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FINAL PROJECT REPORT

Demonstration of Natural Gas Plug-In Hybrid Class 8 Trucks

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PREFACE

The California Energy Commission's Energy Research and Development Division supports energy research and development programs to spur innovation in energy efficiency, renewable energy and advanced clean generation, energy-related environmental protection, energy transmission and distribution, and transportation.

The California Energy Commission Research and Development Program supports public interest energy research and development that will help improve the quality of life in California by bringing environmentally safe, affordable, and reliable energy services and products to the marketplace. The Natural Gas Research and Development Program strives to conduct the most promising public interest energy research by partnering with RD&D entities, including individuals, businesses, utilities, and public or private research institutions.

Funding efforts are focused on the following RD&D program areas:

- Buildings End-Use Energy Efficiency
- Energy-Related Environmental Research
- Energy Systems Integration
- Environmentally Preferred Advanced Generation
- Industrial/Agricultural/Water End-Use Energy Efficiency
- Renewable Energy Technologies
- Transportation

Demonstration of Natural Gas Plug-In Hybrid Class 8 Trucks is the final report for the *Demonstration of Natural Gas Plug-In Hybrid Class 8 Trucks* project (Grant Number PIR-13-012) conducted by TransPower. The information from this project contributes to Energy Research and Development Division's Natural Gas Research and Development Program.

For more information about the Energy Research and Development Division, please visit the Energy Commission's website at www.energy.ca.gov/research/ or contact the Energy Commission at 916-327-1551.

ABSTRACT

The *Demonstration of Natural Gas Plug-In Hybrid Class 8 Trucks* project from 2014 to 2017, demonstrated a new, efficient natural gas hybrid truck technology. It combines cutting-edge electric vehicle technologies with an innovative approach to using a small compressed natural gas engine as an electric vehicle range extender. Researchers built four auxiliary power test units consisting of Ford 3.7-liter natural gas engines mated to permanent magnet generators and performed a series of tests to validate using this auxiliary power unit concept as a range extender for battery-electric trucks. The first auxiliary power test unit was installed onto a Navistar International Class 8 truck that was also equipped with a 115 kilowatt-hour (kWh) battery pack and a unique pickup system enabling power to be drawn from overhead "catenary" power lines. This truck was developed as part of a demonstration involving Siemens, which developed a catenary system similar to those used to power trolleys from overhead power lines. Testing of this truck provided initial validation of the ability of the auxiliary power unit to augment the battery pack and catenary power source to extend vehicle operating range. The second auxiliary power unit test unit was installed into a dynamometer laboratory built into a 20-foot temperature-controlled trailer, where a water-brake dynamometer was used to run the auxiliary power unit while testing more advanced engine control methods. The third and fourth auxiliary power test units were built for installation on two new natural gas hybrid trucks funded under a separate project, and were in operation by the end of 2017. The advanced control methods developed during the project are expected to enhance the performance of these two trucks, while minimizing harmful emissions. This may pave the way for broader adoption of near-zero-emission trucks to help meet California's emission reduction goals.

Keywords: Natural gas, hybrid, CNG, engine, electric vehicle, emissions

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Introduction

Large road vehicles, such as heavy-duty drayage trucks that haul freight containers (generally trucks weighing more than 33,000 pounds), make up only a small fraction of the United States vehicle population, but consume disproportionately high amounts of fuel while producing significant amounts of air pollutants and greenhouse gases. Operating these vehicles on battery-electric power eliminates fuel use and tailpipe emissions entirely. However, past efforts to run large road vehicles on battery power have encountered numerous obstacles, including:

- Weight of battery packs
- Battery costs and limited longevity
- Reduced operating range
- High vehicle capital costs

In addition, many trucks and other large vehicles equipped with battery-electric propulsion systems have exhibited insufficient power and reliability to meet vehicle operator needs. A reliable, cost-effective hybrid-electric propulsion system could potentially address these obstacles and make electric vehicle (EV) propulsion more economically and commercially viable while minimizing tailpipe emissions by employing a natural gas engine as an EV "range extender" generator. Adding such a range extender could reduce battery weight and costs while increasing operating range. Using an inexpensive natural gas engine could avoid unnecessary increases in capital costs while providing improved road performance and lower operating cost per mile than conventional diesel or natural gas trucks.

Project Purpose

This project demonstrated the Natural Gas Plug-In Hybrid Class 8 Trucks project, led by Transportation Power, Inc. (TransPower) from July 2014 through June 2017. By achieving a proof-of-concept demonstration of a new, efficient, viable natural gas hybrid truck technology combining cutting-edge EV technologies with a small CNG engine as an EV range extender, this project created a foundation for future deployments of such vehicles, capable of performing duty cycles beyond the capabilities of pure battery-electric trucks. This hybrid truck would provide a viable alternative to diesel trucks, reducing emissions, while reducing the amount of natural gas fuel required to complete a given duty cycle, thereby enabling additional reductions in air pollutant emissions. The primary target market for such trucks is regional trucking applications involving 100 to 300 miles of truck operation per day. This is beyond the operating range of most current battery-electric truck technologies, but within the range that batteries could support cost-effectively if augmented with some type of range extension technology.

Project Process

The goal of the Natural Gas Plug-In Hybrid Class 8 Truck project was to develop one of the most advanced hybrid-electric propulsion technologies on the market, merging TransPower's proven ElecTruck™ battery-electric drive system with an innovative range extender using a compact, lightweight automotive compressed natural gas (CNG) engine. The concept pursued was to mate the engine to a compact, advanced generator to produce electric energy that can be used to augment and recharge the batteries of the vehicle or to operate the vehicle at modest power levels when the batteries are depleted.

Developing the base ElecTruck™ technologies was initiated by TransPower in 2011, with funding support from the California Energy Commission, South Coast Air Quality Management District (SCAQMD), and U.S. Environmental Protection Agency (EPA). Subsequent funding was provided by the U.S. Department of Energy and the Ports of Long Beach and Los Angeles as this project resulted in several major innovations, such as developing a unique inverter-charger unit and advanced transmission. Seven demonstration trucks using this battery-electric technology were used at the Ports of Long Beach, Los Angeles, and San Diego by mid-2016. The sixth, designated Electric Drayage Demonstration Truck #6, or EDD-6, is shown being operated at SA Recycling at the Port of Long Beach in February 2016 (Figure 1).

Figure 1: EDD-6 Electric Truck During Trials at Port of Long Beach

Source: TransPower

The original project process was to convert one of these EDD electric trucks to a natural gas hybrid truck in 2015 by adding the CNG engine-based auxiliary power unit (APU) subsystem. The truck would then be re-entered into service so the performance could be compared against the other electric drive trucks, as well as conventional diesel and natural gas trucks used in the port region. However, in 2015 TransPower received a new funding commitment from the SCAQMD that covered a significant part of the cost of manufacturing two new trucks using natural gas hybrid systems, therefore the Energy Commission and TransPower jointly agreed to modify the project scope. The project would now focus the resources on manufacturing the two new natural gas hybrid trucks instead reconverting an electric truck to a hybrid. This eliminated removing a productive zero-emission truck from service and enabled more resources to be invested in basic research to develop optimized engine controls—the key to obtaining the greatest environmental and efficiency benefits of the natural gas hybrid technology.

In addition to leveraging significant prior investments in TransPower's core ElecTruck™, the project augmented initial natural gas hybrid R&D that was funded by the SCAQMD under an earlier "Catenary Truck" contract to TransPower. This work was aimed at producing two electric trucks capable of operating on an overhead "catenary" power line, one of which would be a battery-electric truck and one would be a battery-electric truck with a natural gas engine-generator for range extension. These trucks were developed as part of a demonstration project involving Siemens, which developed a catenary system similar to those used to power trolleys from overhead power lines over the past century. Figure 2 shows the two catenary trucks being manufactured by TransPower in 2015, with the hybrid catenary truck in the foreground.

Figure 2: Catenary Trucks During Manufacturing

Source: TransPower

Due to the budget constraints of the catenary truck project, a simple microturbine-based engine-generator concept was originally planned for the hybrid catenary truck. The addition of funding from the project enabled TransPower to upgrade the hybrid configuration used in the catenary truck to use a new engine—a CNG version of the 3.7-liter engine used in the Ford Mustang and F-150, which was certified by the California Air Resources Board and made available commercially in 2014, around the same time frame as the beginning of this project. While this engine was developed for passenger vehicles, when used as a range extender, it was expected to enhance the performance of much larger vehicles up to and including the Class 8 trucks targeted by this project.

By leveraging SCAQMD funds from the 2013 Catenary Truck project and TransPower's 2015 contract to build two new CNG hybrid trucks, this project exceeded initial expectations by improving the functionality of the hybrid catenary truck while resulting in the manufacture of two new natural gas hybrid trucks using the selected hybrid design, providing ample data for evaluation of performance and benefits.

A Technology Advisory Committee was formed at the start of the project comprised of representatives from Cummins-Westport, Total Transportation Services, Inc., University of California, Riverside, Southern California Gas Company and Ford Motor Company. The TAC members reviewed the project plans, or participated in critical project review presentations or critical project reviews. The advisory committee members also reviewed and commented on TransPower's final report for the Natural Gas Plug-in Hybrid-8 project.

Project Results and Future Commercialization Efforts

The Natural Gas Plug-In Hybrid Truck project was successful in most respects. For core research and development, a significant amount of fundamental work was achieved in developing engine and hybrid system controls, moving TransPower closer to its goal of deploying truly optimized, highly efficient Class 8 trucks using natural gas hybrid technology. This work included assembly of an engine dynamometer (dyno) facility, which was a significantly more complex undertaking than initially anticipated. Figure 3 is a photo of a Ford engine mated to a generator in the dyno lab in early 2017.

Figure 3: Engine Being Tested in TransPower Dyno Facility

Source: TransPower

However, the impressive functionality of this "dyno" lab enabled TransPower to develop and test engine controls and software that pushed the envelope of hybrid engine control technology. This helped compensate for one of the unexpected challenges TransPower faced during the project—engine manufacturer Ford was unable to deliver usable engine controls.

