INTRODUCTION

This report provides a comprehensive overview of the battery-electric drive system developed by Transportation Power, Inc. (TransPower) for installation into Class 8 on-road electric trucks. This advanced propulsion technology is designed to meet or exceed diesel truck performance standards while producing zero emissions and greatly reducing operating costs by eliminating fuel use and simplifying vehicle maintenance.

TRUCK VEHICLE MODELS

TransPower’s “ElecTruck™” drive system is inherently flexible and can be installed into a wide variety of vehicle models. TransPower currently offers a version of this battery-electric system customized for use in International ProStar® trucks manufactured by Navistar. Following manufacturing and testing of two earlier prototype trucks, TransPower is midway through a 2014-15 project to convert at least seven ProStar® trucks to electric drive and to evaluate their performance in a pre-commercial demonstration at the Ports of Los Angeles and Long Beach. Building on this experience, TransPower can offer electric propulsion systems compatible with ProStar® trucks immediately. Similar propulsion systems can be provided for other truck models, but for any tractor models other than ProStar® trucks, there would be additional work involved in attaining the same level of seamless vehicle integration that TransPower has already achieved with the ProStar® truck model. Figure 1 is a photo showing one of the ProStar® trucks received by TransPower in late 2013, prior to replacement of its diesel engine with an electric drive system. TransPower can install electric drive systems into new trucks like these or convert existing trucks to electric drive.

ELECTRIC TRUCK DESIGN VALIDATION

The variant of the ElecTruck™ system installed into ProStar® trucks was designed by TransPower specifically for Class 8 truck applications. The current system design is the result of more than three years of analysis, test, and evaluation, which included:

![ProStar® truck prior to conversion.](image)
• Testing and validation of electric motors and other key electric drive components on a water-brake dynamometer throughout 2012;

• Test driving of an initial prototype truck by TransPower in 2011 and 2012; and

• One year of operational testing of a second “Pilot Truck” under actual operating conditions in the Los Angeles area, from late 2013 through November 2014.

The last phase of testing just described is still on-going and, once completed in November 2014, will include several thousand miles of use of the Pilot Truck by a major drayage firm in the L.A./Long Beach port region. Figure 2 shows this truck hauling a loaded container near the Port of L.A. in March 2014. This truck, and the first two of the seven pre-commercial trucks being deployed, have demonstrated performance equal to or superior to diesel trucks in many respects, including faster acceleration, the capacity to pull loads of up to 80,000 lb., and top operating speeds of greater than 65 miles per hour. Equipped with extra-large battery subsystems weighing nearly 6,000 lb., these trucks can haul heavy loads for up to 100 miles on a single battery charge with unprecedented energy efficiency for vehicles of this class.

The extensive testing of TransPower’s first prototype and Pilot Truck identified areas in which the electric drive system required improvement to enhance system reliability and robustness. Acting on the data collected during its extended prototype testing program, TransPower developed an updated drive system design featuring several such improvements. These included development of a more rugged version of TransPower’s unique “Automated Manual Transmission,” which improves performance by using proprietary software to control a manual transmission. TransPower also made major improvements to the design of the ElecTruck™ battery energy storage subsystem, including adaptation of a revolutionary new battery management system, and developed a new integrated approach to installing drive system controls that simplifies vehicle integration and servicing.

Figure 3 is a computer illustration of the updated electric truck design resulting from the prototype testing and design validation process just described. This illustration shows the large battery boxes mounted to each side of the truck and behind the cab. In front of the cab, mounted in the engine compartment, is the new “Power Control and Accessory Subsystem” (PCAS) utilized to pre-integrate major control and accessory components.
These design improvements have already been shown to increase vehicle reliability and serviceability, while reducing assembly time. The updated drive system design also lends itself to packaging in “kit” form for delivery to truck manufacturers, who can integrate these kits into trucks on their own assembly lines once demand increases sufficiently to justify this transition. In the near term, TransPower will continue converting trucks on an after-market basis, following the processes and utilizing the components discussed in more detail in the following sections of this document.

