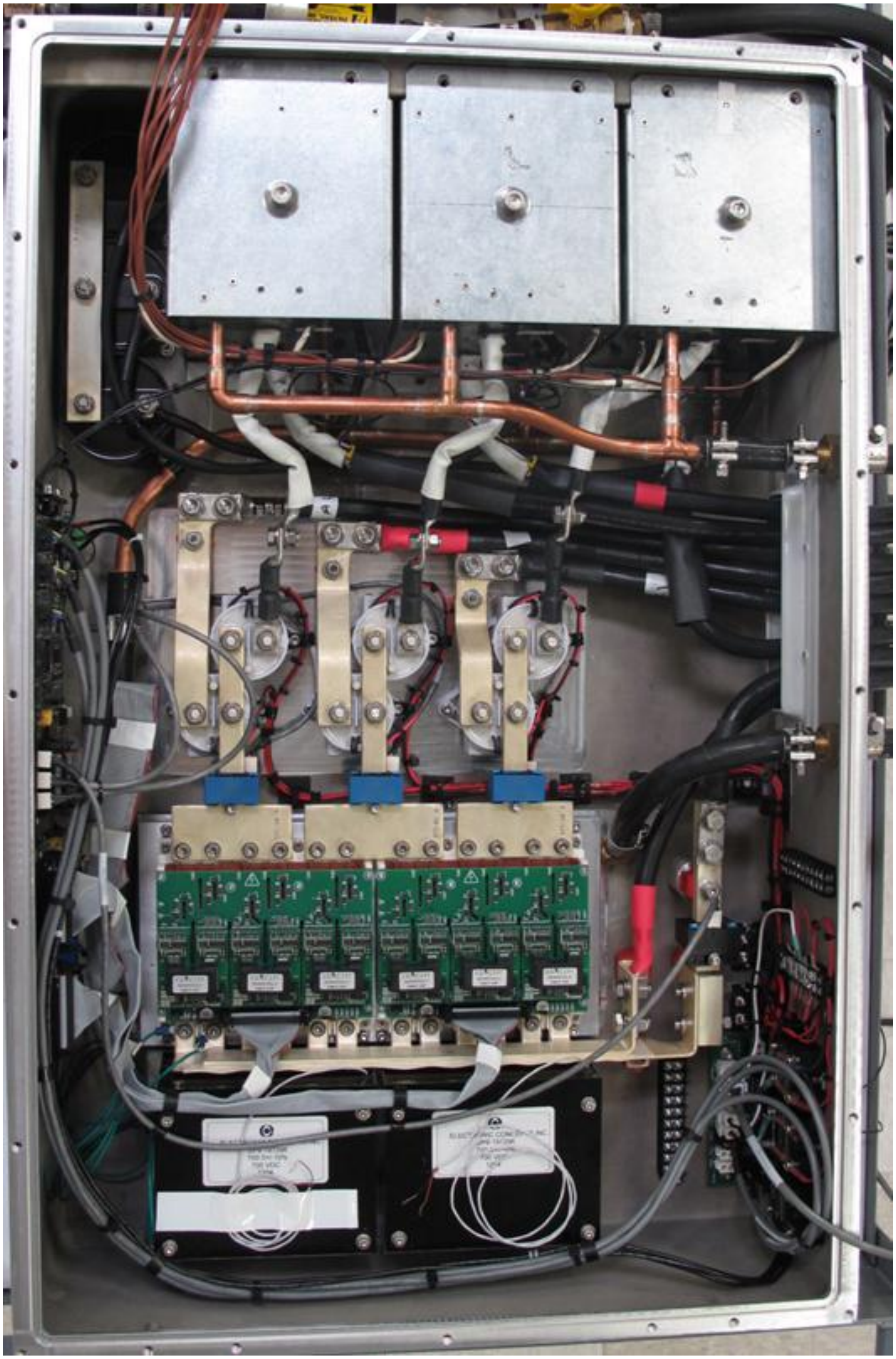


Photo credit: TransPower

Tests performed under the VIFET project included bench tests of the prototype ICU with a drive motor supplied by Imperial Electric, validating the ICU's two main functions of motor control and battery recharging. These tests validated the design of the ICU and its readiness for manufacturing. Subsequently, the drive motor, ICU, and battery modules were installed into two Class 8 trucks supplied by Navistar, along with a full suite of electrically-driven power steering and braking accessories. The first truck was intended to simply enable initial static testing of a prototype vehicle to validate the broader functionality of the entire power conversion and control system, but this truck was successfully upgraded to a truck capable of operating at one-half the power of a full Class 8 truck system in nearly a year and a half of road testing. The second truck, made possible by the infusion of air quality management district funds into the VIFET project several months after the CEC award, features a complete drive system including two ICUs and is capable of operating on public roads and meeting the most demanding Class 8 truck power requirements.

Energy Storage

The second major technology of the VIFET project was energy storage, recognized as the most critical component of EV technology. Conventional lead-acid batteries are impractical for most vehicle applications because of their low energy density. Lead-acid batteries also have other issues in heavy-duty vehicle applications, such as power drop-off as they become discharged, and greater chances of fires or explosions when used in large high-voltage strings. Lithium battery cells are widely viewed as the most promising alternative to lead-acid battery chemistry because they can offer energy densities greater than 100 watt-hours per kilogram, greatly reducing weight. However, prior to the VIFET project, lithium batteries were very expensive, typically on the order of 10 times more costly than lead-acid batteries per unit of energy stored. In addition, lithium battery cells must be manufactured to high quality standards to avoid potentially dangerous cell failures, and integration of lithium cells into the kinds of high-energy packs required for large EVs presents additional safety and reliability challenges. TransPower used the acronym LASER to summarize the challenges associated with using lithium batteries in large electric trucks:

- **Lifetime:** Batteries must achieve lifetimes of at least 1,500—2,000 cycles for cost-effective use, which translates into an operating life of six to eight years for most vehicles. An operating life of 10 years or more (2,500—3,000 cycles) is ideal. More frequent replacement of batteries would be cost prohibitive.
- **Affordability:** The cost of acquiring the batteries must be affordable. At recent price points of $1,000/kilowatt-hour (kWh) and higher, a 300 kWh pack required to achieve a 100-mile operating range (in a heavy Class 8 truck) would cost a prohibitive $300,000. This cost must be reduced by at least one-third to make battery energy storage competitive on a lifecycle cost basis with using diesel fuel.
- **Safety:** Due to their high energy content, lithium batteries can cause severe damage and safety hazards if they overheat or discharge in an uncontrolled fashion. High-energy packs must also be designed for safe handling and fault interruption.
- **Energy Content:** Achieving the high-energy content (~300 kWh) required for even relatively short-range Class 8 truck operation requires a battery with very high energy

content, or "energy density." More than 10,000 kilograms (kg) of lead-acid batteries would be required to provide this level of energy, even if rated at 30 watt-hours per kg of usable energy—a high rating for lead-acid chemistry.

- **Reliability:** Integration of potentially thousands of battery cells into a single vehicle battery pack requires an extraordinarily high level of cell reliability and/or battery pack ability to tolerate cell failures. This requires use of the highest quality lithium cells and design of a battery management system that prevents or isolates cell failures.

During the VIFET project, TransPower developed a series of lithium battery solutions, the latest of which appears likely to meet all of the LASER criteria and hence overcome the principal set of obstacles to widespread adoption of large electric trucks. From early 2011 through mid-2013, TransPower developed several different designs for integrated battery energy storage modules, utilizing lithium iron phosphate (LiFePO4) cells that will last an expected 3,000—5,000 cycles, depending on how deeply they are cycled. Modules were developed and tested using cells rated at 260 ampere-hours (Ah), 300 Ah, and 700 Ah. The 260 Ah cells were utilized on the first prototype VIFET truck, and the 700 Ah cells (Figure 2) were used on the second truck. To achieve a 100-mile operating range, the second Class 8 truck was designed to utilize 120 cells, with a total rated energy storage capacity of 269 kWh. These cells are integrated into 20 "Mile-Max™" modules, each containing six of the very large 700 Ah cells and weighing nearly 400 pounds (lbs.).

Figure 2: Mile-Max™ Module Using 700 Ah Lithium-Ion Battery Cells

Photo credit: TransPower

During the VIFET project, TransPower also experimented with several battery management system (BMS) products to assure proper, safe functioning of the high-energy cells. BMSs use sensors and various types of controllers and software to measure and record critical parameters of the battery system. The first truck used a BMS product supplied by Flux Power, another small company in the San Diego area, but after testing of the Flux BMS on this truck and two electric yard tractors (funded under a separate project), TransPower determined that it was difficult to integrate and maintain, as well as very costly. In response, TransPower designed a new BMS for the second VIFET truck, using sensor boards acquired from Balqon, combined with TransPower's own controller and software. This BMS has shown good initial results and has the ability to be evolved into a very sophisticated product capable of dynamically calculating batter condition and performance based on a cell characterization database, analyzing in real time, and checking against an extensive set of boundary conditions for violations. It provides full-time, continuous monitoring, balancing, and recording with tight accuracy with low operating power. This "Cell-Saver" BMS is CANbus compatible, so it integrates seamlessly with the TransPower vehicle network architecture. It also includes vital safety features, such as short-circuit and over-current protection and general fault shutdown. By combining inexpensive lithium cells with its own very sophisticated BMS, TransPower's Mile-Max™ battery system achieves unprecedented levels of energy storage functionality at a reasonable cost.

Table 1 summarizes the performance and cost advantages of the Mile-Max™ energy storage solution in the context of the five LASER challenges introduced at the outset of the VIFET project in early 2011.

Table 1: The TransPower Batter Solution Meets All of the LASER Challenges

LASER Criterion	Description of Original VIFET Criterion	Impact of Proposed Solution on Transportation Market
Lifetime	Lifetime of at least 1,500—2,000 cycles, which translates into an operating life of 6-8 years for most vehicles. An operating life of 10 years or more (2,500-3,000 cycles) is ideal.	Mile-Max™ modules will greatly exceed target range, providing lifetimes of 3,000—5,000 cycles. This will minimize battery replacement costs; in fact the upgrade cells may last the life of the vehicle.
Affordability	Current prices of $1,000/kWh and higher must be reduced by at least one-third to make battery energy storage competitive on a life-cycle cost basis with using diesel fuel.	TransPower's cost to assemble a complete Mile-Max™ module is approximately $500/kWh, less than half the cost prevalent at the start of the VIFET project. This nearly achieves cost equivalence with $4/gallon fuel.
Safety	Lithium batteries can cause severe damage and safety hazards, and high-energy packs must be designed for safe handling and fault interruption in case of an accident.	TransPower's Cell-Saver™ BMS offers one of the industry's most advanced capabilities for cell monitoring and charge balancing. Cells are manufactured to high quality standards on automated assembly lines.
Energy Content	Achieving the high energy content (~300 kWh) required for even relatively short-	Lithium cells are rated at about 100 Wh/kg., and integrated packs are at about 85 Wh/kg.

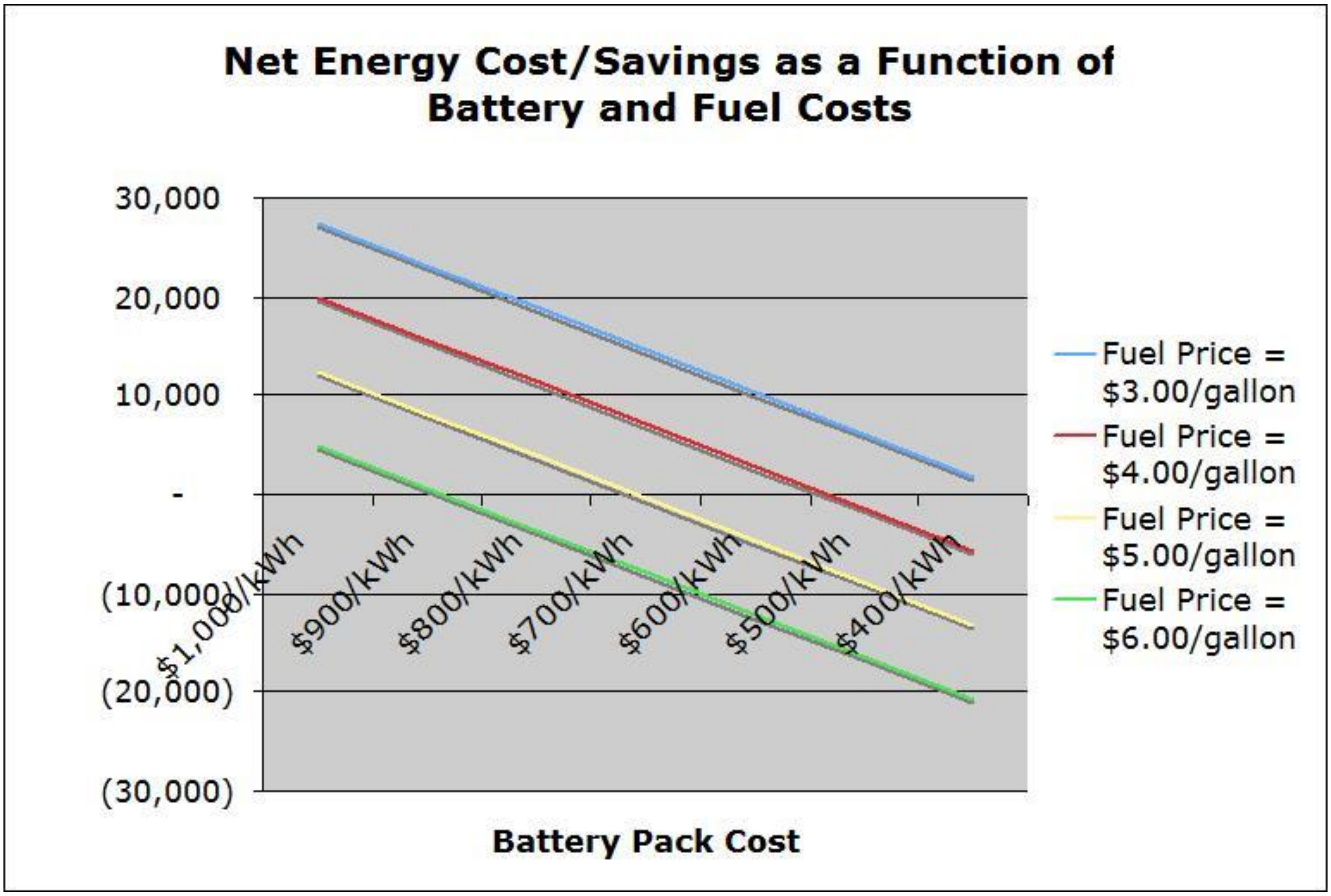
LASER Criterion	Description of Original VIFET Criterion	Impact of Proposed Solution on Transportation Market
	range Class 8 truck operation requires a battery with very high energy content, or "energy density."	Class 8 trucks can achieve a 100-mile range with 3,000—4,500 kg total battery pack weight.
Reliability	Integration of potentially thousands of battery cells into a battery pack requires high level of cell reliability and/or battery pack ability to tolerate cell failures.	TransPower had identified lithium cells manufactured to high quality standards and its Cell-Saver™ BMS can both extend cell life through active balancing and isolate bad cells from the rest of the Mile-Max™ module.