Substantial resources were also invested during the project in evaluating alternative battery technologies. The hybrid catenary truck uses prismatic lithium-iron-phosphate cells, similar to those used in the seven battery-electric drayage trucks built by TransPower between 2013 and 2016. For the first of the two new CNG hybrid trucks enabled with the SCAQMD funding, TransPower used a new cylindrical battery using a higher energy density lithium-iron-phosphate technology. This battery technology provides this truck with about 30 percent more battery energy than the catenary hybrid. Testing the new cylindrical cells by TransPower during the project, however, revealed potential quality and durability issues and, because of these findings, TransPower deferred a decision on what battery technology to use in the second of the two SCAQMD-funded hybrid trucks.

TransPower was able to complete only one of the new SCAQMD-funded CNG hybrid trucks by the end of the agreement, however, the most critical technical objectives were met. Dynamometer testing indicates that the cost of operation for the diesel truck is shown to be $80 at the 100-mile mark, versus $70 for a CNG hybrid truck driven at high speed and about $42 for a CNG hybrid truck driven at low speed. Furthermore, the CNG hybrid truck was operated for 100 miles using an optimal combination of battery electricity and power generated from an onboard CNG engine-generator. The truck was estimated to have an average fuel economy of 6.5 miles per diesel gallon equivalent. This compares favorably with conventional natural gas trucks, which for the same weight class would typically get only 3-4 miles per diesel gallon equivalent.

As of the conclusion of the project, the hybrid catenary truck had been test operated for several hundred miles, including multiple trips between the San Diego and Los Angeles areas, and the first of the two new CNG hybrid trucks was completed and initiating road testing in the San Diego area. These activities validated the proof-of-concept of the natural gas plug-in hybrid technology and, along with the wealth of data produced during dyno testing, provided abundant data to evaluate the benefits of the concept. Most major subsystems for the second new CNG hybrid truck were built, and final installation of these subsystems was completed in the fourth quarter of 2017, following selection of the battery technology to be used in this latest generation natural gas hybrid truck.

Future work on this architecture of CNG range extension of electric trucks will be performed for the two range-extended hybrids funded under a program with the SCAQMD. The primary objective of the chassis dynamometer work and auxiliary power unit (APU) engine tuning is to make progress toward acceptable emissions, particularly NOx, as this "small" APU design approach moves from the 3.7-liter Ford CNG in stationary generator to an engine used in emission-compliant automotive applications. The APU is an onboard power generator that augments the battery energy storage system in a hybrid vehicle. The type of APU developed under this project uses a natural gas engine mated to a permanent magnet generator to produce electricity

Research performed under this agreement demonstrated that the reliance on smaller natural gas engines cannot sustain trucks at freeway speeds, while also producing higher emissions when operated at the higher power levels, particularly in the higher power levels required by larger trucks. The research and design efforts under this project will be used as a part of ongoing research efforts to optimize natural gas hybrid electric configurations in heavy-duty trucks.

In a follow-on agreement with the Energy Commission, TransPower will develop a more efficient, near-zero emission natural gas-based technology to address efficiency and emission issues found through research under this project. TransPower will be using larger engines and battery packs to extend the operating range of recently-developed compressed natural gas (CNG) hybrid trucks. The intended result of the research is to develop a CNG Hybrid-Electric Super-Truck (CHEST)—a truck capable of achieving 700 miles of operating range without refueling or recharging, and that does not require extraordinarily high charge rates or large amounts of grid electric energy to be fully charged. Furthermore, this follow-on research will focus on reducing the cost of manufacturing CNG hybrid drive systems by using mass produced batteries. This research supports continued efforts to optimize the performance and commercial viability of natural gas hybrid electric systems, and make a low-emission option in the heavy-duty vehicle market.

Making This Technology and Knowledge Available

TransPower conducted outreach with a wide variety of stakeholders with potential interests in the viability of using natural gas as an adjunct to electric propulsion in Class 8 trucks and other large vehicles. The projects results were shared with stakeholders which included truck owners and fleet operators, major utilities, CNG and CNG equipment suppliers, engine manufactures, air quality and energy efficiency agencies, electric vehicle technology providers and research institutions.

For example, the benefits of using a natural gas generator to extend the range of electric trucks was discussed with all of the truck fleet operators since they expressed concerns about the limitations of using pure battery-electric trucks on some of their fleets. The two new CNG hybrid trucks built during this project will be used with fleet operators to demonstrate the benefits of the technology in real-world operations.

The team also provided project information to the public including publishing technical papers and fact sheets on the TransPower website http://www.transpowerusa.com/data-center/industry-publications/ and other marketing materials to help promote awareness on the commercial availability of products resulting from this project.

Benefits to California

Enhancing the zero-emission ElecTruck™ system with natural gas range extension capability will help expand the use of battery-electric propulsion. This will help preserve the environment and enhance California's position as a leading force for reducing greenhouse gases to help mitigate climate change. This will have a particularly beneficial effect in communities adjacent to seaports such as the California port regions, where large numbers of highly polluting diesel trucks are congregated in very small areas. Widespread use of hybrid-electric propulsion using natural gas engines will also help reduce the nation's dependence on imported oil. The project will benefit the California economy by creating highly skilled jobs within the state in such areas as:

- Power electronics and battery pack assembly.
- Electric vehicle integration.
- Servicing of hybrid-electric vehicles.

Expanding the use of natural gas as a vehicle fuel will benefit California ratepayers in several ways, including helping insulate ratepayers from increased transportation costs resulting from escalating diesel fuel prices. Moderating transportation fuel costs can help keep the costs of goods movement from increasing, resulting in lower consumer prices. The benefits of the project will be felt beyond the trucking industry because the components used in the natural gas hybrid system can be used in transit buses, school buses, and many other types of vehicles.

CHAPTER 1: Objectives and Approach

Development of Natural Gas Plug-In Hybrid Class 8 Trucks (NGPH-8) was an innovative approach to meeting the objectives of California Energy Commission PON-13-506. As proposed, NGPH-8 sought to maximize benefits by demonstrating proof-of-concept of a natural gas engine-hybrid system in two fully functional Class 8 trucks. Class 8 trucks, weighing up to 80,000 lbs., use the most energy and produce the most emissions of road vehicles, so adapting an efficient, near-zero-emission natural gas-based technology to such vehicles will maximize energy and environmental benefits. Table 1 summarizes how the NGPH-8 project met the requirements of the program.

Table 1: How NGPH-8 Project Met Minimum Requirements of PON-13-506

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Hybrid functionality in a Class 3-8 vehicle	Project leveraged existing TransPower contracts to enable demonstration of an advanced hybrid system in two trucks.
Integration and optimization of the natural gas engine hybrid-electric vehicle	Selected engine, fuel system, generator, and generator controls were added to the two Class 8 trucks, followed by extensive drive testing to optimize the integrated systems.
Ability to achieve emissions targets of: (1) 0.01 g/bhp-hr NOx; (2) 0.01 g/bhp-hr PM; (3) 0.14 g/bhp-hr HC; and (4) 15.5 g/bhp-hr CO or lower, as determined by the heavy-duty engine FTP	The selected engine is a new technology Ford 3.7 liter engine designed for the Mustang and F-150. Adaptation of a small, efficient, technologically advanced engine to Class 8 trucks and the use as a range extender to maximize zero-emission miles per duty cycle, were shown to result in the lowest possible emissions of any hybrid-electric Class 8 truck ever deployed.
Thermal and fuel efficiency with significant improvements when compared to conventional vehicles in the same application. Proposals should include conventional vehicles as the baseline for validating improvements	In addition to using a smaller, more fuel-efficient engine, the hybrid system was designed to operate the engine close to the most efficient operating point most of the time, using a partial load-following technique to meet peak-power requirements beyond the capacity of the battery pack. TransPower is already working with a fleet operator that will be operating diesel and battery-electric trucks on similar routes, providing a baseline.

Table 1. How NGPH-8 Project Meets Minimum Requirements of PON-13-506.	
Improved efficiency at part-load operation	Using the CNG engine electric generator as a range extender for a battery-powered truck is the most efficient way to handle partial loads.
Fuel economy improvement	Fuel economy will be improved by using a smaller, more efficient engine, operating it mainly at its most efficient RPM; and enabling battery-only operation during long idle periods of sustained lower-power operation.
Commercial and economic viability	The entire drive system is based on creative adaptation of the lowest cost components available, such as the Ford automotive engine, integrated using advanced efficient methods perfected by TransPower over the past six years. Lowest cost plus maximum fuel savings will maximize commercial viability.

Source: TransPower

Key Project Objectives

The objective of the NGPH-8 project was to develop an efficient, near-zero-emission natural gas-based technology by combining the attributes of electric propulsion and natural gas engines in an innovative and effective way, resulting in trucks with greater operating range than pure battery-electric trucks and superior performance and fuel economy to conventional natural gas-driven trucks. It was expected at the outset of the project, and it remains TransPower's belief at the conclusion of the project, that on-road adaptation of natural gas hybrid technology will maximize energy and environmental benefits.