TRUCK PREPARATION

The first step in integrating the ElecTruck™ system into a truck is to prepare the base vehicle for installation of the drive system. This principally involves removal of the engines and transmissions from each vehicle to be converted. Figure 4 shows the first of the seven pre-commercial trucks being equipped with the updated ElecTruck™ system, immediately after removal of the engine and before installation of the ElecTruck™ system. The ElecTruck™ system is fully integrated with the ProStar® truck, both structurally and electronically,
so truck preparation also includes decoding all of the vehicle’s control software and identifying the routing and functions of all electrical wiring. Standard dashboard controls and displays are utilized to the greatest extent possible to simplify user adaptation to the ElecTruck™ system.

MOTIVE DRIVE SUBSYSTEM

Following vehicle preparation, the first major task is typically to assemble and install the motive drive subsystem used for vehicle propulsion, which consists of two main drive motors and an Eaton 10-speed manual transmission. A completed motive drive subsystem prior to truck installation is pictured in Figure 5, which clearly shows the main elements of the motive drive subsystem. The transmission is to the left and the main electric drive motors used to propel the rear axle through the transmission are the metallic-colored disks at the right of the assembly. The transmission is specially configured to use TransPower’s proprietary Automated Manual Transmission (AMT) technology, discussed in more detail below. The motors are manufactured by JJE, a Chinese company and one of the world’s leading motor manufacturers. These motors are an interesting choice because they were originally designed for the Fisker Karma, a hybrid-electric passenger car, in a joint development effort involving JJE and Quantum Technologies, Worldwide. The JJE motor provides unusually high power and torque for such a compact design, and has undergone extensive product testing and validation as part of the large investments made by Fisker in its drive system technology. 

Figure 6 is a photo of a motive drive subsystem after installation into a ProStar® truck. Visible near the bottom of this photo is the top of the ten-speed Eaton transmission. On top of the transmission are perpendicular silver cylinders which are the main components of the Eaton “X-Y shifter” mechanism which enables computer-controlled actuation of the transmission. This is a new innovation Eaton has developed over the past decade to improve the efficiency of their transmissions when used with conventional diesel engines. TransPower’s AMT adapts this technology to electric vehicles, using proprietary software that commands the transmission to shift gears based on the speed of the JJE motor and other electric vehicle operating conditions, which are constantly monitored by TransPower’s “EVControl™” control system. One of the innovations of the AMT system is TransPower’s use of the JJE-Fisker drive motor to rapidly synchronize the transmission, which results in extraordinarily
smooth shifting and eliminates the jerkiness associated with most heavy-duty vehicle shifting mechanisms. This makes trucks using the AMT extremely pleasant to drive as well as providing high performance across the tractor's entire speed range. The AMT also improves operating efficiency as compared with conventional automatic transmissions because it eliminates the need for a torque converter, which typically spins all the time and constantly drains energy. System robustness is assured by use of Eaton’s rugged transmission and X-Y shifting mechanism. TransPower's AMT software has been developed and perfected in stages since early 2012, and shown the ability to operate predictably and reliably in a variety of heavy-duty vehicle applications including Class 8 yard tractors and electric school buses as well as on-road trucks.

**ENERGY STORAGE SUBSYSTEM**

As illustrated previously in Figure 3, the current ElecTruck™ design utilizes large battery modules mounted on each side of the truck and behind the cab. Earlier TransPower designs utilized smaller battery modules, but extensive TransPower testing and real-world operating experience demonstrated that it is easier to install and maintain a smaller number of larger battery enclosures, which require less wiring between modules and provide more internal space for interior battery wiring, battery management hardware (discussed below), and associated components. The Class 8 truck configuration uses two battery enclosures side-by-side on each side of the vehicle, each containing up to 48 large format cells (Figure 7). The batteries visible in Figure 7 are 300 ampere-hour (Ah) lithium iron phosphate (LiFePO₄) cells manufactured Winston, a major Chinese manufacturer of LiFePO₄ batteries. Through extensive testing in trucks, yard tractors, and other heavy-duty vehicles, TransPower has found the LiFePO₄ cells to be extremely safe and durable, as have other users of such cells around the world.