Source: TransPower

Energy storage tests performed under the VIFET project included bench tests of small four-cell modules of 200 Ah cells, followed by integration and testing of seven full-size Mile-Max™ modules on the first prototype truck, each containing 16 cells rated at 260 Ah. This testing was followed by use of 20 modules, each containing six 700 Ah cells, on the second VIFET truck. This progression of activities fully validated battery integration and thereby achieved a key milestone required before proceeding to large-scale manufacturing of battery subsystems and heavy-duty battery EVs.

The TransPower energy storage technology can have a transformational impact on the transportation market by enabling large trucks to become economically cost-competitive with conventional trucks using diesel or natural gas fuel. Figure 3 illustrates the significance of battery cost reduction, showing the net energy cost of a battery electric Class 8 truck (assuming 100 miles/day) as compared with a diesel truck performing a comparable duty cycle.

Figure 3: Net Energy Cost/Savings of Batteries vs. Diesel Fuel



Source: TransPower

This illustration clearly shows why electric trucks have not been cost-competitive in the past. At past fuel prices of $3/gallon or less (corresponding to the sloped blue line), and lithium battery costs of $1,000/kWh or more, an electric truck costs about $30,000/year more to operate than a diesel equivalent. However, with fuel prices now exceeding four dollars per gallon (sloped red line), and TransPower's lithium battery costs declining to the $500/kWh range, society is approaching a historic crossover point at which annual energy costs of an electric truck are now equal to or lower than the fuel costs for a diesel truck. The TransPower battery solution capitalizes on this crossover not only by bringing battery costs down to the $500/kWh range, but also by addressing the five aforementioned LASER criteria. By eliminating the "cost penalty" associated with EVs, while maintaining acceptable levels of safety and reliability, the TransPower energy storage technology eliminates the principal obstacles to market acceptance, at least for truck operators whose range requirements can be met with a battery-based solution.

EV Propulsion

Funding for the second VIFET truck not only allowed additional advances in TransPower's vehicle control and energy storage technologies, but also enabled advances in propulsion of large EVs. The main propulsion system installed into the second truck uses a revolutionary 10-

speed automated manual transmission (AMT), which represents a major industry innovation and a huge improvement over the standard two-speed transmission installed into the first VIFET truck. To properly test the AMT technology before installing it into the second truck, TransPower constructed a dynamometer capable of testing the fully integrated powertrain under conditions similar to those to be experienced by fully loaded vehicles. An early version of the AMT was tested on this dynamometer in the summer of 2012, with all major drivetrain components except electrically-driven accessories fully integrated into the test stand. Figure 4 is a photo of this test setup. Visible at the left side of the photo are the ICU and, on top of it, the central control module (CCM) that routes high-voltage power to the ICU and main drive motor. To the right of these items is the dynamometer itself, showing, from left to right, the main drive motor, transmission, and driveline.

With this dynamometer setup, TransPower was able to conduct integrated performance testing by sending control commands directly from the vehicle pedal and shift mechanism, through its CCM, to the ICU and on to the main drive motor. The main drive motor then rotates the drive shaft via the AMT, which changes the gear ratio automatically in response to motor speed and torque data. TransPower's dynamometer testing included a full set of tests of the ICU's ability to control the motor and rotate the main drive shaft through all five transmission speeds. This testing helped validate control rules hardware and component responses, and control code using component in-the-loop testing methods. It also enabled us to measure energy efficiency baseline values for the battery pack and driveline. The version of the AMT shown in Figure 4 uses a shift mechanism supplied by Mastershift and a four-speed Spicer transmission. The version installed into the second VIFET truck is a larger, more rugged system using a 10-speed dynamometer setup with this more advanced version of the AMT, which allows seamless automatic shifting through up to ten speeds in Class 8 vehicle applications, without the efficiency losses created by torque converters on conventional automatic transmissions.

Figure 4: Complete Dynamometer Assembly Showing Fisker Motor, AMT, and Dynamometer Water Brake Mechanism

Photo credit: TransPower

Figure 5: High-Power Main Propulsion System on Dynamometer, Featuring 10-Speed AMT

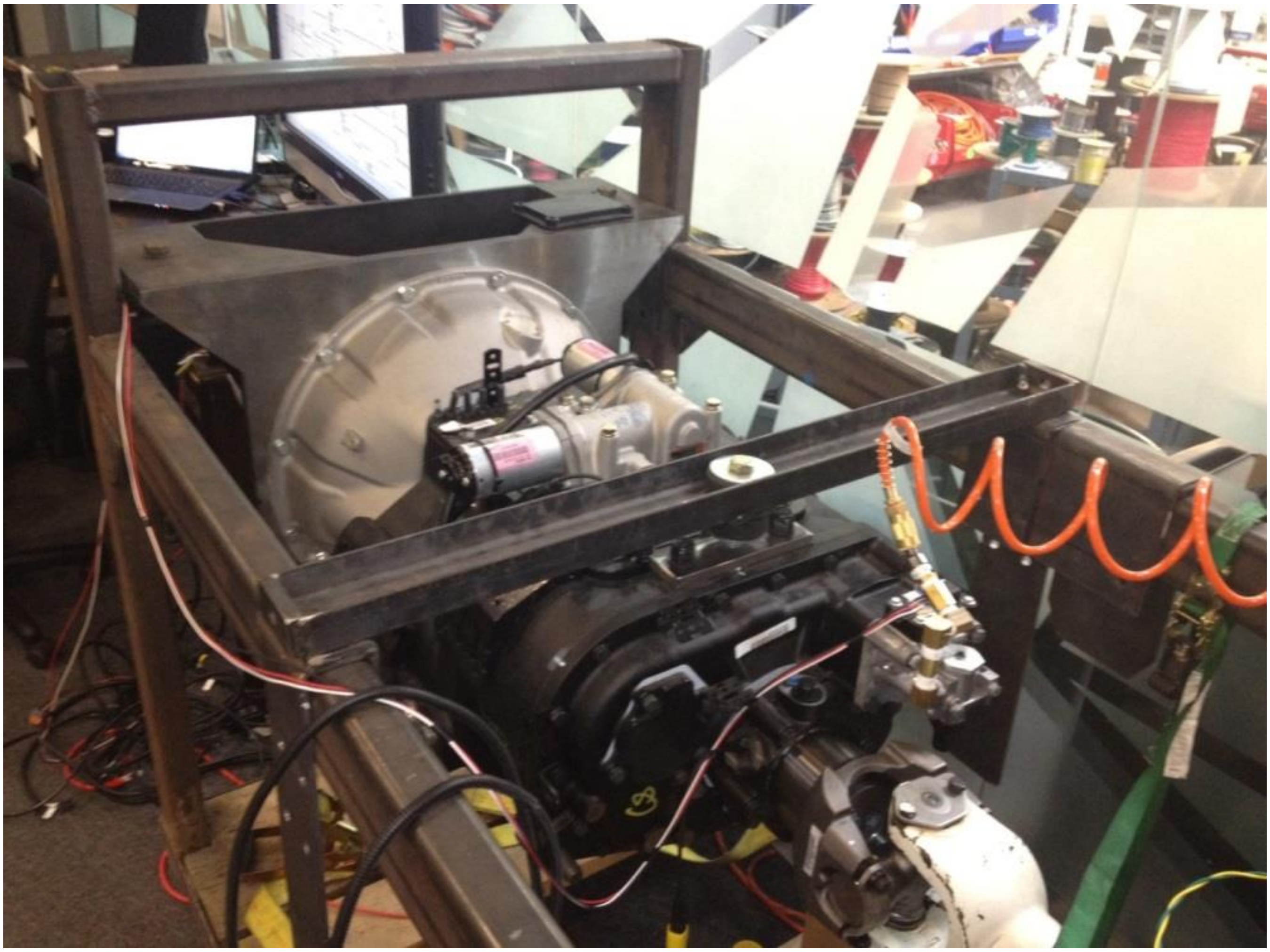


Photo credit: TransPower

Also visible in Figure 5 is the bell housing and dual motor structure used to mate the Eaton 10-speed transmission to the two Fisker electric motors used to propel TransPower's Class 8 on-road trucks. The Fisker motors are extremely compact and lightweight for the amount of power they produce. The attributes of these motors, combined with TransPower's AMT, are showing greater performance and efficiency than have ever been achieved in a Class 8 EV. Other features of the TransPower electric propulsion system include:

- Safe starting—a series of software features to assure effective control of primary and secondary vehicle functions starting with emergency stop, charge cable detection, vehicle key-on, brake released, automated transition through ground fault safety, high-voltage readiness, contactor control for precharging high-voltage DC components, initial wake status and safe initial operational state verification of power train components and user inputs, fault notification.
- Torque security in traction and braking—safe and secure deployment of motor torque are assured by regulating system response to irrational user input such as starting in a

drive mode other than neutral, selecting an initial drive mode without the brake pedal applied, too-rapid sequential shift selection, defective throttle pedal signal, irrational shift selector output, over-temp of battery, over-temp of inverter coolant, over-temp of DC-DC supply, low battery, general communication fault.

- Operating state recognition, transition and communication with the user (to include shifting function)—state recognition, transitions, and user communications have all been verified following safe startup, and once a Vehicle Ready state has been communicated to the operator. Drive mode transitions, gear selections, torque enable events, creep torque application, propulsion, regenerative braking, limp home modes, emergency stop response, response to removal of emergency stop have all been verified. Power de-rating and self-protections were verified by creating spoofed trigger conditions such as coolant over-temperature and battery capacity low and verifying torque authority reduction at the pedal.
- Power de-rating and self-protection (to include cooling function and battery protection) have been validated.

CHAPTER 2: VIFET Truck Number One

TransPower's first major step in development of the electric drive system design for the VIFET project was to evaluate the performance of the first generation ElecTruck™ drive system installed into the first VIFET prototype truck ("Truck #1") in 2011. The following subsections discuss each of the five major ElecTruck™ subsystems and describe how the initial design of each subsystem performed in testing of prior vehicles, followed by an explanation of how test results were used to improve the design of each subsystem. Each subsection concludes with a brief discussion of how performance of the trucks built under the Zero Emission Carbon Transport project is expected to be improved based in the design modifications undertaken.

Truck #1 Main Propulsion System

The main propulsion subsystem (MPS; also referred to as "motive drive" subsystem) converts electrical power from the battery subsystem into mechanical power to drive the vehicle's wheels. The primary component of this subsystem is the main drive motor. For its initial prototype of vehicles, TransPower evaluated numerous motor options and, after several months of analyses and discussions with motor manufacturers, we made a novel choice in selecting a motor originally designed by Jing-Jin Electric (JJE) for a high-performance hybrid passenger car, the Fisker Karma. Developed and supplied by Quantum Technologies, these motors each provide 150 kilowatts (kW) of peak power, more than adequate to meet the most demanding truck and bus requirements. Adapting a motor designed for passenger cars has a potentially high payoff as these motors are more compact, lightweight, and economical than competing motors. They have also undergone extensive testing and certifications by Quantum to qualify them for automobile use, which adds to the degree of confidence in the reliability of the product.

The key challenge involved in adapting these motors for use in heavy-duty vehicles is generating sufficient torque for vehicles with gross weight ratings of up to 80,000 lbs. In the first VIFET Class 8 truck, TransPower's motive drive subsystem achieved this by combining the torque from two motors by integrating two motors with a combining gearbox, as shown in Figure 6. The output shaft of the combining gearbox (visible in the lower right corner of the photo) was then connected to a two-speed manual transmission. TransPower's evaluation of this motive drive configuration, based on experience gained integrating and testing the first prototype truck, is summarized as follows.

Design Strengths: The JJE/Fisker motors appeared adequate for Class 8 truck performance, used in pairs, and despite cost increases of the past two years, the combined cost of two such motors remains well below the cost of larger electric motors capable of supplying 300 kW of peak power. The planed method of controlling the two-speed transmission, via a custom-developed AMT derived from paddle shifters developed by Mastershift for use in racing cars, demonstrated the potential for significant performance and efficiency improvements in TransPower's two Class 8 electric yard tractors. The AMT was shown to be able to provide higher starting torque without compromising efficiency at higher operating speeds. Maintaining high efficiency across the vehicle speed range is important because this directly affects the operating range a vehicle can achieve on a single battery charge.

Figure 6: Original Main Propulsion Unit Developed for First Prototype

Photo credit: TransPower

Design Weaknesses: The combining gearbox is expensive and the side-by-side mounting arrangement was difficult to fit within the frame rails of the Navistar International truck. In addition, further analysis of vehicle performance requirements raised concerns that this motive drive configuration might have difficulty meeting high-end performance requirements such as hauling full 80,000-lb. loads at high speeds. The original approach to developing TransPower's AMT using "paddle shifter" hardware and software developed by Mastershift for use in racing cars, demonstrated numerous shortcomings during TransPower's efforts to adapt AMT technology to the control of electric motors in its two electric yard tractors (funded under a separate project by the State of Texas, concurrently with the VIFET project).

Design Improvements Selected: Based on the above experience and observations, TransPower decided to develop a more efficient way of combining the torque from two drive motors, via a common shaft. TransPower also decided that a more robust AMT system was required, and ended up redesigning much of the shift control hardware and software provided by Mastershift. During the prototype testing phase, TransPower became aware of a relatively new transmission product manufactured by Eaton that also utilizes AMT technology, and following a series of discussions with Eaton personnel, was able to secure Eaton's agreement to supply these specialized transmissions and their more robust shifting mechanisms for use in the second VIFET Class 8 truck.

Truck #1 Inverter-Charger Subsystem

The ElecTruck™ inverter-charger subsystem (ICS) performs two vital functions: while the vehicle is moving, it converts DC power from the battery subsystem into AC power for the main drive motors, and while the vehicle is plugged in for recharging, it converts AC power from the grid into DC power to recharge the battery pack. The central component of the ICS is a new onboard ICU TransPower developed for its initial prototype vehicles in partnership with EPC, a startup company specializing in advanced power electronics. In early testing on TransPower's first prototype on-road truck and its first two yard tractors, the ICU has demonstrated the potential to revolutionize EV design by combining the functions of the inverter, which controls the drive motors, and the battery charger, which recharges the vehicle's batteries on a "plug-in" basis. This innovation, which will reduce the overall cost of ownership of plug-in electric and hybrid vehicles, is made possible by several recent technical advances that have enabled TransPower and EPC to shrink the size of the magnetic materials required for high-power, grid-compliant devices. These advances include new insulated gate bipolar transistors that switch at higher frequencies than competing inverters, producing less electrical switching noise and reducing the materials required to filter this noise. Liquid-cooled heat sinks reduce the cost of cooling and improve reliability by eliminating fans, as well as contributing to the more compact, efficient ICU packaging. Hence two ICUs can easily be integrated into larger trucks and buses, providing a total of up to 300 kW of peak power for the main drive motors and the capability to support battery charging at power levels of up to 140 kW. Figure 1 (page 4) shows the interior of the ICU module.