The key specific objectives of NGPH-8 enumerated throughout Table 1, are listed succinctly here:

- *Objective #1:* Achieve the lowest possible cost integration of two complete NGPH Class 8 trucks. This cost integration will be achieved by (1) augmenting existing funds to build a first prototype "catenary hybrid truck" under an existing contract with the South Coast Air Quality Management District (SCAQMD); and (2) taking an existing battery-electric truck (funded by the Energy Commission) and converting it to hybrid-electric operation. The second of these two sub-objectives was later modified to eliminate conversion of a battery-electric truck and to instead build two new NGPH Class 8 trucks, using funds from the SCAQMD that were committed after initiation of the NGPH-8 project.
- *Objective #2:* Achieve the greatest possible reductions in emissions and fuel consumption per vehicle. This will be achieved by (1) targeting the largest, least

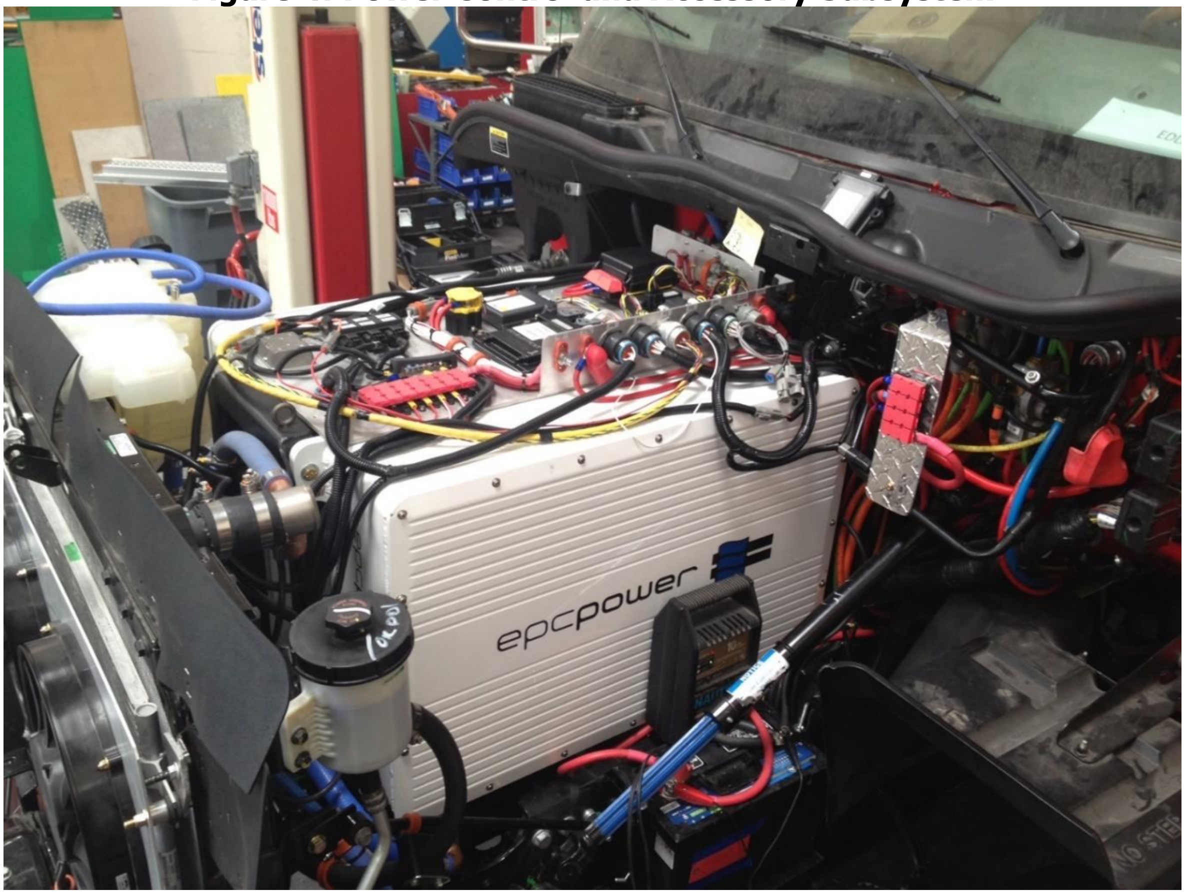
efficient vehicles on the road – locally driven Class 8 trucks; (2) using an advanced technology automotive CNG engine, which will be lighter and more efficient than larger engines; and (3) employing a battery-dominant series hybrid architecture, where the auxiliary power unit (APU) serves as a range extender to enable a mix of pure battery-electric and engine-assisted operation.

- *Objective #3:* Maximize prospects for near-term, large-scale commercialization of NGPH technology. This will be achieved by (1) minimizing cost to the end user, achieved by selecting low-cost components and efficient integration methods; (2) maximizing economic benefits to the user, achieved by maximizing fuel savings and designing the system for robustness, low maintenance, and serviceability; and (3) optimizing road performance to assure driver satisfaction, to be achieved by extensive testing and optimization activities.

Technical advancement and innovation were key elements of achieving these objectives. Adapting a small automotive engine to large trucks by employing the engine as a range-extender is a new approach, and the base hybrid-electric system developed by TransPower over the last six years employs numerous innovations including:

- Automated manual transmission (AMT). Uses a computer-controlled manual transmission to enable high performance across a broad range of duty cycles with a low-cost drive motor, with unprecedented efficiency.
- Inverter-charger unit. Combines the functions of inverter and battery charger, allowing the truck batteries to be recharged using grid power, without a separate charger.
- Advanced battery management system: Monitors temperatures and voltages of all cells and provides active cell balancing at higher currents than competing systems, helping extend operating range and battery life.
- Advanced integration methods: Innovations such as TransPower's integrated power control and accessory assembly (PCAS – Figure 4) help reduce assembly time and vehicle manufacturing costs.

Figure 4: Power Control and Accessory Subsystem



Source: TransPower

Technical Approach

The main feature of TransPower's technical approach is the leveraging of past and concurrent electric and hybrid-electric R&D to achieve more within the NGPH-8 project budget, at lower risk, than would otherwise be possible. When combined with SCAQMD funding, the NGPH-8 project resulted in deployment of two CNG hybrid Class 8 trucks, in accordance with the original project objectives, and a third CNG hybrid truck was partially manufactured.

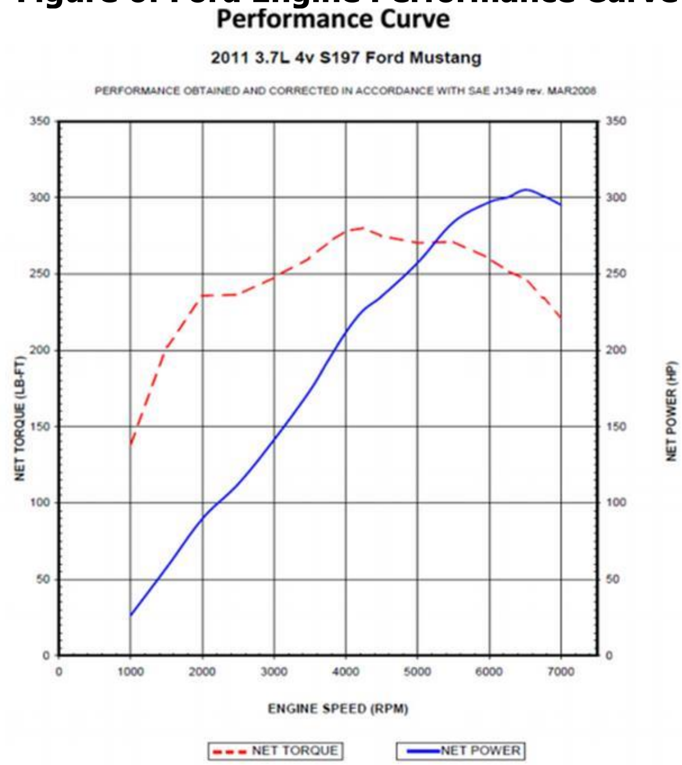
The SCAQMD catenary truck project lacked the funding to perform the engine-related mechanical integration and controls development required to adapt an internal combustion engine— much less an advanced automotive engine such as the Ford 3.7-liter (L) CNG engine (Figure 5)— to a hybrid architecture. The NGPH-8 funding enhanced the SCAQMD project as well as leveraging the related R&D funding by enabling the Ford 3.7L engine-based system to be developed, which was then used in the original hybrid catenary truck and the two new CNG hybrid trucks. This resulted in a more efficient and less expensive option than a microturbine-based auxiliary power unit (APU), which would have been installed into the hybrid catenary truck if the NGPH-8 project was not funded.

Figure 5: Ford 3.7-Liter CNG Engine

Source: Ford

TransPower has evolved into an organization that was capable of meeting project objectives with its existing supply chain. Powertech Engines, Inc., a distributor of Ford engines with which TransPower personnel have a long-standing relationship, agreed to provide the 3.7L Ford engines for this project. A key success factor was the reliability of the base electric drive system—a factor that has undermined the success of many previous hybrid demonstration projects. Risks related to this factor were minimized by using a proven electric-drive platform. A second key factor for success is performance, and TransPower's team measured system performance at all stages of development and took steps when necessary to assure that performance objectives were met. Figure 6 is a performance curve showing that the selected Ford engine has speed and torque characteristics that TransPower engineers determined are well-matched to the permanent magnet generator selected for the NGPH application. A third key factor is proper integration of the CNG-based APU and fuel system, which must include attention to thermal and other issues, and effective control of the APU under all operating conditions.

Figure 6: Ford Engine Performance Curve



Source: Ford

TransPower's technical approach involved providing timely, detailed reports on all aspects of the NGPH-8 project and making detailed information on related technologies and products on the company's website (www.transpowerusa.com). TransPower personnel also disseminated information on the results of this project by presenting technical papers and distributing product data sheets at conferences and symposia, and by demonstrating the two NGPH trucks completed during the project. TransPower personnel also participated in public meetings and hearings organized by the Energy Commission, SCAQMD, California Air Resources Board, and others to elevate public and stakeholder awareness of NGPH technology and benefits.

TransPower teamed with the DOE, SCAQMD, and CALSTART to collect and analyze data from the growing fleet of electric Class 8 trucks TransPower began deploying in 2014. Data from this demonstration have provided comparisons between electric trucks and diesel control trucks, all operated in similar duty cycles near the L.A./Long Beach ports. These data provided a baseline for comparison with the NGPH trucks, which will eventually be tested on similar routes.