The five battery enclosures in the Class 8 ElecTruck™ design provide a total of approximately 215 kilowatt-hours (kWh) of total energy storage, of which 70-90% is...
usable, depending on user needs. The typical approach to battery management is to use up to 80% of the total energy, or about 172 kWh, which is expected to allow 2,000 to 3,000 discharge cycles. Limiting use to 70% of total available energy can increase battery life to as many as 5,000 cycles. These estimates are all based on battery manufacturer test data and will require several years of vehicle operation to be independently confirmed. However, the data suggest that even if these limits are not achieved, batteries in a typical truck experiencing one full discharge cycle per day can be expected to last 10 years or more if properly maintained and balanced.

Providing proper battery maintenance is the job of TransPower’s Cell-Saver™ battery management system (BMS), a new product developed in collaboration with power electronics pioneer EPC Power Corp. Cell-Saver™ utilizes sophisticated sensor/balancing boards which are connected to every other cell, and which constantly measure the temperature and voltage of each individual cell. These values are monitored and recorded by the ElecTruck™ control system, which responds to temperature or voltage values outside of safe limits by alerting the tractor operator or, when necessary, disabling the drive system or specific drive system features to prevent damage to the battery subsystem or vehicle. Figure 8 is a close-up photo of one of the ElecTruck™ battery enclosures providing a good view of the BMS sensor/balancing boards. The Cell-Saver™ central controller can be seen mounted above the batteries to the right.

Some of the monitoring features offered by Cell-Saver™ are common among commercially available BMS products, but the Cell-Saver™ BMS also offers several unique features, including:

Greater processing capability, enabling more accurate measurements of cell voltage. This improves balancing of cells, which can extend vehicle operating range and battery life.

High-current continuous, active charge shuffling, enabling energy from more fully-charged cells to be transferred continuously to lesser-charged cells. Most competing BMS products achieve balancing through passive charge dissipation, which drains energy from higher-charged cells but which simply reject this energy in the form of heat. The active approach of Cell-Saver™ eliminates this energy waste and improves the efficiency of the system. Cell-Saver™ also performs balancing from higher voltage cells to lower voltage cells and vice-versa with 3 amps of current (effectively balancing at a 6-amp rate), a significantly faster rate than competing BMS products, which balances cells quickly and reduces time required to fully charge and equalize the pack.
Bolt-on feature, enabling BMS sensor boards to be bolted directly to the bus bars connecting cell terminals. Other competing BMS products require the routing of wires from cell terminals to the BMS boards. Eliminating this wiring reduces assembly time and maintenance issues relating to the possibility of wires becoming damaged or disconnected.

POWER CONTROL AND ACCESSORY SUBSYSTEM

The Power Control and Accessory Subsystem (PCAS) is integrates most components used for power control and distribution in the ElecTruck™ system. The PCAS also houses most of the major components of the ElecTruck™ electrically-driven accessory subsystem (discussed below). Figure 9 is a photo of two completed PCAS assemblies prior to truck installation. The most prominent element of the PCAS assembly are the Inverter-Charger Units (ICUs), the large white boxes mounted near the top of each assembly. Like TransPower’s Cell-Saver™ BMS, the ICU was developed in partnership with EPC Power Corp. The ICU is an equally revolutionary electric vehicle product which performs two vital functions in the ElecTruck™ system: while the truck is moving, it converts DC power from the battery subsystem into AC power for the main drive motor, and while the truck is plugged in for recharging, it converts AC power from the grid into DC power to recharge the battery pack. Each ICU supplies up to 150 kW to the vehicle traction motors and using one ICU as a charger can recharge a truck battery pack at power levels of up to 70 kW. When used in conjunction with the Cell-Saver™ BMS, the ICU can fully recharge and balance the truck battery pack in less than four hours.