The original ICU operating concept was to use a retractable cord that allows vehicle operators to plug the inverter-charger into 220 volt (V) outlets equipped with the right receptacles. The inverter-charger automatically regulates the recharging of the vehicle's batteries, and safely terminates the charging process when the batteries are brought up to a full charge. The original concept also called for both chargers to be plugged in simultaneously, with the goal of providing a full battery charge for a large 300 kWh battery pack in less than three hours. Eliminating the need for a separate off-board battery charger not only reduces the cost of ownership, but simplifies facility requirements and charging logistics. TransPower believes this will accelerate customer acceptance of plug-in electric and hybrid vehicles using the ICU.

Design Strengths: In testing on our prototype vehicles, the ICU met all expectations. In fact, its development was accelerated so it could replace commercial off-the-shelf inverters that we initially believed could be made to function more quickly, but that turned out to be incapable of handling the high power levels and currents produced by the ElecTruck™ system.

Design Weaknesses: The ICU is large and expensive in comparison with other automotive inverters. In initial vehicle testing, it was not able to operate the main drive motors at their full rated power levels. Vehicle operators advised TransPower that they did not like the idea of carrying heavy charging cables and plugs around on their trucks. Plugging two chargers in simultaneously was determined to be less desirable, from a logistics standpoint, than plugging in a single charger.

Design Improvements Selected: A third party manufacturer in Alabama was selected to help reduce the cost of manufacturing the ICU. Concepts for shrinking the size of the ICU enclosure and packaging its interior components more efficiently were developed, along with concepts for modifying the ICU power electronics so multiple ICUs can charge a single battery string, and concepts for increasing the ICU charge power level beyond 70 kW. However, all these design improvements were determined to be beyond the scope of the VIFET project and will not be implemented until subsequent steps toward commercialization of the ElecTruck™ system.

Truck #1 Energy Storage Subsystem

The ElecTruck™ energy storage subsystem (ESS) was designed to address the importance of battery performance by combining the best value lithium-ion batteries available anywhere in the world with a sophisticated BMS and a well-engineered integration concept. The intended result is an ESS with a lower cost of energy than competing systems, but that also offers high performance and long operating life—possible as long as 10—15 years depending on how the batteries are utilized.

For its first prototype electric truck, TransPower developed an 8.3 kWh battery module consisting of 10 large 260 Ah $LiFePO_4$ cells. Figure 7 shows six of these modules mounted to the side of Truck #1.

Figure 7: Battery Subsystem in Truck #1

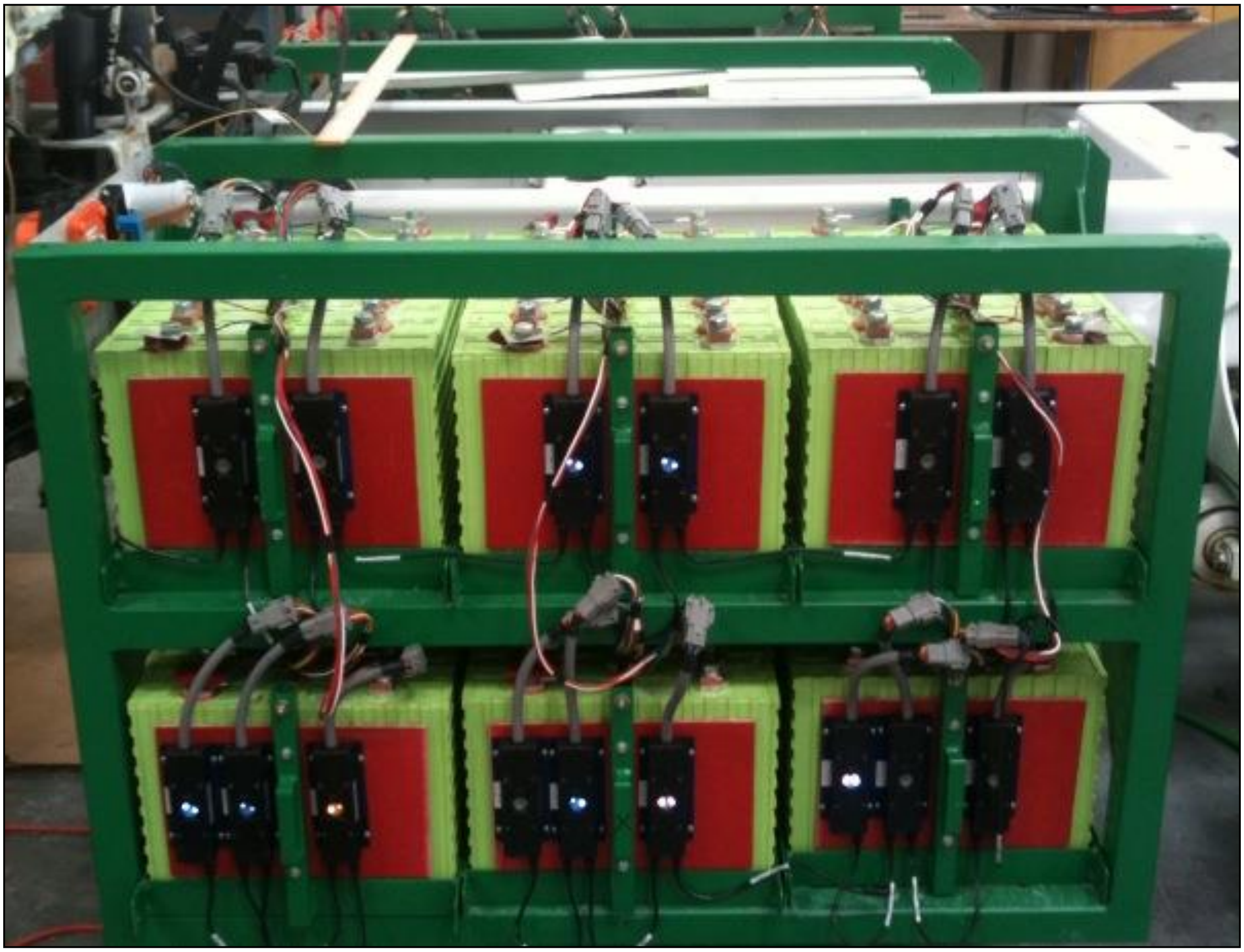


Photo credit: TransPower

The illuminated black boxes and wiring on the side of the unit are elements of the Flux Power BMS we selected for our first prototype vehicles. The BMS is intended to help assure proper, safe functioning of the high-energy cells by monitoring the condition of each individual cell, storing this data indefinitely, and providing early warning of changes in cell voltage or temperature that could indicate a problem. The BMS also helps to equalize charge among cells—which can extend cell life—and works in conjunction with TransPower's vehicle electrical safety and control systems, is intended to assure that batteries are not damaged by overcharging or over-discharging.

Design Strengths: The large format LiFePO4 cells we selected for our ESS showed favorable performance characteristics in our first prototype vehicles, including high energy density and voltage and temperature stability. TransPower also identified additional suppliers of such cells that enabled us to command more attractive prices and to obtain cells of different sizes that could be customized for a broad range of applications.

Design Weaknesses: Testing of the first prototype on-road truck demonstrated a need to improve the overall robustness of the battery modules and their structural supports. The design shown in Figure 7 was determined to be subject to various types of structural failures if subjected to extreme shock or vibrations. TransPower also determined that the integration concept didn't provide sufficient protection of cells and electrical connections against environmental contaminants such as water or dust. In testing of the prototype truck and our yard tractors, TransPower found the Flux Power BMS difficult to calibrate and maintain, as well as expensive.

Design Improvements Selected: TransPower elected to completely redesign its battery modules and support structures after testing of Truck #1. This process has proceeded in phases, beginning with development of a new Mile-Max™ module, which became TransPower's new standard ESS building block. The first version of Mile-Max contained 16 lithium-ion cells. Each rated at 260 Ah and stored about 13.3 kWh of energy. In mid-2012, this version was installed on Truck #1 in place of the configuration shown in Figure 7. Similar modules, using 300 Ah cells, were then used in both of TransPower's electric yard tractors. For Truck Number Two (Truck #2), TransPower then progressed to the module design pictured in Figure 2 (page 7), which uses six 700 Ah cells.

Truck #1 Electrically-Driven Accessory Subsystem

The TransPower electrically-driven accessory subsystem (EDAS) designed a new means of powering vehicle accessories such as power steering, braking, heating, ventilation, and air conditioning. Figure 8 shows the main components of the EDAS installed into Truck #1. In conventional vehicles, these functions utilize engine-driven power takeoff units, but in TransPower EVs, the engines are removed. TransPower's EDAS assembly uses a rugged air compressor and hydraulic pump to make the truck accessories fully electric, allowing them to function without an engine or alternator. TransPower also supplies electrically-driven accessories to provide power for lighting, refrigeration, and any other electrical appliances or leads. In fact, these accessories can be combined with lithium battery packs and installed into conventional diesel trucks to provide electric power without having to idle the engine. TransPower's accessories are activated only when required, which makes them significantly more energy-efficient than accessories that are run all the time.

Figure 8: EDAS Components Installed into Truck #1

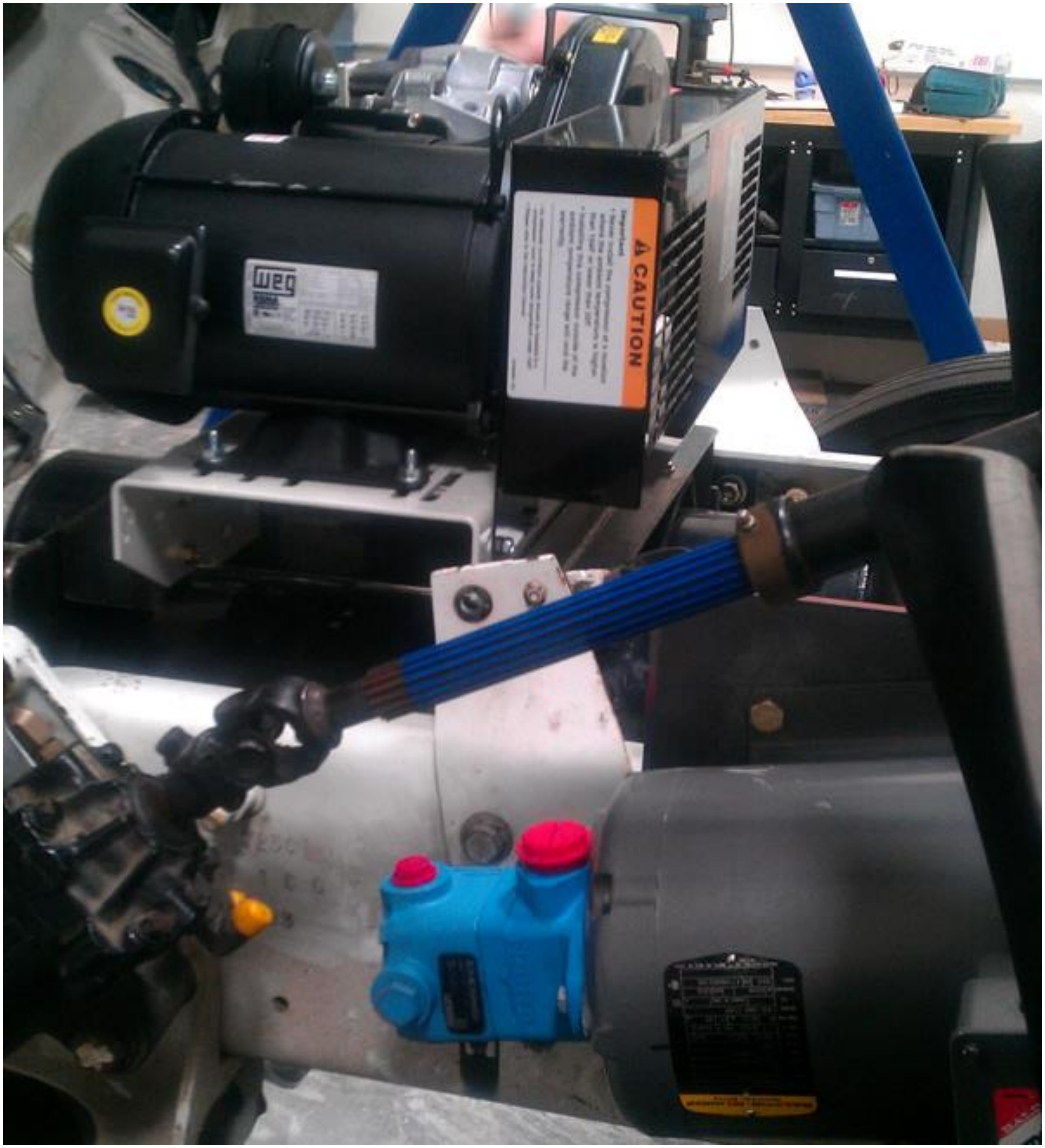


Photo credit: TransPower

Design Strengths: In testing on TransPower's first prototype electric truck, the EDAS worked adequately, providing power for the steering and braking subsystems. Air conditioning was not provided in this truck but was provided in TransPower's two electric yard tractors, which uses a more evolved version of the EDAS to support this function.

Design Weaknesses: The EDAS utilizes fairly expensive components and requires additional in-house assembly. In testing with the yard tractors, TransPower discovered that at high power levels, the accessory inverters malfunctioned intermittently.

Design Improvements Selected: TransPower elected to purchase more EDAS components separately, which reduced component cost enough to offset higher in-house assembly costs. TransPower traced the intermittent inverter faults seen at high power levels to an incompatibility issue between its variable frequency drives and the soft starter circuits were employed.

Truck #1 Vehicle Control Subsystem

The TransPower vehicle control subsystem (VCS) controls all vehicle functions and makes the difference between battery-electric propulsion and conventional propulsion via internal combustion engines virtually transparent to the vehicle operator. All vehicle components are fully integrated into the vehicle's usual system of controls and displays, allowing drivers to easily monitor such parameters as vehicle speed and battery SOC using dashboard displays similar to those to which they are accustomed. As discussed in preceding sections, the VCS combines a network control architecture, control software, and power conversion modules into an integrated subsystem that links all drive system components and enables them to communicate with vehicle controls and displays via a CAN-based architecture.

Design Strengths: The "plug n' play" nature of the VCS enables TransPower to develop variants of its drive system customized for different vehicle models more quickly and efficiently than competitors. It will also facilitate the smooth evolution of TransPower's drive system as new technologies and components become available. In testing on Truck #1 and TransPower's electric tractors, the VCS worked adequately, providing smooth vehicle control and facilitating the acquisition of data for diagnostic and other purposes.

Design Weaknesses: The CCM housing the high-voltage distribution assembly and several power control devices was found to be difficult to troubleshoot and service when electrical problems were detected. In testing on Truck #1 and TransPower's electric tractors, intermittent problems were observed within the CAN communications network, which limited vehicle reliability and availability.