CHAPTER 2: Auxiliary Power Unit and Natural Gas Hybrid System Design

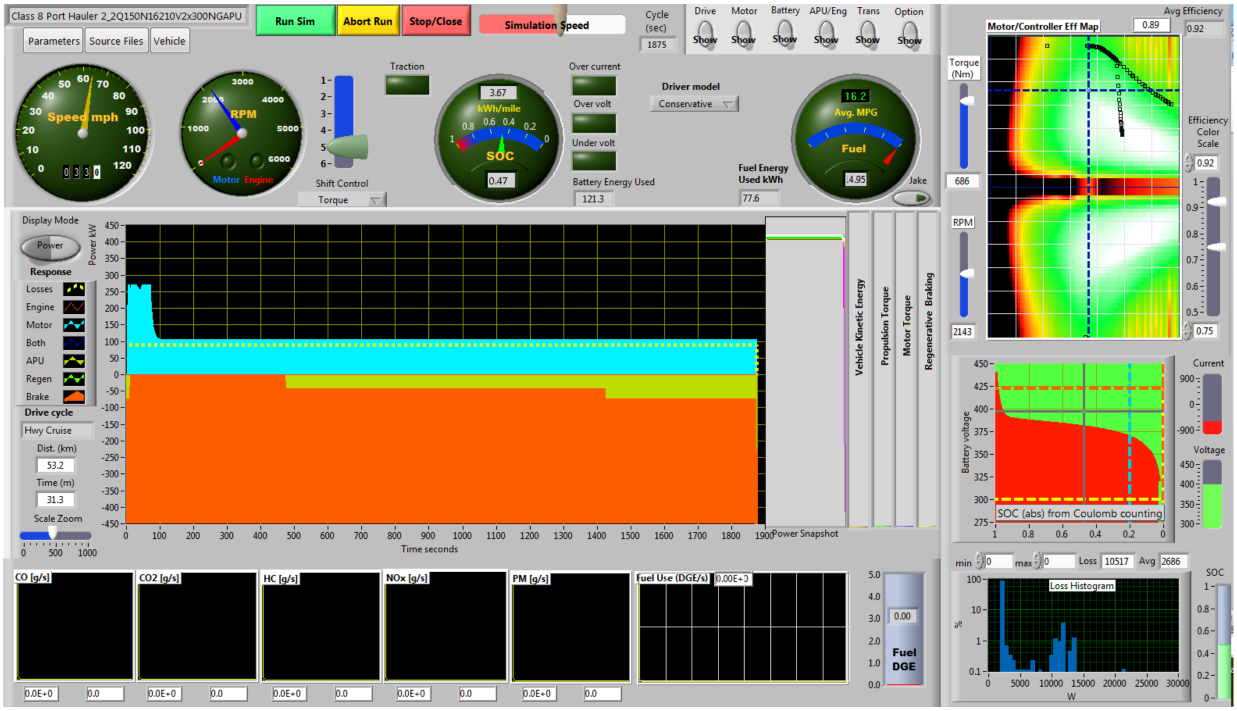
The NGPH-8 project was predicated on the theory that the use of natural gas engines for onboard power generation represents a logical extension of the state-of-the-art of hybrid propulsion. Many thousands of gasoline and diesel hybrid vehicles have been deployed over the past 25 years in a variety of weight classes, ranging from subcompact cars such as the Honda Insight to diesel hybrid articulated transit buses weighing up to 65,000 pounds. Large Class 8 trucks are the targeted application for the NGPH-8 project because such vehicles, weighing up to 80,000 lbs., use the most energy and produce the most emissions of any road vehicles. While there are a variety of alternative fuel options being employed to address this problem, various limitations such as battery-electric operating range and natural gas engine performance have thus far limited the conversion of diesel trucks to cleaner fuels.

The large size of the vehicles targeted by the NGPH-8 project resulted in numerous design challenges. These were addressed by project Task 2, Auxiliary Power Unit Design, and Task 4, Natural Gas Hybrid System Design. This chapter summarizes the work performed on these two tasks.

Preliminary Class-8 CNG Serial Hybrid Simulation Results

Before engaging in the project design tasks, TransPower personnel performed simulations to help identify power requirements and sizing parameters for the auxiliary power unit (APU) and the integrated natural gas hybrid system. TransPower personnel's authorship of advanced vehicle simulation tools spans more than 15 years. Figure 7 illustrates a proprietary simulation tool, the Efficient Vehicle Design Studio (EVDS), that was adapted and enhanced for use in this program. The simulator "dashboard" shown in the figure calculates vehicle response to drive-cycle demands for both cycle-matching and for the power generated and consumed to do so. The tool provides further information for subsystem and component responses and collects these responses to calculate battery energy and fuel energy consumption. During simulation, dynamic responses such as gear selection, instantaneous motor and engine efficiency and pollutant generation, and battery voltage fluctuation are all displayed so that particular responses to adjustable control rules can be examined for correlation with observable features in a drive cycle in real time while viewing the dashboard results. Modeled driver behavior, gear shift schedules, power-split rules, gearing choices, and other adjustable parameters of operation can then be modified in simulation to search for more optimal outcomes for the current vehicle and for hints to vehicle design changes that may yield better outcomes in design and demonstration of subsequent vehicles.

Figure 7: Simulator Dashboard Predicting Vehicle and Subsystem Performance



Source: TransPower

EVDS is a dynamic simulator, and as such, its outputs are not well represented in picture form. Nonetheless, the following paragraphs will be used to discuss the progress in simulation of the serial hybrid configuration of interest in this project and the information sought to complete this initial modeling.

Vehicle design generally starts from a vehicle technical specification (VTS) combined with a list of off-the-shelf (OTS) components and related specifications. The VTS embodies the designer's targets for performance, and these targets may change during design. Table 2 shows a partial list of vehicle technical specifications that have influenced early simulation. Some of these are really constraints dictated by the base vehicle chassis and other common components from the original equipment manufacturer. These off-the-shelf components, through the related specifications, provide the constraints that bind the problem to potential solutions that are commercially achievable without significant new investment. Selection of different components during the virtual phases of design, and use of the specifications to provide adjustable parameters to the simulation, provide a means for discrete optimization. Adjustment of the more flexible parameters of control settings and throttle and transmission response provide further means of applying optimization strategies through continuous parameters. It is often difficult to obtain vehicle component specifications that are of sufficient verified detail to predict the response of a simulated vehicle of highest confidence, but in general, reasonable assumptions for poorly understood specifications provide informative results in simulation.

Table 2: Partial VTS for Class-8 Range-Extended Serial Hybrid

Characteristic	Specification
Vehicle Weight Base	<21,500lbs: 9730kg
Vehicle Weight Combined	CGVW 80klb Class 8: 35,200kg
Frontal Area	103 ft2: 9.6 m2
Drag Coefficient	0.6
Rolling resistance (1st. coeff.)	0.008
Nonreserve Energy Storage	92 kWh
Nonreserve CNG Storage	(2x) 17 GGE
Drayage Range Target With APU	150 miles
Hybrid Economy@55mph Cruise	<3.0 kWh/mile
EV Economy in Drayage	<2.7 kWh/mile
Vincent Thomas Bridge Min Speed	>20mph

Source: TransPower

Initial simplified control rule sets for vehicle energy management have been tested on a "black box" model of the APU. This black box assumes an across-the-board thermal efficiency of 0.25. Until detailed engine efficiency is either modeled or measurements obtained through Ford or Ford partners, internal operational optimization of this subsystem will be delayed. Results for vehicle range and energy efficiency as simulated now are presented in Table 3. These results are preliminary, but they validate most initial assumptions for the proposed system related to use of a 3.7 L SI engine. Initial modeling of APU control focused on a charge-depleting strategy for the substantial capacity of the energy storage system under a variety of proposed conditions. The first is regional hauling, in this case from TransPower's demonstration partner Ikea's location in Bakersfield to Long Beach, with an aim of roughly 135 miles of freeway cruise at maximum CGVW. Second was two-shift local drayage, as practiced in service with the drayage demonstration partner TTSI. As the Table 3 indicates, under these drive-cycle conditions, a generator output of 117 kW is sufficient in continuous APU operation to support charge-depleting operation down to a reserve absolute state of charge of 0.20 to a range of about 135 miles from 34 gasoline gallon equivalents of CNG at 55 mph. This is around the expected continuous duty power of the proposed APU concept, which is limited by cooling limitations for the electric machine component. Roughly 140 kW APU output is required to cruise the same distance with charge depletion to the same level at a steady cruise of 60 mph. This is outside the design space for the APU subsystem components proposed for this project. With modest aerodynamic and rolling resistance loss reductions, a slightly larger battery, or a more typical maximum CVGW of 67,000 lbs., the proposed APU could meet this target speed constraint. Adding fuel storage does not help in this case because peak APU power over the fixed drive period is the limiting parameter. Again, these are worst case drive cycles reflecting regional hauling more than port drayage. Simulation results for extrapolated port drayage at the documented economy of 2.7 kWh/mile suggest that the vehicle range can be almost 150 miles over two shifts with that same natural gas tank capacity.

Table 3: Preliminary Simulation Results for APU Controls Development

Cycle/ Condition	Avg. Speed (MPH)	Trip Range (miles)	Operating Economy (kWh/mile)	Time to Goal (hrs)	APU Output (kW)	DC Energy Req'd (kWh)	Battery Capacity (kWh)	APU Energy Req'd (kWh)	CNG Req'd (DGE)	Min Tank Req'd (GGE)
eco cruise	55	135	2.8	2.45	117	378	92	286	30.1	34.2
truck cruise	60	135	3	2.25	139	405	92	313	33.0	37.5
hwy cruise	65	135	3.3	2.08	170	446	92	354	37.3	42.3
Drayage	10	75	2.7	7.50	15	203	92	111	11.6	13.2
Drayage 2 shifts	10	150	2.7	15.00	21	405	92	313	33.0	37.5

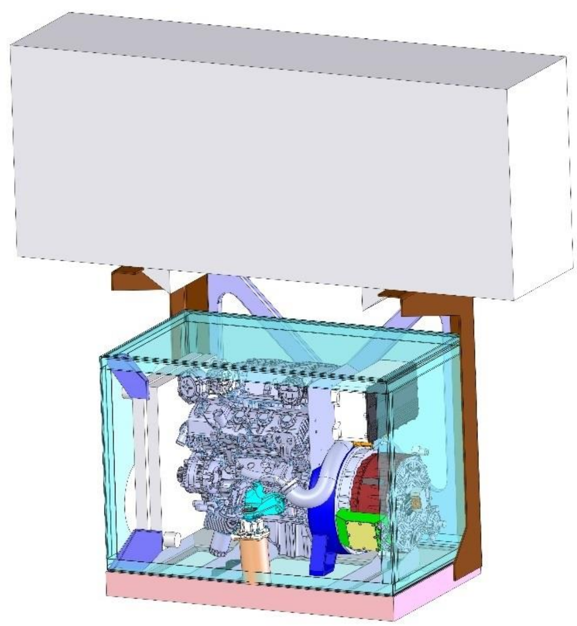
Source: TransPower

These levels of APU output are predicated by the original proposed battery pack size of 92 kWh and by the premise that efficient APU operation is associated with starting the APU early in the drive cycle and running it at a level sufficient to arrive at the target trip distance with an "empty" battery pack. This strategic premise maximizes the benefits of the battery in displacing fuel use, but more detailed engine performance data will be needed to determine whether these APU power settings result in the highest operational APU subsystem efficiencies. It is conceivable that a higher APU power output than required in this early simple vehicle control strategy would result in better fuel conversion efficiency or lower pollution, or both, and that running at a higher output in a punctuated fashion is a strategy that will produce more benefits. As more and better engine performance and economy data are received, this APU subsystem optimization strategy will be explored. In the case of extended drayage operation, with the associated lower power requirements of localized driving, the lower average APU output required would likely result in an APU operating point different than either of the highway cruise cycles. The shift drayage scenario calls for an APU output of 21 kW, a figure that may be associated with higher thermal efficiency than the 25% figure assumed here. This engine is more likely optimized for an output in the 20 kW range than would a 6 L or larger natural gas engine that was a potential candidate for use in this project.