Specific design features of the ICU include use of high-voltage insulated gate bipolar transistors (IGBTs), liquid-cooled heat sinks, and high switching frequencies. Figure 10 is a photo of the interior of an ICU. The high charging power level of the ICU will be particularly valuable in situations where trucks are heavily used for more than one shift per day. For example, using the ICU for “opportunity charging” of the truck batteries during one-hour layovers could enables a truck to complete three 4-hour shifts each day.
The PCAS also includes high-voltage wiring harnesses and a High-Voltage Distribution Module (HVDM) which routes power from the ICUs to the main drive motors and the battery enclosures. Another prominent element of the PCAS is the Central Control Module (CCM). The CCM houses many of the specialized electronic components used to control the ElecTruck™ system, including vehicle control microprocessors, a DC-to-DC converter, and fuses. Figure 11 is a photo of the interior of a CCM showing many of these components. The ElecTruck™ system uses modern models-based controls which enables TransPower to rapidly adjust control parameters to reflect lessons learned during vehicle operation or to accommodate new components as technologies advance and newer products become available. The inherent flexibility of the ElecTruck™ control system and TransPower's commitment to continuously updating the ElecTruck™ design help assure customers that its truck drive systems will never be out of date. The ElecTruck™ system is also equipped with a sophisticated UniCAN data acquisition system which monitors and records data from all components, providing diagnostic data critical to proper vehicle maintenance and troubleshooting of problems as they occur.

Figure 11. Interior of CCM as integrated into each PCAS assembly.

ELECTRICALLY-DRIVEN ACCESSORY SUBSYSTEM

The function of the electrically-driven accessory subsystem in the ElecTruck™ system is to provide electrical power to operate the following critical vehicle devices:

- Power steering
- Pneumatic braking
- Heating, ventilation, and air conditioning
- Miscellaneous electrical loads for lighting, horns, radio, etc.

Electric vehicles require special electrically-driven accessories to operate these devices, which in conventional engine-driven vehicles are typically powered by belt-driven alternators connected to the engine. Obviously, electric vehicles don’t have engines so these types of “power take-off” (PTO) devices cannot be used. In the ElecTruck™ electric drive system, various electronic and mechanical devices are integrated to enable energy from the main battery subsystem to be used to power these vehicle functions.

As mentioned previously, some elements of the TransPower accessory subsystem have been integrated into the Power Control and Accessory Subsystem (PCAS). Figure 12 is a PCAS photo highlighting several of the main electrically-driven accessory
components. The black cylinder to the right is the motor used to drive the hydraulic pump which pumps power steering fluid to the power steering system. Directly to the left of the steering pump motor is the air compressor assembly for the braking system, which consists of an electric motor that drives a belt-driven oil-less scroll compressor. The air system is quiet and efficient, charging the air system only when air pressure needs to be restored. Directly above the air compressor assembly in Figure 12 is a DC-to-DC converter which steps down the battery voltage to the 12-volt level required by several truck systems, such as the lights horn, and radio. The higher power required for the larger accessory motors is supplied by an accessory inverter (not shown), which converts DC power from the battery subsystem to AC power as required by the accessory motors. The accessory inverter used in the latest version of the ElecTruck™ system is a new inverter manufactured by a German company, Lenze, which was designed specifically for heavy-duty automotive applications. The Lenze inverters are compatible with standard automotive control protocols and are packaged in sealed enclosures for environmental protection.