Design Improvements Selected: TransPower redesigned the interior of the CCM to make the wiring cleaner and easier to service, and moved some components outside the CCM to make the box less cluttered and more serviceable. TransPower's updated VCS concept will employ improved shielding of cables to reduce noise issues that were determined to be responsible for much of our CAN communications difficulties.

Truck #1 Integration and Testing

The subsystems and components just described were installed into Truck #1 between July and October 2012. Figure 9 is a photo of Truck #1 as it was nearing completion at TransPower's Poway, California, integration facility. Visible directly behind the cab are the top tiers of batteries mounted on both sides of the frame rails.

Following completion of integration in October 2011, Truck #1 was put through a series of tests to validate proof of concept of the TransPower electric drive system architecture, test key components such as the energy storage system, and to identify critical improvements needed to evolve the drive system into a commercially viable product. One of the early lessons learned during testing of Truck #1 was that the off-the-shelf inverters purchased to power the main drive motors had insufficient power and frequently failed. This caused numerous delays in testing and caused TransPower and EPC to accelerate development and perfection of the ICU. The ICU was originally not expected to be used until Truck #2 was built, but to complete testing of Truck #1 it was necessary to install one ICU into the vehicle, which enabled operation of the truck at half power. This testing was accomplished during the summer of 2012. By this time, Truck #1 had also been upgraded to use a new battery subsystem, incorporating the new Mile-Max™ module design, as discussed in Chapter 2.3.

Figure 9: Truck #1 during Integration

Photo credit: TransPower

A new battery support structure was designed and built to accommodate four Mile-Max™ modules on each side of the truck, or 128 cells in total. However, the number of cells in each series string was reduced from 120 to 112 after initial testing of the first full-scale battery module to reduce the vehicle bus voltage. The higher bus voltage of 384 VDC nominal was close to the limits of the Quantum inverters used in the first truck and was suspected as a possible cause of frequent failures of these inverters. Truck #1 will continue to use Quantum inverters, even though all subsequent trucks will utilize the more advanced ICU described previously in this report. Figure 10 shows the four Mile-Max™ battery modules installed on the passenger side of Truck #1, along the frame rails just behind the cab.

Figure 10: Updated Battery Module Design Incorporated into Truck #1

Photo credit: TransPower

Figure 11 shows Truck #1 during initial drive testing in late 2011. This testing was performed before the truck was upgraded to use the ICU of the Mile-Max™ battery design. However, sufficient testing of the truck was performed over a four-month period to validate the basic functionality of the TransPower electric drive system architecture. In February 2012, after repeated failures of the Quantum inverters that had been originally selected for Truck #1, the truck was taken out of operation for four months. During this period, the Quantum inverters were replaced with the ICU and the battery subsystem was upgraded as just described. Because only one ICU was available at this time (and because the project did not budget for installing any ICUs in Truck #1, much less two), the truck was limited to half-power operation. However, this was sufficient to validate the functionality of the ICU and new ESS, and set the stage for design and manufacturing of Truck #2.

Figure 11: Truck #1 during Initial Road Tests in Late 2011

Photo credit: TransPower

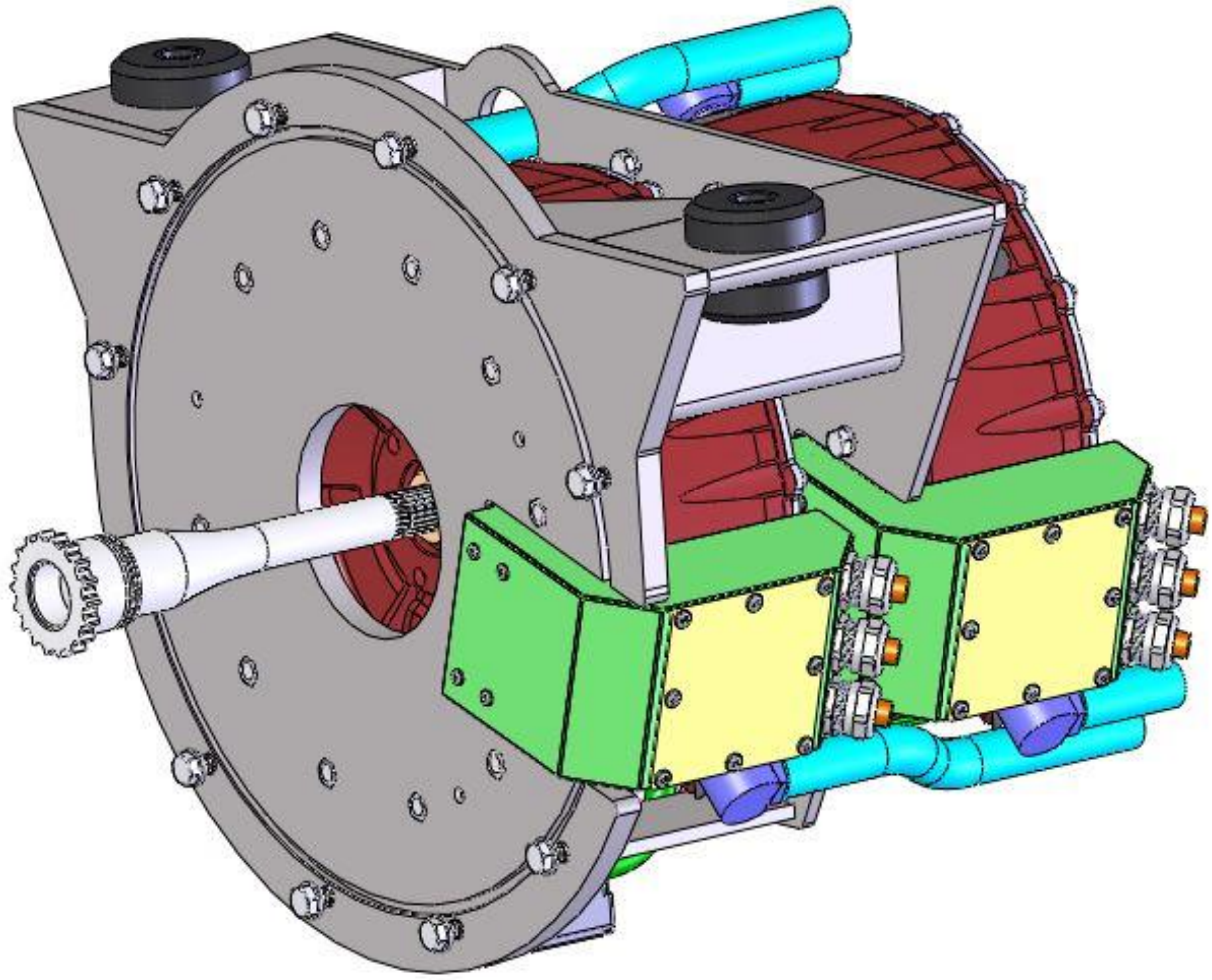
CHAPTER 3:
Truck #2 Design

TransPower's second major step in development of the electric drive system design for the VIFET project was to design a second generation ElecTruck™ drive system based on lessons learned from manufacturing and testing of Truck #1. Integration of Truck #2 was delayed from mid-2012 to mid-2013 to enable the design of the more advanced drive system to also incorporate lessons learned from operation of TransPower's electric yard tractors, and to take advantage of additional electric Class 8 truck research and development funding TransPower received from the CEC as part of the subsequent electric drayage demonstration (EDD) project. The following sections describe the updated drive system design developed for Truck #2. The subsections are arranged in the same sequence as the previous section, discussing each major ElecTruck™ subsystem in turn.

Truck #2 MPS Design

As discussed in Chapter 2, the main propulsion design concept developed for VIFET uses two JJE/Fisker interior permanent magnet motors. For Truck #2, the side-by-side motor configuration tested in Truck #1 was abandoned in favor of mating two motors in tandem using a custom-designed dual motor support structure. Figure 12 shows the design of the dual motor assembly that mates the two JJE/Fisker motors together and combines their output onto a common shaft. The motors are the maroon-colored disks partially obscured by the gray dual motor weldment, a highly specialized piece of integration hardware designed by TransPower and machined to our specifications by R&I Industries, a Southern California supplier.

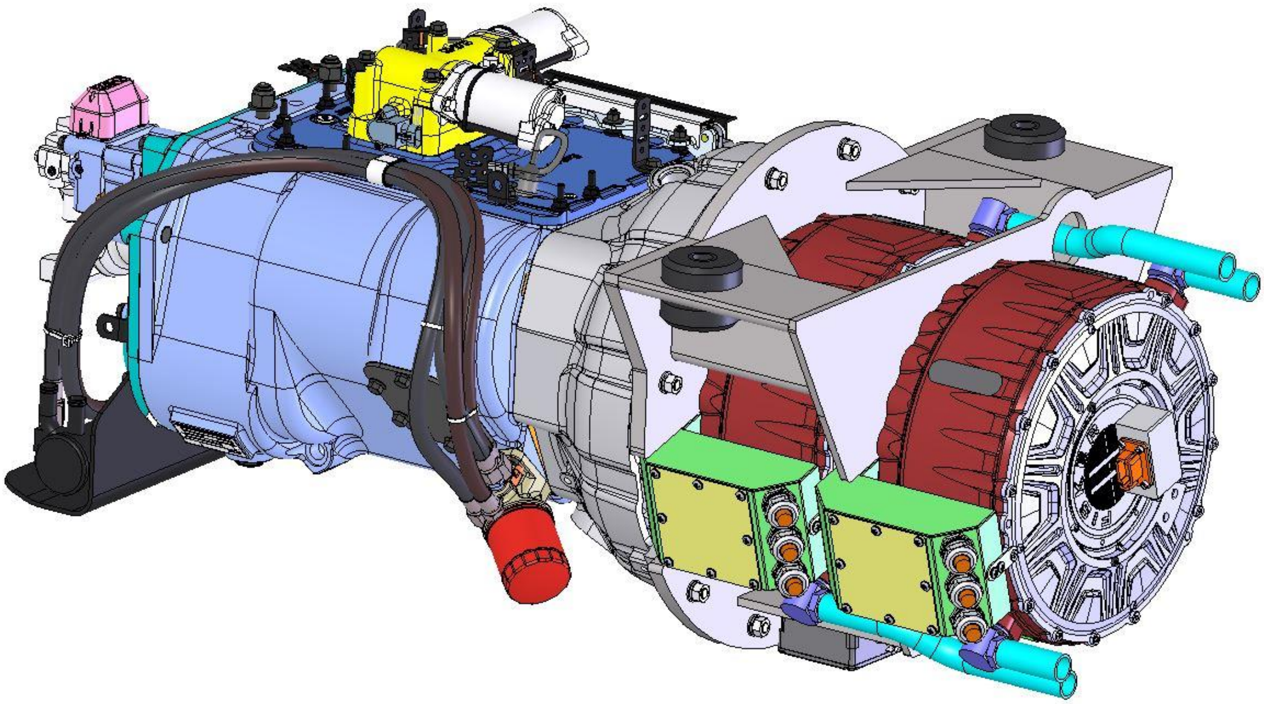
Figure 12: ElecTruck™ Dual Motor Assembly



Source: TransPower

A custom-designed bell housing was designed by TransPower to interface the dual motor structure to a 10-speed Eaton transmission. The Eaton transmission is controlled using AMT technology perfected by Eaton over the past decade for use with internal combustion engines, but modified by TransPower for use with electric motors. Figure 13 shows the design of the dual motor assembly as integrated with the Eaton 10-speed transmission.

Figure 13: ElecTruck™ Main Propulsion System with Two JJE/Fisker Motors Mated to an Eaton Manual Transmission



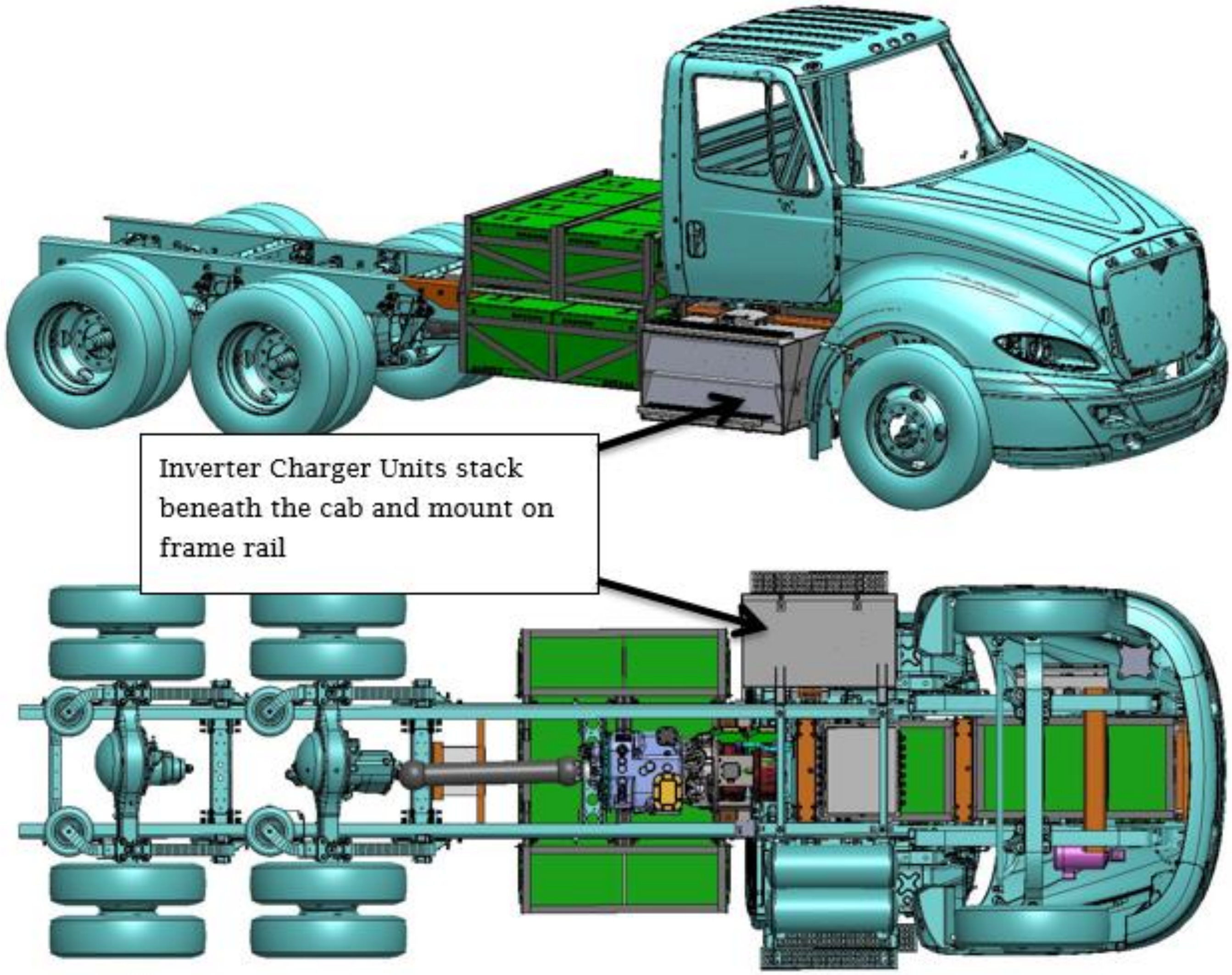
Source: TransPower

The gray cone-shaped object between the dual motor assembly and the transmission (colored light blue) is the customized bell housing, also designed by TransPower and fabricated locally. The Eaton transmission is a manual transmission that enables use of automated shifting with a device referred to as an "X-Y shifter." The X-Y shifter, shown mounted on top of the transmission in Figure 13, is provided by Eaton as well, and is tested to handle the mechanical requirements of heavy Class 8 trucks. TransPower's use of this device is unique, as we will utilize custom-developed software that matches shifting to the requirements for transmitting torque from electric motors to the truck axle. The configuration shown above will be the world's first adaptation of automated manual shifting to an electric Class 8 on-road truck.