Auxiliary Power Unit Design

Development of the conceptual design of the natural gas hybrid APU was completed in April 2015. Figure 8 illustrates the APU design concept. The white box at the top of the illustration represents the natural gas fuel system. Directly below is an enclosure containing the engine-genset. The Ford engine is shown to the left, and the JJE permanent magnet generator can be seen to the right. The entire subsystem is supported by a rack structure designed to be mounted on top of the truck frame rails directly behind the cab.

Figure 8: Early Conceptual Design of Natural Gas Hybrid APU

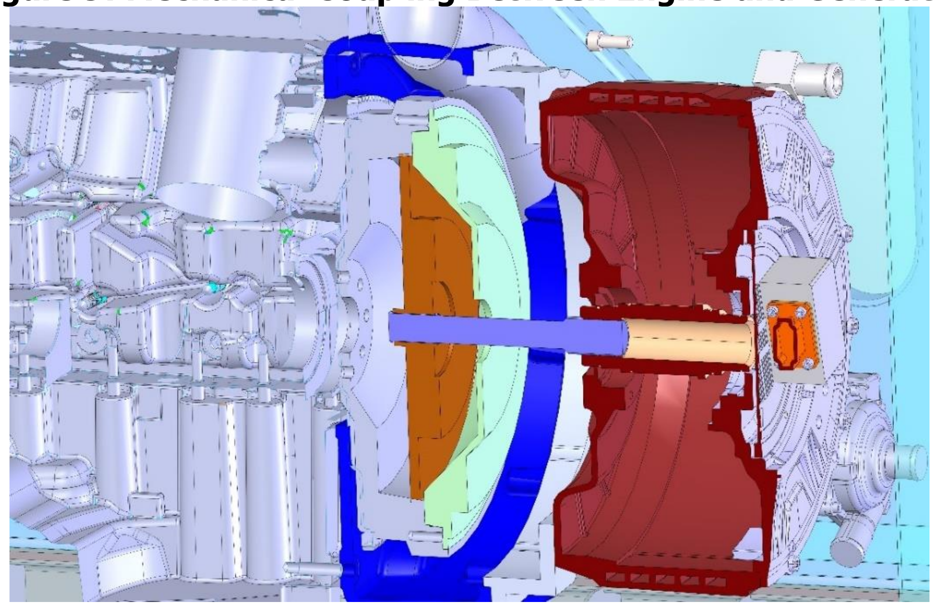


Source: TransPower

A key feature of the APU design is the design of the mechanical coupling between the engine and generator. Figure 9 is a close-up illustration of this design.

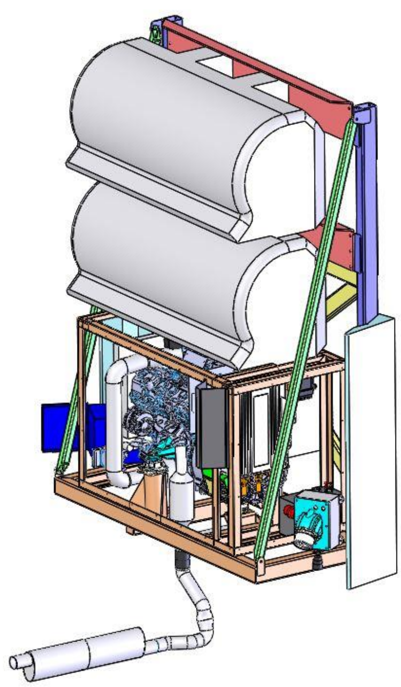
The APU design evolved considerably between April 2015, when this design was produced, and early 2017, when the first APU subsystem was fully assembled and integrated onto a truck. Figure 10 illustrates how the APU design appeared in July 2015, when procurement of structural steel to begin fabricating the subsystem was initiated.

Figure 9: Mechanical Coupling Between Engine and Generator



Source: TransPower

Figure 10: APU Subsystem Design as of July 2015



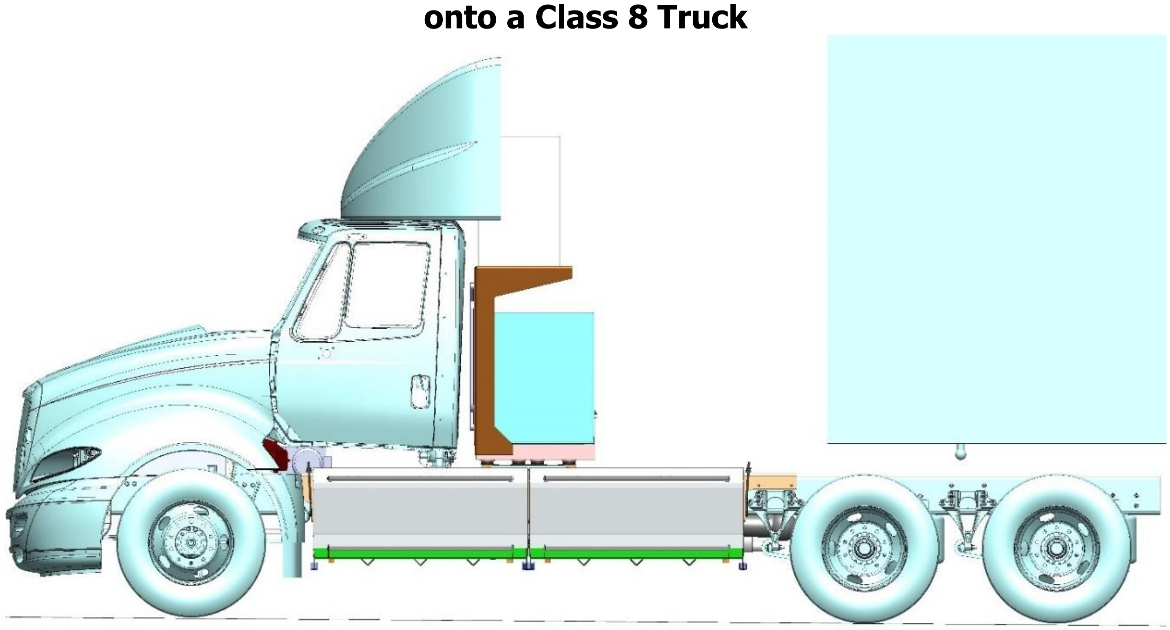
Source: TransPower

As the APU design evolved in 2015, so did TransPower's strategy for achieving the advanced engine control capabilities targeted by this project. At the beginning of the NGPH-8 project, TransPower expected to procure automotive CNG engines from Ford, identical to those used in Ford cars such as the Mustang, along support from Ford to adapt its automotive engine controls to the requirements of the hybrid system. However, despite assurances from Ford in 2014 that this support would be available, it became apparent by early 2015 that Ford had a shortage of supply of the automotive 3.7-liter engine and would not provide the controls support TransPower expected. To address this supply chain hiccup, TransPower decided in mid-2015 to use a stationary version of the Ford 3.7-liter engine offered by Powertech Engines. As discussed in Chapter 3, Controls Development, it was determined that this engine could be operated initially using simplified controls to provide a basic level of hybrid functionality and eventually upgraded to provide an equivalent level of controllability as the automotive version of the Ford engine. The only physical change to the engine required to achieve the higher functionality would be the addition of fuel injectors, a modification well within TransPower's capabilities to perform. TransPower could then develop its own engine control software without Ford's support, resulting in an engine capable of delivering sufficient power to fully use the JJE generator, with the degree of controllability required to maximize efficiency and minimize emissions over a range of hybrid truck duty cycles.

Natural Gas Hybrid System Design

Developing the conceptual design of the natural gas hybrid system was also completed in April 2015. Figure 11 illustrates an early hybrid system design concept as installed onto a Class 8 truck. This early concept was based on reuse of one of the Electric Drayage Demonstration (EDD) battery-electric trucks previously deployed (under a prior Energy Commission grant, ARV-11-014). The two large boxes along the side of the truck between the front and rear axles are the battery used in the EDD design.

Figure 11: Early Conceptual Design of Natural Gas Hybrid System as Installed onto a Class 8 Truck

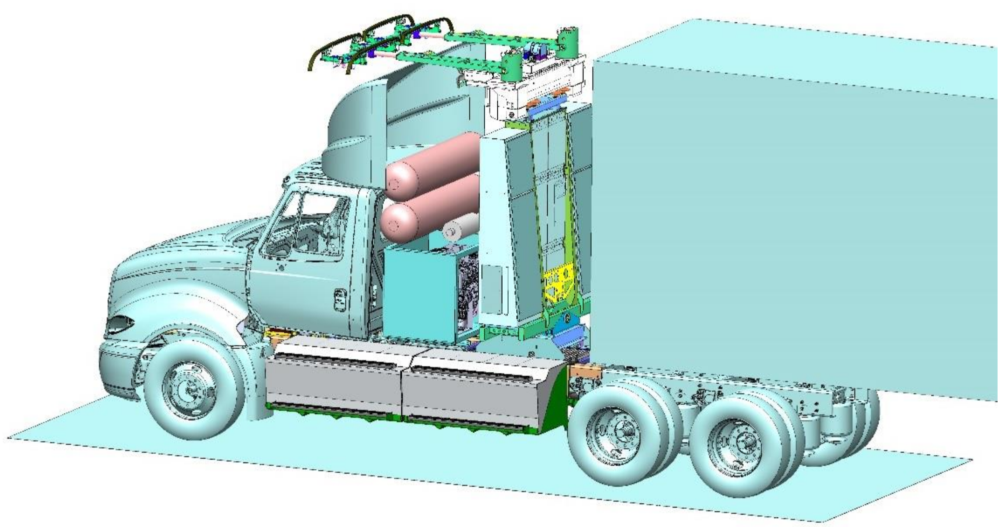


Source: TransPower

Shortly after this design was completed, TransPower received funding from the SCAQMD that enabled manufacturing of two new natural gas hybrid trucks. As discussed previously, an agreement was subsequently reached with the Energy Commission to use these trucks as rolling test beds for the natural gas hybrid system (along with the hybrid catenary truck), rather than pulling an EDD electric truck out of service to convert it to a hybrid. Given an opportunity to develop a "clean sheet" hybrid system design, TransPower opted to modify the battery enclosures, mainly reflecting the fact that the hybrid system does not require as much battery energy storage capacity as the pure battery-electric/EDD design shown above.