INTEGRATED ELECTRIC DRIVE SYSTEM

The major ElecTruck™ subsystems just described are available individually or in various combinations to Class 8 truck manufacturers, as well as being installed by TransPower into trucks for individual truck owners or fleet operators as a turn-key vehicle conversion service. TransPower manufactures and supplies all of the mounting hardware, wiring harnesses, and other integration hardware required for installation of the ElecTruck™ subsystems into trucks. Figure 13 is a photo showing the PCAS assembly just described after installation into the engine compartment of a ProStar® truck.

Similar drive systems using the same basic components are available for conversion of nearly every type of heavy-duty vehicle to electric drive, including on-road Class 7
trucks, Class 8 yard tractors, school buses, transit buses, and even various types of rail vehicles. Hybrid range extension subsystems using various fuels including natural gas and hydrogen are also available.

SUMMARY

Understanding that the electric truck industry is in need of new successes, TransPower believes it was imperative to make the major investments necessary to take truck performance to the next level. Based on its positive results to date, TransPower believes these investments are already yielding returns and that can have a transformative effect on the automotive industry – with significant environmental benefits. Incorporating all of the technology advances described in this document, trucks using TransPower’s ElecTruck™ products are arguably the most technologically advanced electric trucks in the world. Their technological sophistication is resulting in performance attributes that other electric truck providers have tried to meet, unsuccessfully, over the past decade, including the ability to:

- Haul fully loaded containers up steep grades
- Accelerate to freeway speeds as rapidly as conventional trucks
- Provide sufficient starting torque while also being able to sustain high speeds while operating on freeways
- Provide full power at all times, even at low battery state of charge
- Operate quietly and with high efficiency
- Deliver sufficient operating range to meet daily drayage duty cycle requirements
- Permit easy access to key components for servicing and support
- Be replicated in the form of transportable “kits” that can be delivered to major truck original equipment manufacturers (OEMs) and installed on their own assembly lines

The trucks TransPower has been test operating since late 2013 provide a preview of what trucks can achieve using TransPower’s products, and have validated that the ElecTruck™ drive system will meet all of the above requirements. Figure 14 displays the route the Pilot truck took during a February 2014 test of its high-end performance, which included multiple trips up and down bridges near the Ports of Los Angeles and Long Beach with grades of up to 7%. Below Figure 14 is a sampling of the data collected during this testing. Few if any electric vehicles have survived this type of testing or have reported results, including operating efficiencies, as favorable as those observed during this set of tests.
Weight Front Axle: 12960 lb
Weight Rear Axle: 33620 lb
Weight Trailer Axle: 28180 lb
Max Speed: 56 MPH
Average Speed: 19.5 MPH
Distance: 39 mi
Ah Consumed: 281
Average kWh/mi: 2.58
kWh/mi TTSI to Port: 1.33
kWh/mi with trailer: 3.25
kWh/mi Port to TTSI: 1.38
Max Motor Temp: 165C
Average Motor Temp: 80-85C
Max ICU Derate due to temp: 60% of max torque.
Max ESS Temp: 30C
Max Pack Voltage: 410V
Average Pack Voltage: 390V
Min Pack Voltage: 361V
Min Cell Voltage: 2.76V (during a transient, likely speed match)
Min Correct Cell Voltage: 2.9V

Figure 14. Route taken during February 2014 testing of the TransPower Pilot Truck. A sampling of data collected during these tests is shown below.
Since the updated ElecTruck™ system being installed into TransPower’s pre-commercial trucks (as described in this document) incorporates additional technologies and features beyond those installed into the Pilot Truck, performance of the pre-commercial trucks and future trucks vehicles is expected exceed these metrics. Initial testing of the first two pre-commercial trucks which have followed the Pilot Truck (Figure 15) is validating this expectation. Data from these trucks provide high confidence that the ElecTruck™ technologies will help accelerate adoption of electric trucks and do more than any previous electric truck technology to reduce fossil fuel consumption and emissions of carbon and criteria pollutants.

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Figure 15. First two pre-commercial trucks using the ElecTruck™ system.