Truck #2 ICS Design

As discussed in Chapter 2, the TransPower ICS is designed to use two ICUs to control the two drive motors, with one of the ICUs also used for charging the selected single-string battery pack. Figure 14 provides side and bottom views of the drive system layout, showing the design concept for integrating the two ICUs into the Navistar International ProStar® chassis used for Truck #2.

Figure 14: Vehicle Layouts Showing ICU Integration Concept



Source: TransPower

To implement this design, a single charging receptacle was installed on Truck #2, and during charging a cable and plug wired to the electrical service at the operator's facility is used to plug into the receptacle and initiate charging. This is a departure from our initial concept, which was to mount the plug and a length of charging cable to the vehicle. Fleet operators expressed concerns about the added weight and space needed for stowage of the charge cables and plugs on each truck. The selected approach requires a relatively inexpensive installation of the charger cables and plug at any facility that has 208 V, three-phase electrical service, and minimizes onboard equipment other than the ICU.

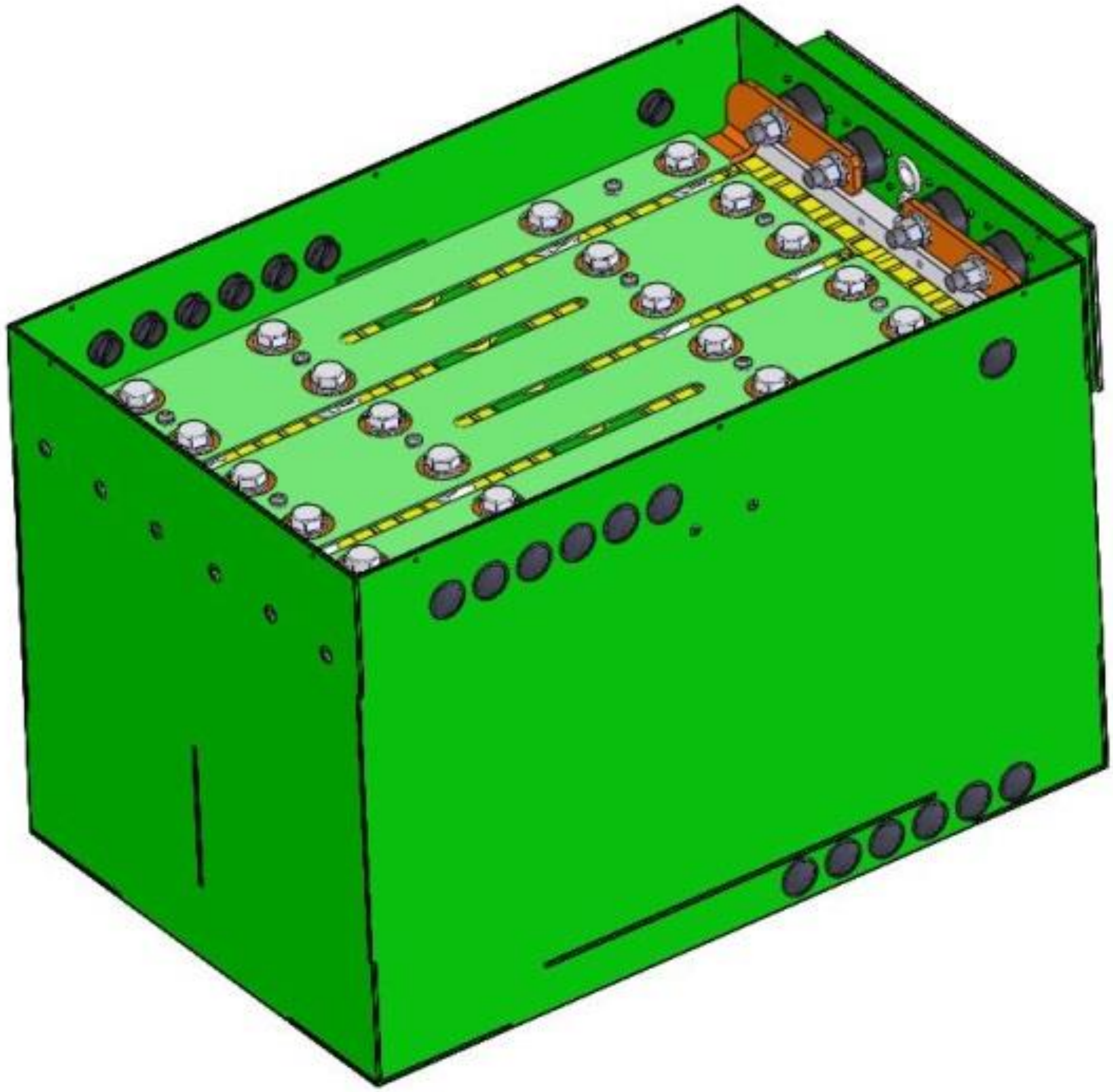
The original ICS design concept, as discussed in Chapter 2, utilizes both ICUs for motor control and provides the option of using either one ICU or both ICUs simultaneously for battery charging. Truck #2 will normally be charged using one ICU, as this will provide a full battery charge in a relatively fast three hours or less, while minimizing charging infrastructure and complexity. However, TransPower is developing a modified energy storage system for future commercial trucks that will return to the use of two parallel battery strings, which will enable a user to charge with both ICUs simultaneously (see Chapter 3 below). Users desiring this capability will require a second charging port on each truck (wired to the second ICU) and installation of a second transformer and dedicated 200 ampere circuit at the charging site. This would reduce maximum charging time from three hours to as little as 90 minutes. This is a more costly option than charging with one ICU, but could be selected by some truck operators in future situations where particularly fast charging is required. One example of such a situation could be for a truck operated on two daily shifts, where the ability to fully charge the batteries within a 60—90 minute period between shifts could enable the electric truck to be used for both shifts. While this would require dedicating two separate charging circuits to each truck and the logistics of plugging into two outlets at once, the additional cost savings of operating the truck for two shifts per day could justify these additional measures.

Truck #2 ESS Design

For Truck #2, the TransPower energy storage system utilizes a single 120-cell string of 700 Ah cells, providing 269 kWh of total energy storage operating at a nominal voltage of 384 VDC. Figure 15 shows the Mile-Max™ battery module design concept selected as the common building block for this system, consisting of six of the 700 Ah cells in an enclosed container.

Within the module, the cells are electrically connected with bus bars and conductive plates, and are packed tightly within the module to restrict their movement during vehicle operations. A custom-designed printed circuit board is mounted on top of the cells to provide power and data connections between the cells and the BMS. The 700 Ah cells and our BMS sensor boards are supplied by Balqon, although the cells are manufactured on the Winston assembly line in China. A total of 20 of these modules are connected in series to meet the energy storage requirements of Truck #2. As each module weights approximately 400 lbs. and is the size of a small steamer trunk, integrating 20 of these modules into a truck represents a significant packaging challenge.

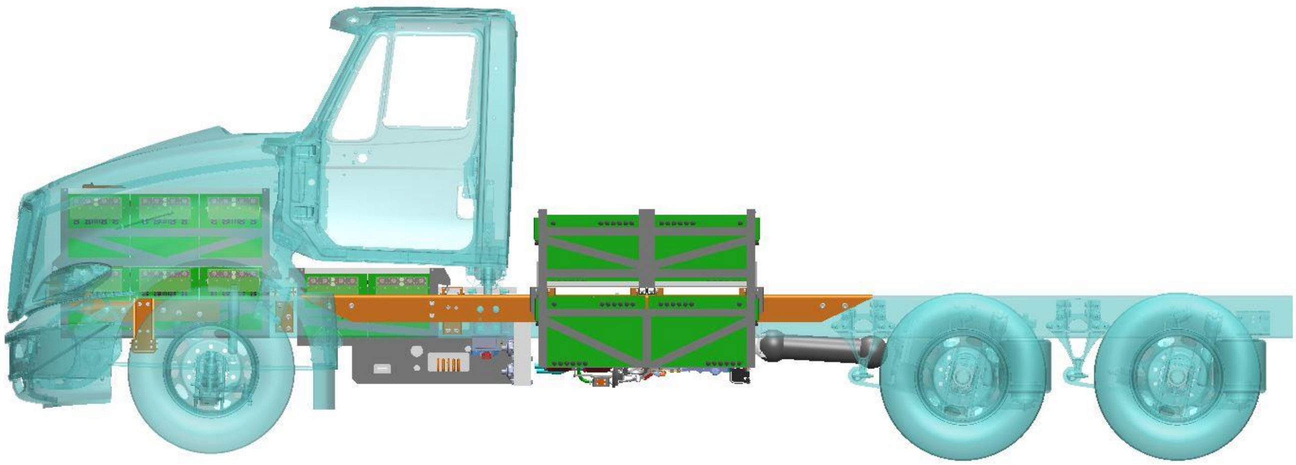
Figure 15: Mile-Max™ Battery Module Containing Six 700 Ah Cells



Source: TransPower

Figure 16 is a side view of the Truck #2 design that provides some insights into how the battery module packaging issues were addressed for this vehicle. Battery modules, shown in green, can be seen integrated in several different locations, including within the engine compartment, between the frame rails under the cab, and outside and on top of the frame rails just behind the cab. This configuration was selected to provide a low center of gravity and to minimize the number of cells directly exposed to side impacts or potential road debris. However, given the large volume of battery modules that has to be accommodated, it was impossible to completely shield all modules from such potential hazards.

Figure 16: Side View Showing Battery Modules



Source: TransPower

As discussed previously, our ESS uses large format LiFePO4 cells, which offer high energy density and stability. With 269 kWh of total onboard energy storage capacity, the system provides 188 kWh of usable energy down to a cell SOC of 30 percent. Limiting discharge to 30 percent SOC is expected to result in cell lifetimes of 3,000—5,000 cycles. Occasional discharges down to 20 percent SOC can increase usable energy to 215 kWh per cycle. Based on these figures, Truck #2 was projected to be able to operate for 70—100 miles on a single battery charge, depending on duty cycle.

The LiFePO4 cells selected for this ESS have shown favorable performance characteristics in all of TransPower's early prototype vehicles, including high energy density and voltage and temperature stability. TransPower has identified multiple suppliers of such cells, which enabled TransPower to command more attractive prices and to obtain cells of different sizes that could be customized for a broad range of applications. For commercial trucks beyond Truck #2, TransPower has decided to adopt a modified ESS design that will consist of two parallel strings of 300 Ah cells, instead of one parallel string of 700 Ah cells. This option is being pursued because experience to date with the 700 Ah cells has shown that they vary in true charge capacity more than smaller cells in the 180—400 Ah range. These variances can make it more difficult to maintain long-term battery health, and if cells vary too far below their Ah rating, operating range can be severely compromised.

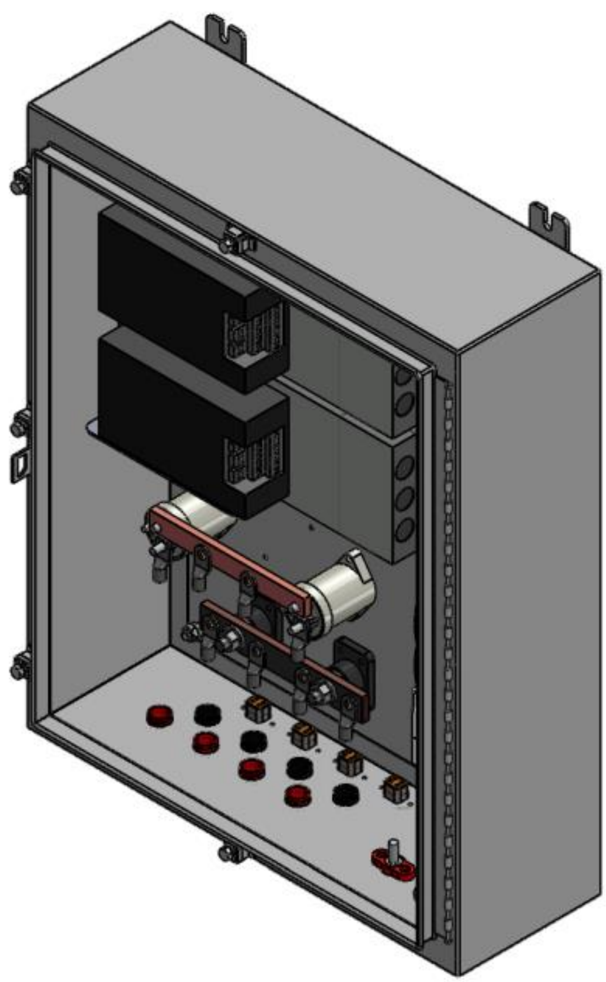
Truck #2 EDAS Design

As discussed earlier, the EDAS powers vehicle accessories such as power steering, braking, heating, ventilation, and air conditioning, without the use of engine-driven power takeoff units. Numerous design improvements have been made to this subsystem in the course of building and testing TransPower's first-generation prototype vehicles. As discussed in Chapter 2, TransPower eliminated the use of soft starters in the EDAS midway through the VIFET project, employing a series of contractors instead and an additional variable frequency drive so continuously running accessories such as power steering can be separated from ones that are activated intermittently such as charging the air system to maintain adequate pneumatic pressure for braking. TransPower also eliminated the air cooler purchased as part of the EDAS for Truck #1, which was determined to be unnecessary in such trucks due to natural cooling that occurs as air moves through the longer air lines in these large vehicles. For Truck #2, TransPower was also able to reduce the cost of the EDAS by several hundred dollars by purchasing elements of the air compressor assembly separately and assembling them in-house.

Truck #2 VCS Design

The TransPower VCS, which controls all vehicle functions, has shown its inherent strengths during testing of early prototypes and is constantly being improved and extended to new vehicle models. As discussed in preceding sections, the VCS combines a network control architecture, control software, and power conversion modules into an integrated subsystem that links all drive system components and enables them to communicate with vehicles controls and displays. The main element of the VCS is a CCM that houses high-voltage distribution assembly and several power control devices. The CCM design for Truck #2 is shown in Figure 17.