Before developing the two new natural gas hybrid trucks, TransPower completed manufacturing of a hybrid catenary truck designed to use battery-electric power, augmented with power from both an onboard natural gas generator and a power pickup system designed to draw power from overhead "catenary" power lines. Initial funding for the hybrid catenary truck was provided by the SCAQMD, but funding from the NGPH-8 project enabled TransPower to make significant improvements to the design of the APU subsystem of the truck. Figure 12 shows the design of the hybrid catenary truck. In this illustration, the APU subsystem is directly behind the cab, with the engine-generator set directly above the frame rails and the natural gas tanks mounted above the APU. The catenary power pickup system is visible behind the APU, with cantilevered electrical pickup devices extending over the cab.

Figure 12: Design of Hybrid Catenary Truck

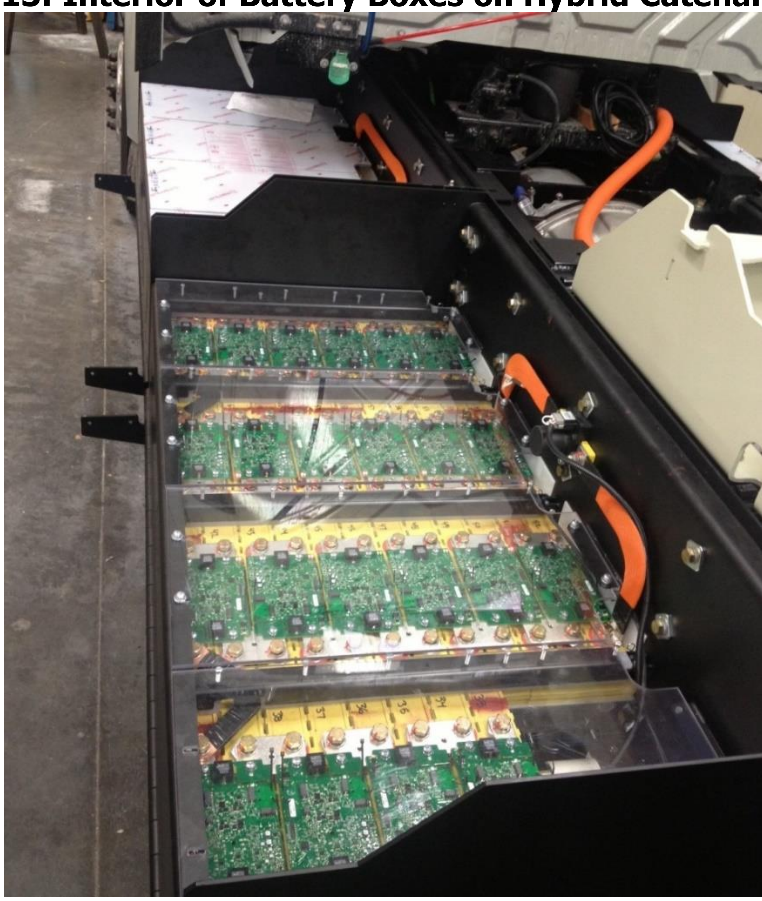


Source: TransPower

This design evolved throughout the NGPH-8 project, with the final configuration ultimately consisting of just one natural gas tank. (See Chapter 4, *APU Assembly* section.) One aspect of the natural gas hybrid design that remained constant through the hybrid catenary truck was the use of bulky boxes on both sides of the truck to house the batteries. This was a holdover from the battery-electric EDD design, which used five such boxes to house 224 cells. On the hybrid catenary truck, four such boxes are used to house 120 cells, with a fair amount of wasted space inside the boxes. Figure 13 shows the interior of the battery boxes on the driver side of the hybrid catenary truck. The battery cells are the yellow blocks seen beneath the green circuit boards, which are the sensing/balancing boards used in TransPower's battery management system. Each yellow cell shown has a storage capacity of 300 ampere-hours (Ah) at 3.2 volts (V) and stores just under one kilowatt-hour (kWh) of energy. Hence, the 120 cells provide about 115 kWh of energy storage in a battery subsystem that weighs about 3,000 pounds.

For the two new natural gas hybrid trucks built during the NGPH-8 project, TransPower made a novel battery choice in mid-2016 and selected a new cylindrical battery cell product with higher energy density. A total of 480 such cells, each rated at 90 Ah and 3.2 V, would provide 138 kWh of energy storage – in a package weighing just over 2,000 pounds. The cells would be installed into two boxes, one on each side of the truck, each box containing 240 cells in three 80-cell modules. Otherwise, the design of the hybrid system on the two new trucks would be similar to the design of the system on the hybrid catenary truck.

Figure 13: Interior of Battery Boxes on Hybrid Catenary Truck



Source: TransPower

Unfortunately, numerous delays were encountered between mid-2016 and early 2017 in acquiring the new cylindrical batteries, which delayed completion of the two new natural gas hybrid trucks. An additional setback occurred in March 2017, when a cylindrical cell of the type to be used in the natural gas hybrid trucks ruptured shortly after a test drive in one of the EDD battery-electric trucks, which had been modified to utilize the cylindrical cells. Further testing of the cylindrical cells indicated that the new natural gas hybrid trucks could be safely built and tested using this battery product, but left in doubt how safe it would be to deploy these trucks in real-world service with the cylindrical cells. Toward the end of the NGPH-8 project, a decision was made to complete manufacturing of one of the two new natural gas hybrid trucks with the cylindrical cells, a task that was accomplished at the very end of the project. Figure 14 shows the two battery boxes filled with cylindrical batteries for the first natural gas hybrid truck in June 2017, shortly before installation of the battery boxes onto the truck. The cylindrical batteries themselves are not visible in this photo because they are behind the battery management boards.

Figure 14: Battery Boxes for First New Natural Gas Hybrid Truck

Source: TransPower

This first truck, completed at the end of the NGPH-8 project, will be used for further testing and optimization of the natural gas hybrid system for several months. By the time this testing is completed, TransPower will determine if the cylindrical batteries in the truck are safe enough to allow the truck to be entered into commercial use in the current configuration. If not, TransPower expects to have a new battery product ready to install into both new natural gas hybrid trucks. Either way, it is expected that both trucks will be in regular commercial use by 2018.

CHAPTER 3: Controls Development

Controls development consisted of three interrelated parts: 1) simulation, both at the truck system level and the subsystem functional control level; 2) subsystem controls code development to oversee the operation, in real-time context of vehicle operation, of the APU subsystem; and 3) high-speed engine-control code development for operation of the engine portion of the APU subsystem. TransPower's choice of EPC and related motor inverter hardware as a familiar product and development partner for the electric generator subsystem hardware and control code made this additional aspect of subsystem development a very simple solution.

All these choices were clarified with the procurement of required engine hardware and controller programming resources for this project in early 2015. At that time, availability of the proposed 3.7 L engine directly from partner Ford had become infeasible. Ford could not, at that time, supply an open, "calibration" version of the engine controller for development, either. TransPower had a choice to hire a remote specialist suggested by a Ford contact to provide a calibration version of a proprietary engine controller with code that could be modified and updated only by that specialist, or to develop dyno testing and code development capabilities and create Transpower's own calibration controller and code. TransPower chose the second path and acquired and extended an existing code library – one compatible with the company's traditional EV-only controls development tools and techniques. The code library also provides an extensible framework to grow engine control capabilities in future and to seamlessly integrate those controls with control at the level of the subsystem and of the vehicle as a whole. The advanced features of this code library segment provided the tunable features required to rapidly develop code to meet emissions and economy targets.

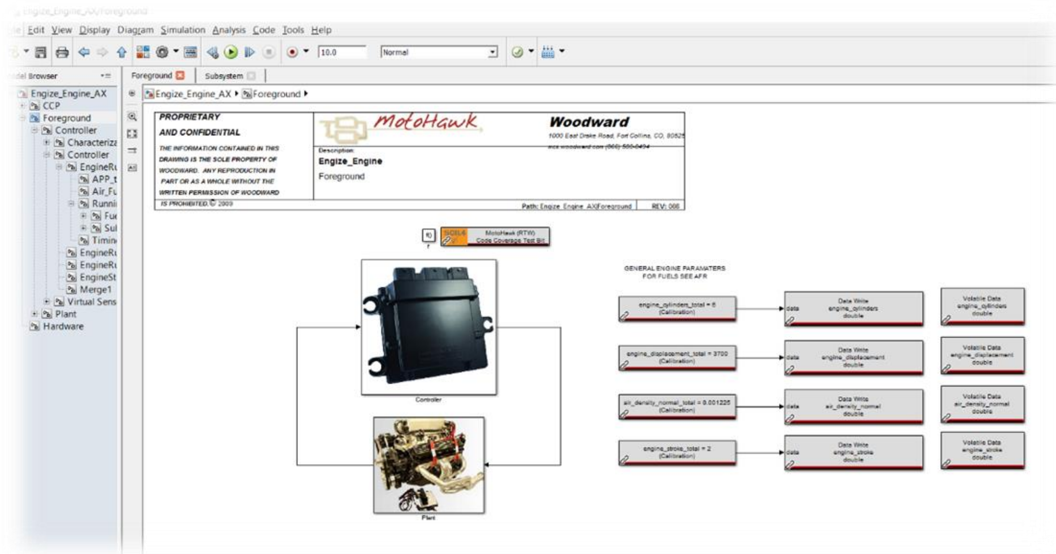
Class-8 CNG Serial Hybrid Simulation Results

Vehicle simulation was used to estimate bounds of operation and potential benefits of the serial hybrid design prior to control system development. Some of these simulations were used to estimate the fuel economy and emissions benefits of the proposed approach and are discussed in another section of the report, along with measurement of fuel consumption and emissions needed to validate the design. In this section, whole vehicle energy simulations discussed in other sections were used to set physics model parameters, to size the subsystem components such as the battery energy storage system and the APU output required, and to estimate and report fuel use during operation.

CNG Engine Controls Development

At the heart of the APU development strategy was the ambitious goal to take full control of the OEM engine and develop TransPower's own proprietary calibrations and secondary control rules for operation of the subsystem. Figure 15 provides a view of the visual code development environment and the modular structure of code developed in this way. This is the top level that shows the engine and ECU relationship. Some engine constants are set here.

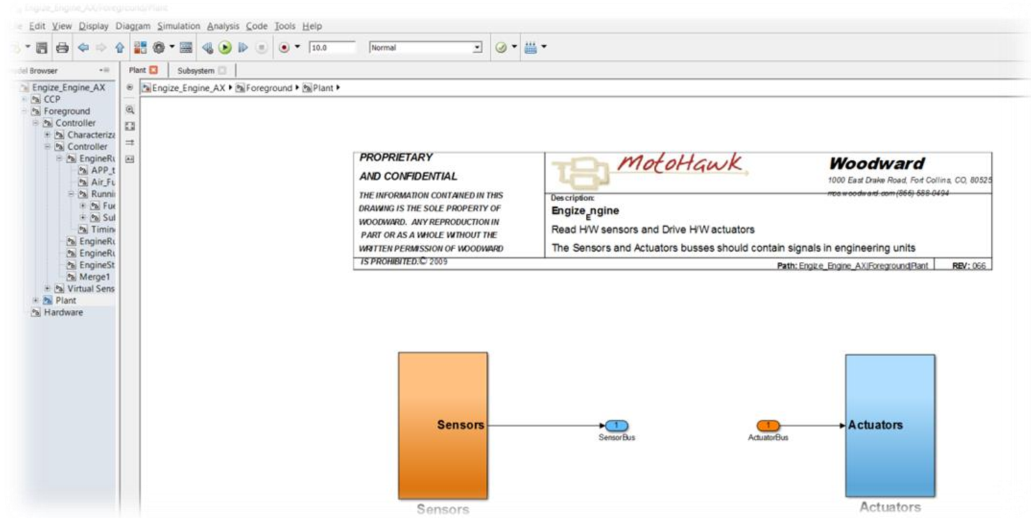
Figure 15: The Motohawk Control Code Environment Was Used to Govern Engine Control



Source: TransPower

Figure 16 expands the actuator block in Figure 3-1 and represents the top level of the sensor reads and actuator writes that are influenced by the main control logic.

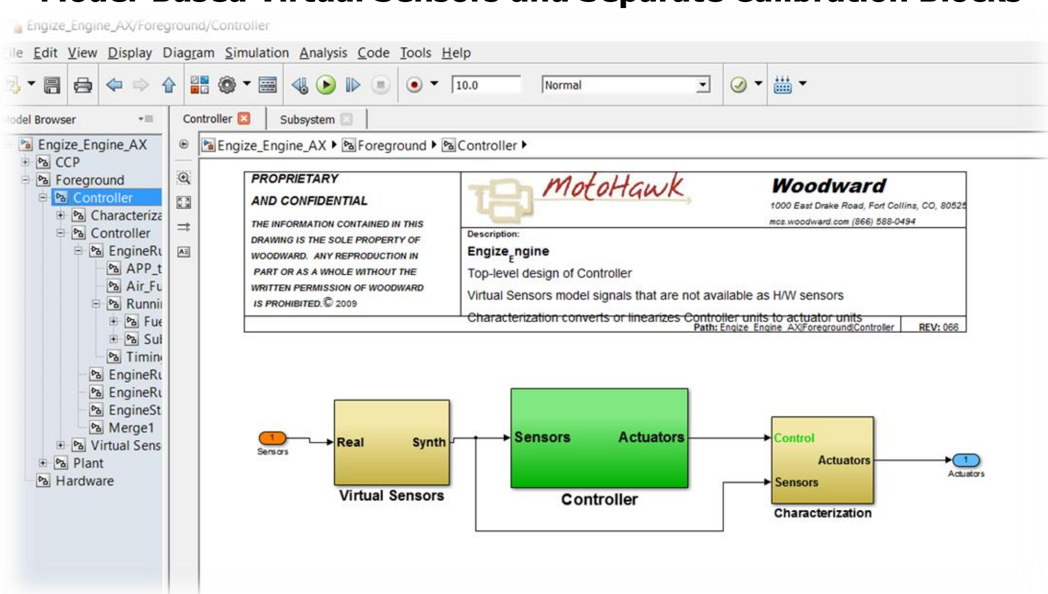
Figure 16: Modular Sensor and Actuator Code Aids Rapid Debugging of Control Code



Source: TransPower

Figure 17 illustrates the main controller code block in context with sensor and actuator blocks. This block reads sensor data, makes decisions based on the sensor inputs and built-in physical models, and writes to the actuators. The functional control of the engine resides here.

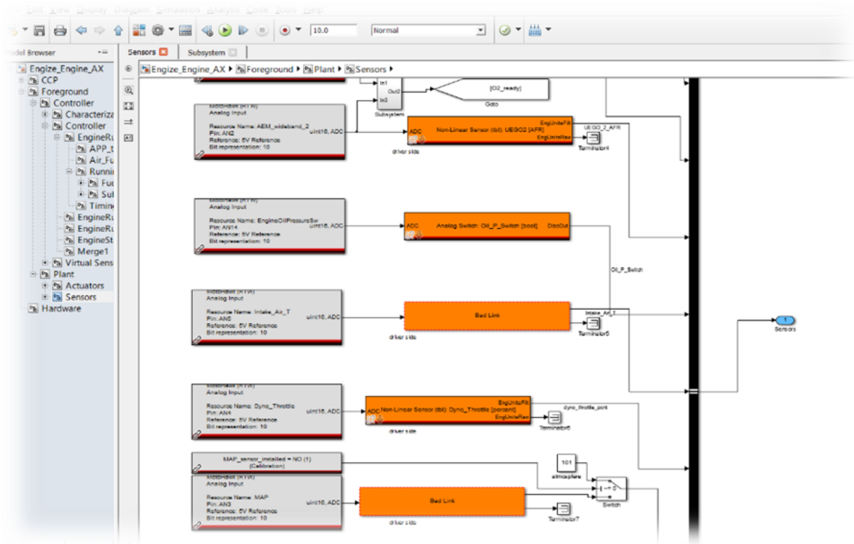
Figure 17: The Controller Definition is Separated from Those of Physical Model-Based Virtual Sensors and Separate Calibration Blocks



Source: TransPower

More specialized engine control code related to these physical models, including fuel management, spark and injector timing, as represented in Figure 18. These code blocks are specific to engine control and allow for future development of additional variations of APU design, including different engines, different fuels, and other variations.

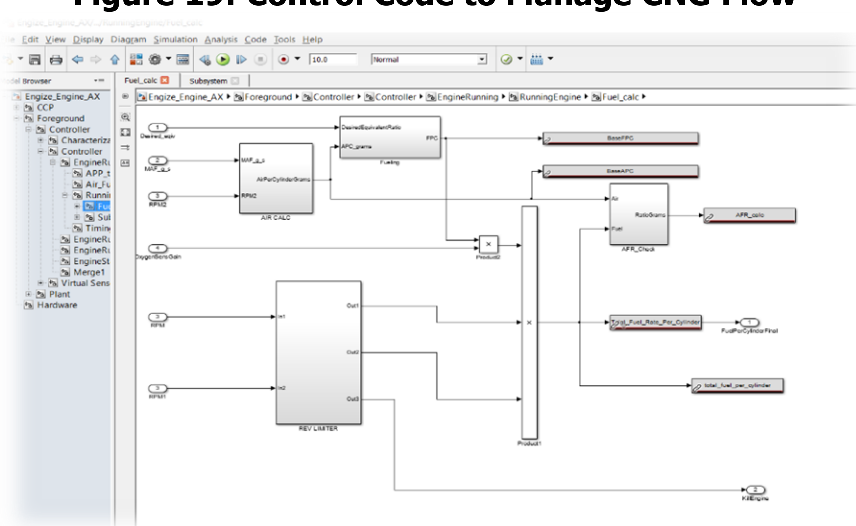
Figure 18: Specialized Code for Common Engine Sensors Is Managed in Its Own Block



Source: TransPower

A closer look at the sensors block shows logic that defines how the data are read and converted. It then assigns the data to variables for use in the control loop. Fuel control is a part of the logic handled in the main control loop, as shown in Figure 19. This block reads data from the sensor variables and writes data to the actuator variables that control real-time fuel injection to hit air-fuel ratio targets over a range of other conditions.

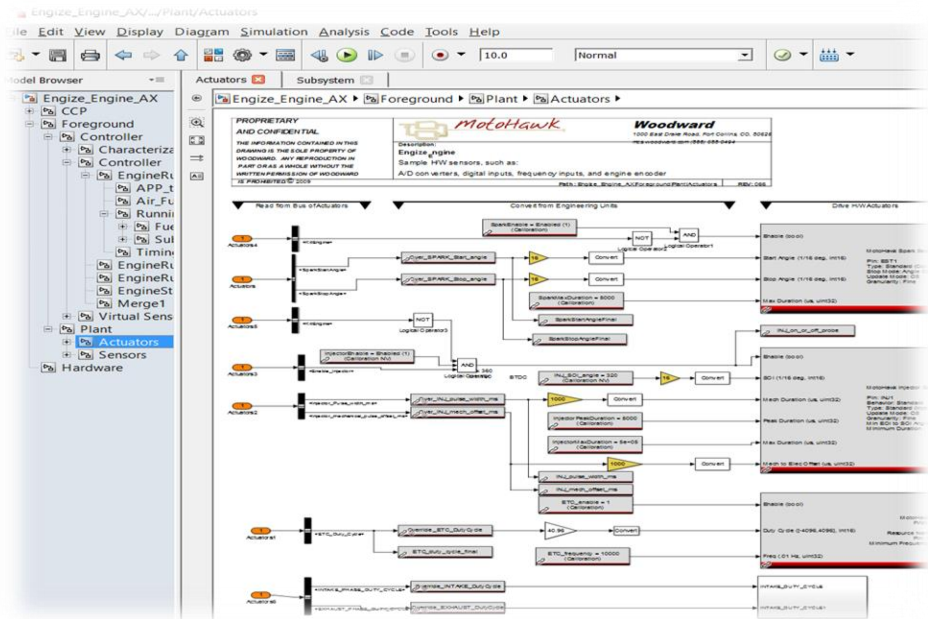
Figure 19: Control Code to Manage CNG Flow



Source: TransPower

Figure 20 dives deeper still into code details to outline the real-time calculations that govern both ignition timing and fuel injection timing.