Figure 17: CCM Design for Truck #2



Source: TransPower

As discussed in Chapter 2, the interior of the CCM was redesigned for Truck #2 to make the wiring cleaner and easier to service, and some components were moved outside the CCM to make the box less cluttered and more serviceable. The CCM built for Truck #1 was constantly rewired as the truck was tested and as certain modifications became necessary. However, by the time TransPower built and tested its next two EVs (yard tractors), which use a similar CCM, its engineers were able to develop a much cleaner wiring scheme that TransPower believes will make this component more reliable and serviceable.

Another key element of the TransPower control system is the control software used to control the AMT. Truck #2 benefits from a year of research and development specifically focused on this product, which began with dynamometer testing of the earliest version of our AMT in July 2012, and continued through testing of several variants of the AMT on test benches and two electric yard tractors during the second half of 2012 and the first half of 2013. The AMT has been shown to significantly improve the performance of TransPower's EVs, and TransPower is expecting even better long-term results with Truck #2, which will utilize more rugged AMT hardware supplied by Eaton.

CHAPTER 4: Truck #2 Manufacturing and Testing

Implementation and evaluation of the design discussed in Chapter 3 was completed in three stages:

1. Manufacturing of major subsystems for Truck #2 from April through July 2013.
2. Integration of subsystems and other components into Truck #2 from June through August 2013.
3. Commissioning and testing of Truck #2 beginning in September 2013.

When additional cost-sharing to enable manufacturing of Truck #2 was acquired by TransPower in mid-2011, the initial expectation was that this vehicle would be built by 2012 and that it would undergo nine months of testing under drayage operating conditions before the conclusion of the VIFET project. However, the period from mid-2011 through 2012 was a period of unexpectedly rapid growth for TransPower and the EV industry, which opened up a broader range of opportunities for TransPower to incorporate new technologies and design concepts into Truck #2. By the time Truck #1 was built and completed its initial series of road tests in late 2011, TransPower had the choice of building a second truck fairly rapidly, which would be restricted to using technologies and components similar to those installed in Truck #1, or taking additional time to develop new design concepts reflecting lessons learned during testing of Truck #1. While Truck #1 demonstrated the proof of concept of TransPower's basic electric drive system architecture, it was still just a very early prototype and TransPower recognized that its drive system design would need to go through a series of revisions and upgrades for it to become truly commercially viable. Therefore, TransPower determined that the VIFET project would produce more value if Truck #2 could be upgraded to a design closer to the ultimate commercial version, even if this meant delaying the completion of Truck #2 and reducing the amount of time available for its testing during the VIFET project.

During the early stages of redesigning its drive system for Truck #2, TransPower received a second CEC award to fund a broader precommercial demonstration of electric drayage trucks. During 2012, this new project produced or accelerated a series of technology advances, such as the AMT and the Cell-Saver BMS, which were not even remotely feasible when the VIFET project began or when Truck #2 was initially funded by the South Coast Air Quality Management District (SCAQMD) While the new EDD project provided funding for a completely new fleet of electric Class 8 trucks (originally two, and subsequently growing to seven with the infusion of additional funds from the CEC, SCAQMD, and ports of Los Angeles and Long Beach), TransPower elected to continuously upgrade the design of Truck #2 under the VIFET project to keep up with the new designs being developed for the EDD trucks. Had this not been done, Truck #2 would have been obsolete within a few months of its deployment. Stretching out the design phase for Truck #2 also allowed TransPower to capitalize on lessons learned from the first electric trucks it placed into actual revenue service: two yard tractors that were operated at a retail distribution center in Texas from April through July 2013.

The net results of prolonging the Truck #2 design process were twofold. On the positive side, Truck #2 incorporates newer technologies and components that give it superior performance to what could have been achieved if the truck were built on a faster track, and is much closer to a commercially perfected product. On the negative side, designing and manufacturing Truck #2 consumed nearly all of the remaining time on the VIFET project, even after extending the project for six months to September 30, 2013. As a result of the latter consequence, less data are available in the way of test results from Truck #2 than was originally expected by the end of the VIFET project. However, the test results that have been acquired are generally positive and TransPower believes the long-term benefits of improving Truck #2 far outweigh this one drawback. Truck #2 now serves as a "pilot truck" for seven EDD trucks; in fact, the first EDD truck will be identical to Truck #2 and subsequent EDD trucks will use the same components, with a few exceptions to accommodate additional lessons learned from the assembly of Truck #2. The following sections summarize the steps taken to convert the design discussed in Chapter 3 into the working Truck #2 that is now blazing the way for a new generation of electric Class 8 trucks.

Subsystem Manufacturing

By April 2013, TransPower acquired all of the major components required to build the drive system to be installed into Truck #2, and began the process of building the five key subsystems described in the preceding sections (main propulsion, energy storage, etc.). Figures 18 and 19 show the integration of the main drive motors for Truck #2 into the dual motor support structure that houses both motors and mates them to the transmission bell housing and the truck frame. This creates in effect a single motor with a peak power rating of 300 kW. Even accounting for the cost of the dual motor structure and the assembly required, the dual motor configuration can be built for about half the cost of competing AC motors with comparable performance characteristics.

Figure 20 shows the dual motor assembly mounted to the Eaton 10-speed transmission. This device is expected to provide an unprecedented blend of high performance characteristics in a wider variety of duty cycles than any electric motor or electric motor and transmission combination previously built. Figure 21 is a photo of several of the Mile-Max™ battery modules for Truck #2, with batteries installed and wiring complete, just prior to installation into the vehicle. As shown, the metallic-colored modules are arranged into groups of two, three, or four cradle assemblies, which are then used to life the modules and bolt to the vehicle frame. As discussed previously, Truck #2 has 20 of these modules installed, housing a total of 120 batteries, each rated at 700 Ah.

Figure 18: Drive Motors Installed in Dual Motor Support Structure

Photo credit: TransPower

Figure 19: Completed Drive Motors after Integration into Dual Motor Support Structure

Photo credit: TransPower

Figure 20: Dual Motor Assembly Mounted to 10-Speed Eaton Transmission

Photo credit: TransPower

Figure 21: Battery Modules Prior to Installation in Truck #2

Photo credit: TransPower

Grouping of the cells into modules was conceived as a way of using a common building block (namely the Mile-Max™ module), which would be adapted to many different vehicles and thus produced economically in large quantities. Modules of the size shown were also expected to be easier to remove and service than larger enclosures. However, one of the principal lessons learned during the manufacturing of Truck #2 was that the approach of installing such a large number of modules on each truck entails significant additional costs. Each module structure is specially built to accommodate several hundred pounds of battery weight and to support various electrical connections, air flow for cooling of the batteries, and other design requirements. Hence these modules turned out to be very expensive to manufacture: approximately $300 each. After incurring this cost, it was still necessary to install the modules into heavy cradle structures to provide proper attachment to the truck frame. The combined cost of the 20 module boxes and the cradles for Truck #2 turned out to be more than $10,000.

In addition, as indicated in Figure 18, use of a large number of modules required a significant amount of high-voltage cabling for connecting each module to its other. Connecting all these cables required more than $1,000 in connectors and turned out to be very labor-intensive. Also, during initial vehicle testing (discussed further below), the large number of connections between battery modules was suspected of causing erratic readings of battery conditions by the BMS. For these reasons, for commercial versions of the TransPower electric drive system, a simpler battery design is being developed that will eliminate many of the individual modules and involve placement of batteries directly into larger enclosures. This will be a major departure from the modular approach viewed as preferable since the start of the VIFET project, but this provides a perfect example of the types of lessons that can't be learned until a vehicle is actually built and tested.

Figure 22 is a photo of the partially completed CCM prior to its completion and installation into Truck #2. Visible near the top of the photo are the variable frequency drives used to provide power for the electric accessory motors used in the power steering and braking systems.

Figure 23 is a photo of electrically-driven accessory components during the process of assembling the EDAS. Electric air compressor assemblies are visible on the conveyor in the foreground, with electric accessory motors on the bench in the far background.

These photos provide a sense of the level of subsystem assembly that is performed with the TransPower drive system before it is installed into a vehicle. Subsystem preassembly outside the vehicle has numerous benefits, such as reducing the amount of time a vehicle must be tied up for completion of the integration. Another benefit of this approach is that during the commercialization phase, TransPower can utilize similar subsystem assembly practices to build "kits" that can be delivered to vehicle manufacturers for installation into trucks on their own assembly lines. This is expected to be a more efficient model for high-volume electric truck manufacturing than for TransPower to continue performing truck conversions on an after-market basis.

Figure 22: Partially Assembled CCM

Photo credit: TransPower

Figure 23: Electrically-Driven Accessory Components

Photo credit: TransPower

Truck #2 Manufacturing

The first step in conversion of Truck #2 was removal of its diesel engine and stock transmission, which was initiated in May 2013. By June 2013, TransPower was able to begin installing subsystems and components into the truck. One of the first major elements to be installed was the motor-transmission assembly. Figure 24 shows this assembly in Truck #2 shortly after its installation. The round silver object near the center of the photo is the bell housing connecting the two motors to the Eaton 10-speed manual transmission shown near the bottom of the photo. The drive motors themselves are largely obscured by the dual motor structure used to connect the two motors to each other and the entire assembly to the truck frame. As discussed previously, the Eaton transmission is uniquely controlled by TransPower's AMT.

Figure 24: Motor-Transmission Assembly after Installation into Truck #2

Photo credit: TransPower

Figure 25 shows three of TransPower's Mile-Max™ battery modules installed into the front engine compartment of Truck #2, precisely where the diesel engine used to sit. Within the 20 Mile-Max™ modules installed into this truck are 120 prismatic LiFePO4 cells, with six 700 Ah cells in each module. These modules also house the voltage and temperature sensors used in TransPower's new proprietary BMS, which was demonstrated for the first time on this vehicle.

Figure 25: ESS Mile-Max™ Modules Installed in Engine Compartment of Truck #2

Photo credit: TransPower

Figure 26 shows one of the ICUs being prepared for installation into Truck #2. Two ICUs are integrated into the structure visible in the left-hand portion of the photo, each controlling one of the two main traction motors. Either ICU can be used to recharge the battery pack, at a power level of up to 70 kW. At this rate, the battery pack can be fully recharged from a low SOC in approximately three hours. The ICUs can also be configured to be used together for charging, which can reduce charging time for a given size battery pack in half. As mentioned previously, the ICU was developed as part of the VIFET project by TransPower, in collaboration with EPC, a startup company focused on development of power electronics technologies and products.

Figure 26: ICU Being Installed into Truck #2

Photo credit: TransPower

Figure 27 shows Truck #2 during the final stages of assembly in August 2013. Several of the 20 battery modules are clearly visible in the engine compartment and behind the cab. Not visible in the photo are the main driveline under the cab, components of which were shown in Figure 24, or either of the two ICUs installed into the compartment shown in Figure 26. Integration of the truck was completed in early September 2013, and the public was given a sneak preview of the truck at the PortTech Expo near the Port of Los Angeles on September 11, 2013. Following the Expo, the truck was returned to TransPower for commissioning and initial troubleshooting. During this process, a few minor wiring errors were identified and corrected, and adjustments to our new BMS were made to facilitate communication with the BMS sensing boards used in this vehicle, the first set of Balqon-supplied sensing boards used in any TransPower vehicles. These achievements set the stage for initial powering-up of Truck #2 and its testing.

Figure 27: Truck #2 Nearing Completion in August 2013

Photo credit: TransPower

Truck #2 Test and Evaluation

The last several weeks of the VIFET project were spent performing initial road trials of Truck #2, to achieve the following goals:

- Validation of basic drive system functionality.
- Calibration of various vehicle controls, such as transmission shifting.
- Initial evaluation of component performance, enabling repair or replacement of components found to show operational problems during vehicle operation.
- Initial assessment of vehicle operating capabilities, such as hauling capacity, top speed, acceleration, and operating range.

These tests were initiated in late September 2013 and were in process when the VIFET project ended on September 30, 2013. Preliminary results of these tests were quite favorable in that they validated the basic functionality of the latest version of the ElecTruck™ drive system and numerous innovations employed for the first time, such as TransPower's dual JJE/Fisker motor configuration, use of TransPower's AMT with Eaton's heavy-duty 10-speed transmission, and simultaneous use of two ICUs in an EV. Figure 28 is a photo of Truck #2 during its second day of road trials in early October 2013.

Figure 28: Truck #2 Test Drive in October 2013

Photo credit: TransPower

Unfortunately, initial tests of Truck #2 confirmed some of the concerns about the quality of the 700 Ah cells used in its battery subsystem, which were discussed briefly in Chapter 3. Due to significant differences in impedance among cells, cells with higher impedance levels were dropping in voltage during efforts to extract full power from the battery pack. Based on drive testing results as of the date of this report, along with prior lab testing of 700 Ah cells, we believe that the poorest performing 10—20 of the 120 cells on Truck #2 will need to be replaced for the truck to be able to achieve full power operations and approach the operating range goals set for this vehicle. Identification and replacement of the weaker cells is expected to be a process that will take a few additional weeks to complete, after which it is hoped that the superior capabilities of the ElecTruck™ design can be proven.

CHAPTER 5: Project Benefits

In its original proposal for funding of the VIFET project, TransPower argued that the project deserved state funding because it is consistent with the objectives of Assembly Bill 118. Electric trucks enabled by this project will provide a measurable transition from use of petroleum fuels and significant petroleum reduction, along with significant environmental and economic benefits.

Transition from Petroleum Fuels

A drayage truck operating 100 miles/day, 300 days/year, and averaging five miles per gallon, will consume 6,000 gallons of diesel fuel each year.

Gross Petroleum Reduction, 2015—2022: To estimate petroleum reduction over the 2015—2022 period, we make the following simplifying assumptions:

- Commercial electric truck deployments ramp up from 25 vehicles in 2015 to 2,500 vehicles in 2022. Our assumed ramp-up is to 100 trucks in 2016, 250 in 2017, and 500 in 2018, with subsequent increases of 500 each year until reaching 2,500 in 2022.
- This equates to 19,900 truck operating years. Given the uncertainty in these projections, we round this figure to 20,000 for convenience.
- Based on the above estimate of 6,000 gallons of diesel saved per truck year, this results in 20,000 x 6,000 = 120 million gallons of gross fuel reduction from 2013 through 2020.

Divided by the grant funding amount of $1,000,000, this equates to 120 gallons of petroleum saved per dollar of grant funding provided under this project.

Net Petroleum Reduction, 2013—2020: A more precise way of estimating petroleum reduction, which accounts for the fuels used to produce the electricity used to recharge EV batteries, is to estimate the amount of fuel used for this purpose and to deduct this amount from the gross fuel savings calculated above, resulting in a calculation of "net" petroleum reduction. Using CEC data, EVs provide a 69 percent net reduction in carbon emissions, based on an average mix of California grid energy. This figure will probably increase as we expand our use of renewable energy. However, using the current 69 percent figure as an approximation of net reduction in petroleum use, net savings over 2015—2022 = .69 x 120 million = 82.8 million gallons. This equates to 82.8 gallons saved for each dollar invested by the CEC in this program. Ove subsequent years, this payback could be multiplied many times over.

Emissions Benefits

Using CEC data, low-sulfur diesel trucks produce 88 grams (g) of carbon per megajoule (MJ) of energy, and EVs produce 27 g/MJ. Table 2 shows the annual carbon emissions from diesel versus electric trucks, based on usage of 30,000 miles/year. Since the electric truck is nearly three times as energy efficient as the diesel truck, its carbon reduction is based not only on lower emissions per unit of energy but also on its lower overall energy use. The net result, as indicated, is that an electric truck is projected to produce about 8.7 million g/year of carbon, versus 77.4 million g/year for diesel trucks—a reduction of nearly 90 percent.

Therefore, assuming 20,000 truck operating years from 2015—2022, total carbon reductions over this period would be 75.57 x 20,000 = 1,511,400 tons. Divided by the $1,000,000 in CEC grant funding, this represents approximately 1.5 tons of carbon reduction per dollar of grant funding.

Table 2: Carbon Emissions Reductions from Trucks Using ElecTruck™ Drive System

Metric	Diesel Truck		Electric Truck	
	Value	Units	Value	Units
Fuel consumption	5	Miles/gallon	N/A	N/A
Energy content of fuel	146.66	MJ/gallon	N/A	N/A
Energy per mile	29.33	MJ/mile	3.0	kWh/mile
			10.8	MJ/mile
Vehicle use	30,000	Miles/year	30,000	Miles/year
Energy use	879,900	MJ/year	324,000	MJ/year
Carbon emissions rate	88	g/MJ	27	g/MJ
Carbon emissions	77,431,200	g/year	8,748,000	g/year

Source: TransPower

This benefit would be invaluable in helping to meet the greenhouse gas emissions limits established by the California Air Resources Board (ARB). For example, if 5,000 electric trucks are deployed in California by 2022, this would achieve an aggregate emissions reduction of 378,500 tons of carbon per year—a significant step toward achieving the ARB 2020 limit of 427 million tons. As the ARB's "business as usual" estimate of 2020 carbon emissions is 600 million tons, a reduction of 173 million tons is required from this level to meet the ARB goal. Therefore, approximately 0.2 percent of the statewide carbon reduction could potentially be achieved with the commercialization and relatively focused application of this one technology. More widespread commercial adoption of the technology could multiply this benefit.

In addition to reducing carbon emissions, electric trucks will also reduce emissions of criteria pollutants such as oxides of nitrogen, carbon monoxide, and hydrocarbons. If these emissions reductions come anywhere near the 90 percent reduction in carbon emissions that has been calculated, the overall environmental benefits of electric truck adoption will be enormous.

Economic Benefits

The actual and projected economic benefits of the VIFET project include:

- Significant short-term business opportunities for three California-based participants: TransPower, EPC, and PortTechLA. The VIFET grant was the first source of income for both TransPower and EPC, and since receipt of this initial grant, TransPower has secured $15 million in additional business and has grown from a two-person startup operation to a rapidly growing company with 30 employees.

- Deployment of Truck Number 2 is expected to accelerate adoption of electric propulsion technology by large trucks, thereby helping to expand the EV industry and to enable California to develop a leading role in its growth.
- The innovations enabled by the VIFET project, such as the ICU, low-cost battery subsystems, and adaptable control architecture, will make electric trucks more affordable.
- Deployment of electric trucks using the technology developed under the VIFET project will enable continued growth of the Los Angeles and Long Beach ports—which contribute to the stabilization of economically distressed areas—by providing the first practical, zero-emission alternative for port drayage.
- Building on the success of the VIFET project, TransPower is developing innovative financing methods to make higher-end electric trucks more affordable to independent owner-operators, who are generally among the lowest-paid workers in the logistics industry.
- Commercialization of the VIFET technology will serve as a catalyst for U.S. truck manufacturers to convert assembly capacity to electric drive integration, helping U.S. truck companies maintain global technology leadership.
- The ElecTruck™ drive system developed under the VIFET project will reduce the cost of truck operations by eliminating fuel use and reducing maintenance costs.

The types of jobs that will be created by this project are permanent and varied. Most of these jobs will be high-paying professional jobs related to engineering and assembly of high-tech drive systems, and associated business management functions such as marketing, program management, and financial and supply chain management. TransPower has already started talking with nonprofit training organizations (such as the CleanTech Institute) about creating training programs for mechanics, so they can be retrained to work on high-voltage electrical systems. Independent owner-operators who take advantage of such innovative financing programs will have a unique opportunity to lease and eventually own higher-end trucks that will increase their earning potential, based on the demonstrated willingness of cargo owners to pay premiums for use of "green" transportation solutions.

In the longer term, if our commercialization goal of producing 2,500 electric drive systems/year is achieved by 2020, specific economic impacts could include:

- Creation of approximately 300 jobs directly related to drive system kit assembly, plus another 600 jobs in indirect support.
- Creation of about 400 jobs related to converters and battery modules. This estimate is based on creation of one person-month of direct and indirect employment for each converter and vehicle battery subsystem produced.
- Creation of about 100 jobs at California-based suppliers of wiring, cabling, machined assemblies, and other small parts used in TransPower drive systems.

- Creation of about 100 jobs related to servicing and support of electric trucks, based on production of 7,875 electric trucks through 2020, of which an estimated 5,000—6,000 would be based in California.

This adds up to a total of 1,500 new jobs, and does not include additional jobs created in the trucking industry if electric propulsion opens up new growth opportunities. Based on an average taxable income of $70,000/year and a tax rate of 9 percent, this level of job creation would generate $9.5 million/year in additional state income tax revenue.

In addition, purchases of 2,000 electric trucks/year within California, at an average price of $300,000 each, would generate $48 million/year in state sales tax revenue, based on a sales tax rate of 8 percent.

As the Los Angeles and Long Beach ports are surrounded by economically depressed areas with high minority populations, targeting the port drayage market will concentrate many of these economic benefits on this population. Adoption of electric trucks in the region will also promote social justice by reducing pollution, which is disproportionately affecting poor people who live and work near freeways in the area.

Various end-users will benefit from this activity. Truck owners and drayage firms such as Total Transportation Services will benefit from increased business, as cargo owners are attracted to the opportunity to use zero-emission vehicles. The cargo owners will benefit from their ability to meet their sustainability goals, helping them to sustain a positive public image while complying with environmental regulations. Cargo traffic into state ports could increase as a result. Utilities will benefit from increased sales of electricity for vehicles.

Opportunities for Drive System Cost Reduction

TransPower believes that ElecTruck™ drive systems and components must be justified on economic grounds to achieve significant market acceptance. Over the last two decades, a number of alternative fuel technologies have penetrated the heavy-duty vehicle markets solely due to their environmental benefits, including thousands of natural gas and hybrid vehicles. However, today's gasoline and diesel engines have dramatically lower emissions than they produced 10 or 20 years ago, so the game is changing. In the long term, TransPower does not believe that EVs or hybrids will attract large subsidies or command high price premiums based on emissions reductions alone. Therefore, TransPower's approach is to provide drive systems that enable vehicles to be acquired and operated for lifecycle costs equal to or lower than the costs of owning conventional vehicles.

This is the primary reason TransPower is focusing on battery-electric and battery-dominant hybrid vehicles. The engine-dominant hybrid vehicles commercialized to date typically do not offer significant economic benefits. They reduce fuel consumption, but generally only by 10—30 percent, which is not enough of a fuel saving for a typical user to recover the higher cost of the hybrid system. At the other end of the "EV spectrum," a pure battery electric system eliminates all fuel consumption, maximizing operating savings. In addition to net energy savings, we believe that properly designed electric trucks will offer other major advantages that will quickly speed their adoption. In particular, electric trucks will have much less brake wear and will not require oil changes or engine tune-ups. Quiet operation and ease of maintenance are examples of other key advantages of electric trucks.

The flip side of the coin in this case is that many of the vehicle attributes that will enable electric trucks to offer significant operational cost savings also present issues that will increase the capital cost of these vehicles. The key to commercial success will be to reduce these capital costs to acceptable levels in the marketplace while preserving the expected operational cost savings. With these as our guiding principles, and incorporating the experience gained in building our first generation electric trucks and tractors, we have completed a design cost reduction assessment. Our report on the results of this assessment is contained in the following subsections, organized by major subsystem as in the case of the preceding section.

MPS Cost Reductions

The ElecTruck™ MPS represents about 15 percent of the cost of the complete drive system. The MPS does not offer much opportunity for cost reduction because it is already a comparatively cost-effective subsystem, based on the following considerations:

Main drive motors: The Fisker main drive motors (more accurately JJE/Fisker motors, because JJE is the name of the company in China that manufactures them) represent just under half the cost of the MPS. These motors are already in high rates of production, at least in comparison with rates of production for other high-power electric motors, because of their use in the Fisker Karma hybrid car. With the recent decline in the fortunes of Fisker, it is uncertain how many of these motors will be produced in the future, and whether these motors will continue to be available at the prices paid over the past year. There does not appear to be much of a chance for reducing these prices significantly. Their production is most likely already highly automated and whatever labor is involved is provided at the comparatively low rates prevalent in China. TransPower presently purchases the motors from Quantum, which modifies the motor cabling slightly and adds a markup.

Toward the very end of the VIFET project, TransPower received a price quotation for these motors directly from JJE, which is more than one-third lower than the prices charged by Quantum. Therefore, developing a direct relationship with JJE and performing the cable modification in-house could potentially save TransPower nearly $4,000 per drive system. Adapting a different motor design may offer long term cost reduction potential. Switched reluctance and brushless DC motors and other motors that eliminate expensive magnetic materials appear to have the potential to drive motor material costs down, but no such motors are in production today that can meet the performance requirements of Class 8 trucks. Some existing motors using these designs could potentially be scaled up to meet TransPower requirements, possibly cutting the motor cost by 50 percent or more and saving as much as $5,000—$7,500 per MPS. However, this would require a large up-front investment, at least on the order of $1 million and potentially significantly more, so these are not options for the EDD or other near term projects.

Transmissions: The Eaton transmission is the next highest cost element in the MPS after the main drive motors, representing about one-third of the cost of the MPS. We do not see much likelihood of reducing this cost in the near future. These transmissions are already in high rates of production and Eaton's pricing reflects this; the motors are priced more or less the same whether you buy one or one hundred. The transmissions do have design features driven specifically by the requirements of internal combustion engines, and some of these features could potentially be removed from transmissions used in EVs such as TransPower's. However, the up-front cost to design these features out of the motor are presently cost prohibitive. Near term cost reduction potential for this component is insignificant; in the longer term, a transmission custom-designed for heavy EVs could potentially be built or acquired for as much as $3,000—$4,000 less than the Eaton transmission, if produced in sufficient quantities.

Other MPS elements: The only other MPS element with a significant cost is the dual motor structure used to connect the two JJE/Fisker motors to each other and mount them to the transmission. These structural elements currently comprise about 12—15 percent of the cost of the MPS. This cost could potentially be reduced by as much as $2,500 per MPS if the structures were forged instead of machined. This is a possibility for large scale production but would require prohibitive tooling costs for a small scale project such as the seven-truck EDD program.

MPS summary: In high rates of production, with changes to the designs of the motor and dual motor structure, the cost of the MPS could be reduced by as much as about one-third, saving about $10,000 per drive system. In the nearer term, changes in how the JJE/Fisker motors are procured and modified—and location of a lower cost vendor for the dual motor structure—could potentially save as much as about $3,000—$4,000 per vehicle. While none of these changes can be implemented for the EDD project, the EDD design does represent a cost advantage over the dual motor design used in TransPower's first prototype truck, as the combining gearbox and mounting structure used on that vehicle cost about $5,000 more than the dual motor structure and shaft assembly designed for the EDD trucks.

ICS Cost Reductions

ICUs: The two ICUs used in the ElecTruck™ ICS represent about 30 percent of the cost of the complete electric drive system, so they are a significant cost driver. As discussed in Chapter 1, a manufacturer has been identified in Alabama that can assemble the ICUs for a lower cost than ICU development partner EPC, but these economies were already factored into the price charged for the ICUs for the EDD project. Going forward, this change is expected to save about $5,000 per ICU (or $10,000 per drive system) for subsequent orders of more than a few ICUs. If TransPower continues to use only one ICU for vehicle charging, then some components could be removed from the ICU used only for motor control, saving as much as $5,000 more on that ICU. In the longer term, another $5,000 or so could be saved per ICU in larger rate production by modifying the design of the enclosure and taking advantage of higher volume pricing on certain ICU components. Another potential path to cost savings would be to merge all of the electronics for controlling both motors and for charging into a single enclosure.

Other ICS elements: The cables and connectors used for grid charging, and the structures used to mount the ICUs to the vehicle, add a total of about $3,000 to the cost of the ICS. If purchased and manufactured in high quantities, another $1,000 or so in savings might be found here.

ICS summary: For future drive system manufacturing, ICS components are expected to cost at least $10,000 less than they currently cost, and as much as $30,000 lower, depending on volume. This therefore represents one of the largest areas of potential cost savings for the ElecTruck™ system.

ESS Cost Reductions

The ESS is by far the most costly element of the ElecTruck™ drive system, representing approximately 50 percent of the total ElecTruck™ cost.

ESS battery cells: As might be expected, the cost of the ElecTruck™ ESS is driven by the cost of the battery cells used the ESS. TransPower has addressed this cost and achieved some cost reductions for the EDD project by finding suppliers offering the lowest cell cost (measured in cost per kWh of cell capacity). Even with these cells procured for the comparatively low price of about $330/kWh, the cells still represent nearly half the total cost of the ElecTruck™ drive system. Experts differ on whether costs of lithium and other high-power batteries can fall much further—the $330/kWh price is about one-fifth of the lowest price available in the market just three years ago. However, every one percent reduction in cell cost can reduce the cost of the overall ElecTruck™ drive system by nearly $900, so the potential exists for significant drive system cost reductions with even relatively small reductions in battery cell costs.

BMS: TransPower has taken significant steps toward reducing BMS costs by locating lower cost BMS products and by reducing the number of battery cells used in the ElecTruck™ system. The latter design change reduces BMS costs because BMS sensors are typically installed on every one or two cells, so the fewer cells in the ESS architecture, the lower the BMS sensor cost. As a result, for Truck #2, the total BMS cost was about $10,000 lower than the cost of the BMS configuration installed on Truck #1 and TransPower's first two yard tractors. An additional $2,000—$3,000 in cost reductions per vehicle are believed to be possible if the costs of BMS sensors and controllers continue to decline as more and more of these types of products are brought onto the market. Manufacturing more of our BMS hardware in-house is another possible strategy for achieving cost savings of this magnitude.

Battery support structures: Battery support structures remain a major ESS cost item, as their total cost exceeds $10,000, representing more than 10 percent of the cost of the ESS and about 5 percent of the cost of the entire drive system. These structures are expensive because in low production volumes they are welded rather than stamped or forged. Going into higher production volumes, the cost of these elements should be reduced by at least 50 percent, saving a minimum of $5,000.

Other ESS elements: Cables, connectors, and other miscellaneous ESS items add about another $4,000 in costs, a figure that has been cut nearly in half by our decision to reduce cell count by using a single string of larger cells. Further reductions on the order of $1,000—$2,000 could potentially be achieved in higher production volumes.

ESS summary: Excluding cell costs, TransPower has already reduced the total cost of the ESS by about $15,000 by reducing cell count and the BMS and connector costs that are driven by this metric. Further reductions of up to about $10,000 per vehicle are possible in higher production volumes. Battery cell cost is a wild card and future changes in cell prices could increase or decrease total drive system costs in increments of as much as $10,000.

EDAS Cost Reductions

The EDAS and VCS, combined, represent only about 5 percent of the total cost of the ElecTruck™ drive system, so there is not enormous cost reduction potential here. TransPower has reduced its EDAS parts cost by about $1,000 by moving some assembly in-house and eliminating the air cooler. However, recurring problems with the variable frequency drives used in TransPower's first several prototype vehicles may force us to adopt more expensive inverters, which could drive the cost of the EDAS complement up by approximately $2,000. For future truck orders, a reduction of this magnitude might be achieved by buying EDAS and VCS components in higher volumes, resulting in a total long term cost slightly less than the current EDAS cost.

Cost Reduction Assessment Conclusions

Table 3 summarizes the results of TransPower's ElecTruck™ drive system cost reduction assessment.

Table 3: Near-Term and Long-Term Cost Reduction Potential

ElecTruck™ Subsystem	Component	Near Term Cost Reduction Potential ($)	Long Term Cost Reduction Potential ($)
Main Propulsion	Drive Motors	500	2,000
Main Propulsion	Transmission	0	4,000
Main Propulsion	Other MPS Structures	500	2,500
Inverter-Charger	ICUs	10,000	30,000
Inverter-Charger	Other ICS Elements	500	1,000
Energy Storage	Battery Cells	10,000	30,000
Energy Storage	BMS	1,000	2,500
Energy Storage	Structures	3,000	8,000
Energy Storage	Other ESS Elements	1,000	2,000
Electrically-Driven Accessories and Vehicle Control	Various Elements	1,000	3,000
TOTAL POTENTIAL COST REDUCTIONS		$27,500	$85,000

Source: TransPower

Economic Implications of Establishing a Vertically Integrated Manufacturing Facility

To support its economic assessment of establishing a vertically integrated manufacturing facility, with a focus on evaluating possible locations in the Los Angeles-Long Beach port region, TransPower awarded a subcontract to PortTech LA to study this topic and prepare a formal report of its findings. PortTech LA submitted an initial report to TransPower in October 2012, and following receipt of feedback from TransPower, delivered an update report to TransPower in August 2013. The reports provided findings in three major areas:

1. Government business incentives available to California manufacturers.
2. Evaluation of economics of relocating to specific cities in the Los Angeles-Long Beach region.
3. Identification of specific properties in the Los Angeles-Long Beach region that meet TransPower vertically integrated manufacturing facility criteria.

This report will not address the first of these topics, as the CEC does not need advice on state government incentives.

With respect to the second topic above, PortTech LA narrowed its geographic evaluation to seven cities which it felt were particularly attractive sites for a future TransPower vertically integrated manufacturing facility for electric trucks. These cities, and the key attractive features of each, are summarized briefly as follows:

1. **City of Carson:** Strong international business presence, major industrial center, proximity to ports, low utility tax (2 percent), no gross receipts or property tax, availability of large development sites, competitive land prices, expedited permits.
2. **City of Compton:** Proximity to ports, existence of "quiet roads" that could be used for road testing of TransPower trucks, Target Employment Opportunity Zone, within 44th Congressional District represented by influential Congresswoman Janice Hahn, operates an aging bus fleet, and is potentially interested in purchasing electric-powered buses to replace its diesel buses.
3. **City of Gardena:** Expedited permit process, Planning Review and Economic Development Teams available to support local businesses, low development fees, three specialized "opportunity site corridors," $10,000 commercial rebate for new signage, painting, and/or stucco; proximity to ports and railways.
4. **City of Long Beach:** Newly developed Business Planning District, no utility user tax for cable, parking tax, or development impact fees; business loan program, new market tax credits, small business loan support, Foreign Trade Zone, proximity to ports, equipment and machinery sales/use tax credits, skilled workforce, will consider in certain cases: industrial development bonds, tenant improvement subsidies, financial relocation assistance, and direct project land or development subsidies.
5. **City of Los Angeles:** Zero emission goal, interest in a "clean technology cluster," location assistance, tenant improvement grants, business tax holiday of three years or more, no gross receipts tax for three years, reduced water and power rates, support for acquisition of federal grants, preference in competing for City of Los Angeles contracts, Business Assistance Virtual Network, employee credits, on-the-job training program, utility discount.
6. **City of Torrance:** Site of several alternative fuel vehicle companies, availability of grant loan agreements, no gross receipts tax, proximity to ports, freeways, and Los

Angeles International Airport, recycling market development zone, business improvement district, South Bay Entrepreneurial Center, potential interest in acquiring electric-powered transit buses.

7. **City of Vernon:** Low taxes and utility costs, fast track permitting process, no utility user taxes.

With respect to the third topic above, PortTech LA provided detailed information on about a dozen specific properties that it felt meet TransPower vertically integrated facility requirements. The buildings identified range in size from an 85,000-square-foot building in Gardena to a 135,781-square-foot building in Carson. Rental rates ranged from $0.35/square foot for a building in Los Angeles to $0.67/square foot for a building in Carson. All of these rates are significantly lower than what TransPower currently pays for rent in Poway or what it would likely pay for other similar buildings in San Diego County. All but three of the properties had 800 amperes or more of electric service.

Based on the data provided by PortTech LA, establishment of a vertically integrated manufacturing facility in the Los Angeles-Long Beach region seems economically feasible, with the potential to reduce TransPower's monthly lease rate by 15—65 percent and greater, and with greater opportunities for tax abatements and other subsidies, along with proximity to the ports and key port customers.

CHAPTER 6: Conclusions and Recommendations

The VIFET project sought to achieve major technology advances in two key areas: vehicle control and integration, and advanced energy storage. The VIFET project not only made major advances in these two areas, but also achieved significant advances in the area of EV propulsion, and moderate advances in several other technology areas. Specific accomplishments that are particularly noteworthy include:

- Development and demonstration of a robust inverter that can also serve as a high-power onboard battery charger.
- Development and demonstration of a unique method of providing the high tractive power (300 kW) peak required for large vehicles, using a combination of two smaller, mass-produced motors that greatly reduces the cost of achieving this performance level.
- Development and demonstration of a unique AMT that provides a blend of improved road performance and higher operating efficiency than automatic transmissions.
- Development of advanced battery management software and hardware, enabling low-cost batteries to be used safely and effectively in demanding road vehicle applications.
- Evaluation and characterization of several different sizes of lithium-ion batteries, providing valuable insights into which battery sizes work best in vehicle applications.
- Attraction of several millions of dollars in additional funding to demonstration projects that will field trucks and tractors using TransPower's ElecTruck™ drive system over the next year.

During the course of the VIFET project, TransPower successfully built a lab test vehicle that demonstrated the basic functionality of the new ICU developed under this project, as well as most of the other core components of the new ElecTruck™ drive system. Following nearly a year of tests with the lab test vehicle, TransPower engaged in a nine-month effort to update the ElecTruck™ drive system to reflect lessons learned during assembly and testing of the lab vehicle, as well as lessons learned in assembly and testing of two electric yard tractors built under a separate project. The new ElecTruck™ drive system design was then reflected in the assembly of a second electric drayage truck, which was completed right at the end of the VIFET project and which showed promising results in several weeks of road testing completed as of the publication of this report.

The combined effect of VIFET technology advances is expected to have a transformative effect on the heavy-duty vehicle industry. As of the date of this report, TransPower is engaged in the completion of a third generation ElecTruck™ drive system design, reflecting lessons learned during assembly and initial testing of Truck #2 on this project, which will be reflected in a fleet of seven new electric drayage trucks to be built between late 2013 and mid-2014 under a new EDD project funded by the CEC, U.S. Department of Energy, and ports of Los Angeles and

Long Beach. TransPower recommends continued funding for development and demonstration of electric and hybrid-electric propulsion technologies for heavy-duty vehicles, with emphasis on helping to fund the ramp-up to large scale commercial manufacturing and deployment. Key areas of research and development that require additional support include:

- Continued evaluation and characterization of advanced battery chemistries, with specific emphasis on testing cells in real-world vehicle applications.
- Continued development of advanced batter monitoring and battery management technologies.
- Development of low-cost electric motor technologies capable of handling the power and torque requirements of heavy-duty trucks.
- Continued evolution of vehicle control and diagnostic capabilities.
- Further development of various means of extending the operating range of battery-EVs, including use of battery-dominant hybrid systems using various types of internal combustion engines, microturbines, and fuel cells.
- Support for development of manufacturing facilities capable of producing electric and hybrid-EV components on a larger scale, including development of vertically integrated manufacturing facilities that can combine component manufacturing with integration of vehicle subsystems and integration of components and subsystems into medium- and heavy-duty vehicles.
- Accumulation of a large number of miles of “real world” experience in the operation of large trucks and other vehicles using battery-electric and battery-dominant hybrid-electric propulsion technologies.
- Exploration of opportunities to enhance the value proposition for operation of EVs, including provision of vehicle-to-grid ancillary services and the use of vehicle batteries for stationary energy storage applications following the end of the useful lives of batteries in vehicle applications.

TransPower is grateful for the support of the CEC for the VIFET project, and is confident that this investment will yield large and increasing dividends in the years to come.

GLOSSARY

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

AMPERE-HOUR (Ah) – A unit of electric charge, usually used for batteries. This unit combines the amount of current with how long that current can be sustained until the battery completely discharges. Large batteries have several ampere-hours, but cell phones and other small devices have batteries with a total charge measured in milliampere-hours. This measured quantity is called battery capacity.[1]

AUTOMATED MANUAL TRANSMISSION (AMT) – A key new technology that enables the TransPower ElecTruck™ Main Propulsion System (MPS) to achieve superior road performance and efficiency, while enhancing drivability. The AMT provides improved road performance at both high and low speeds, while enabling the use of a more efficient manual transmission, which reduces energy consumption and increases operating range. Shifting is accomplished smoothly and automatically, resulting in a favorable driver experience.[2]

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

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

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

1. Forecasting future statewide energy needs
2. Licensing power plants sufficient to meet those needs
3. Promoting energy conservation and efficiency measures

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

2 Transportation Power, Inc. website (http://www.transpowerusa.com/automated-manual-transmission/)

4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
5. Planning for and directing state response to energy emergencies

CENTRAL CONTROL MODULE (CCM) – A type of electronic control unit, an embedded system in automotive electronics that controls one or more of the electrical systems or subsystems in a vehicle.[3]

CONTROLLER AREA NETWORK (CAN) – A serial network technology that was originally designed for the automotive industry, especially for European cars, but has also become a popular bus in industrial automation as well as other applications. The CAN bus is primarily used in embedded systems, and as its name implies, is a network technology that provides fast communication among microcontrollers up to real-time requirements.[4]

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

ELECTRIC DRAYAGE DEMONSTRATION (EDD) – References a project funded by the CEC, SCAQMD, and ports of Los Angeles and Long Beach (via a "Technology Advancement Program" grant) to deploy advanced, zero-emission Class 8 drayage trucks at the two ports.[5]

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

ELECTRICALLY-DRIVEN ACCESSORY SUBSYSTEM (EDAS) – Uses a rugged air compressor and hydraulic pump to make truck accessories fully electric, allowing them to function without an engine or alternator. Provides a new means of powering vehicle accessories such as power steering, braking, heating, ventilation, and air conditioning.

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

3 Wikipedia (https://en.wikipedia.org/wiki/Electronic_control_unit)

4 Copperhill Technologies (https://copperhilltech.com/a-brief-introduction-to-controller-area-network/)

5 Transportation Power, Inc. (http://www.transpowerusa.com/press-releases/transpower-secures-3-7-million-funding-demonstration-electric-drayage-trucks/)

EPC POWER CORPORATION (EPC) – Engineers and manufactures fully functional designs, prototypes, production hardware, and commercialized power electronics technology for use around the world. Based in San Diego, California.[6]

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

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

JING-JIN ELECTRIC (JJE) – A world leader of motor systems and electric drive assembly for new energy vehicles. Following a technical roadmap covering pure EVs, plug-in hybrids, and hybrids, JJE provides highly competitive drive motor products featuring high power intensity, high torque intensity, and high reliability. It also extends its technology and products to electric drive assembly and its core parts and components, supplying to customers more complete electric propulsion solutions of these products including motors, motor controllers, transmissions, reducers, and advanced control software.[7]

KILOWATT (kW) – One thousand watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon, a typical home—with central air conditioning and other equipment in use—might have a demand of 4 kW each hour.

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

LITHIUM IRON PHOSPHATE (LiFePO4) – In reference to a type of rechargeable battery, specifically a lithium-ion battery, which uses LiFePO4 as the cathode material, and a graphitic carbon electrode with a metallic backing as the anode. The specific capacity of LiFePO4 is higher than that of the related lithium cobalt oxide chemistry, but its energy density is less due to its lower operating voltage. Because of low cost, low toxicity, well-defined performance, and long-term stability, LiFePO4 is finding a number of roles in vehicle use, utility scale stationary, and backup power applications.[8]

MAIN PROPULSION SUBSYSTEM (MPS) – A TransPower system that converts electrical power from the battery subsystem into mechanical power to drive the vehicle's wheels.

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6 EPC Power Corporation (https://www.epcpower.com/)

7 Jing-Jin Electric (http://www.jjecn.com/en/?c=about&id=10)

8 Wikipedia (https://en.wikipedia.org/wiki/Lithium_iron_phosphate_battery)

MEGAJOULE (MJ) – A joule is a unit of work or energy equal to the amount of work done when the point of application of force of one newton is displaced one meter in the direction of the force. It takes 1,055 joules to equal a British thermal unit. It takes about one million joules to make a pot of coffee. A megajoule itself totals one million joules.

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

STATE OF CHARGE (SOC) – Available capacity expressed as a percentage of its rated capacity.[9]

TRANSPORTATION POWER, INC. (TRANSPOWER) – A privately-held California company that develops and provides clean power generation and conversion technologies and products.[5]

VEHICLE CONTROL SUBSYSTEM (VCS) – Controls all vehicle functions and makes the difference between battery-electric propulsion and conventional propulsion via internal combustion engines virtually transparent to the vehicle operator. Combines a network control architecture, control software, and power conversion modules into an integrated subsystem that links all drive system components and enables them to communicate with vehicle controls and displays via a CAN-based architecture.

VERTICALLY INTEGRATED FACILITY FOR ELECTRIC TRUCK MANUFACTURING (VIFET) – TransPower's conceptual three-stage facility for manufacturing electric Class 8 trucks.

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

9 State of Charge Definition (https://www.mpoweruk.com/soc.html)