Figure 20: Control Code for Spark and Injector Timing

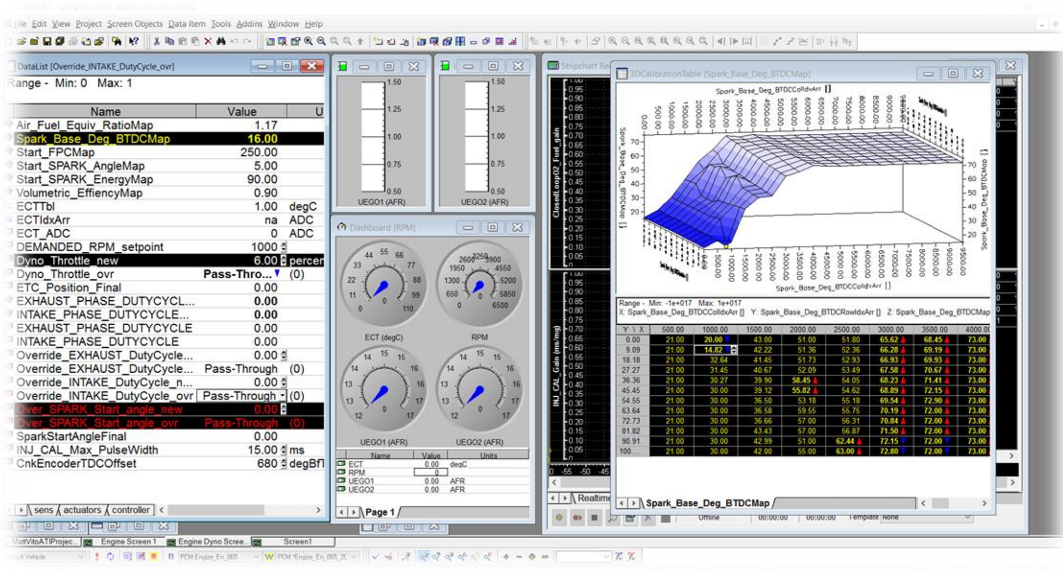


Source: TransPower

These variables dictate the response of the engine in real time, and it is at this level that additional safety and longevity enhancing features will be added during additional dynamometer refinement over the next few months, now that engine operation has been demonstrated with this code and calibrated in the test cell.

The deepest level of controls development is calibration of the code rules represented in the prior figures. Adjustable parameters must be set and verified to deliver stable operation of air measurement, fuel injection timing and amount, and spark timing in a fast feedback loop. Sensors for oxygen measurement (which indicate the completeness of combustion), cylinder head temperatures, exhaust temperatures, and, in the future, ignition event knock are used to adjust operation regardless of air temperature, RPM, or throttle request, to avoid engine damage and produce desired power and torque. The user interface that helps guide the rapid calibration and tuning of engine performance is shown in Figure 21. This interface assists the engine calibrator in visualizing calibration tables and the effects of performance and in managing these tables

Figure 21: The Specialized Module That Displays and Manages Engine Controls Calibration Tables

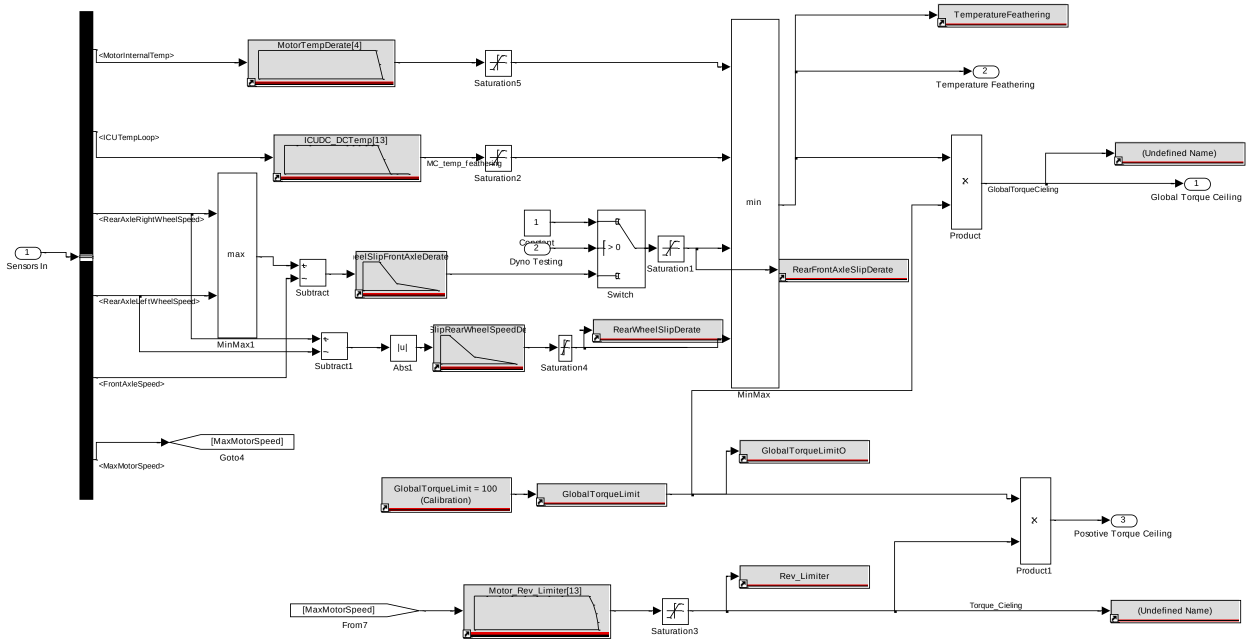


Source: TransPower

CNG Serial Hybrid APU Controls Development

In addition to the engine controls development outlined above, control commands are sent to those subsystems and coordinate the APU starter, generator, inverter, and thermal control systems and manage generation in response to the truck varying battery voltage, state of charge, the grade the truck is climbing, and other contextual and internal variables such as thermal limits, location (for idle suppression) or driver override. Figure 22 illustrates a portion of this code that governs the generator safe start and stop functions, and torque control under various drive conditions. This code is responsible for generating stable engine torque targets in response to the limit behavior of battery and generator component behaviors and driver needs.

Figure 22: A Screen Capture of Generator Torque Control Code



Source: TransPower

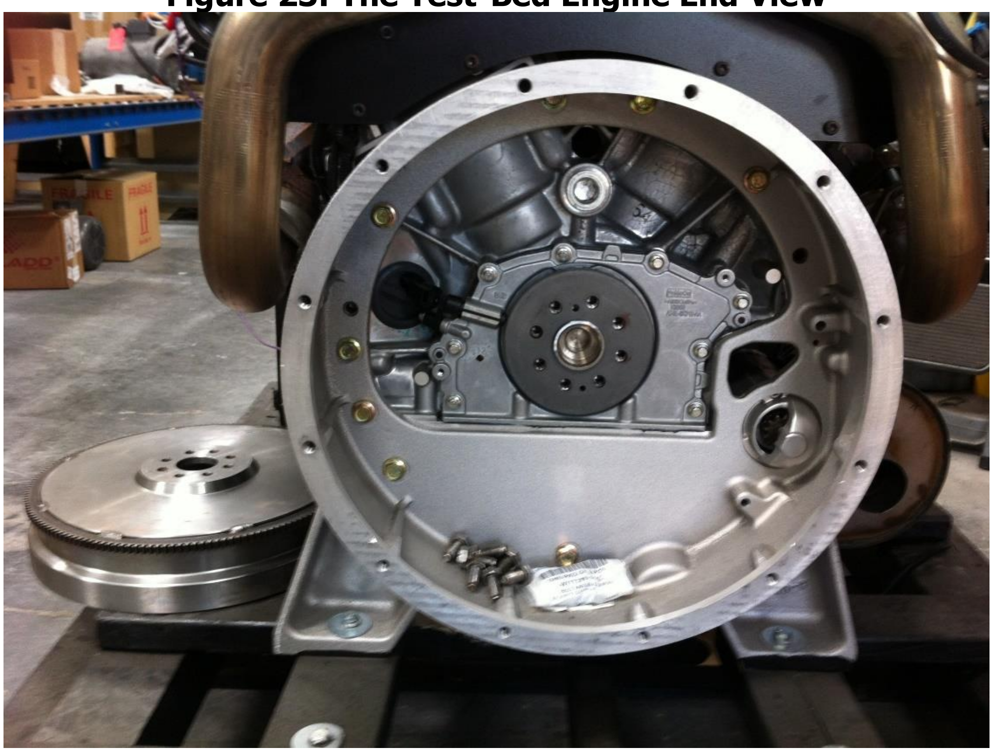
CHAPTER 4:
APU Integration and Checkout

Once top-level APU design work was completed, TransPower initiated procurement of the components required to integrate the first natural gas hybrid APU. The key components, as detailed below, were the Ford 3.7 liter natural gas engine, the JJE permanent magnet generator, clutch hardware, structural hardware for the APU enclosure, and the natural gas fuel system.

APU Component Procurement

The procurement of required engine hardware and controller programming resources for this project was clarified in early 2015. Engine clutch and flywheel hardware procured during this period are shown in Figures 23 and 24.

Figure 23: The Test-Bed Engine End View



Source: TransPower

Figure 24: Clutch Hardware

Source: TransPower

The next step was to manufacture the APU enclosure structures. Structural steel for the enclosures was procured in the spring of 2015, and by mid-summer 2015, the first APU enclosure began to take shape (Figure 25).

Figure 25: APU Enclosure Under Construction

Source: TransPower

Figure 26 shows the first APU enclosure at a slightly later stage of assembly in September 2015. The radiator is visible to the left, and the partially completed support structure for the JJE generator is visible to the right.

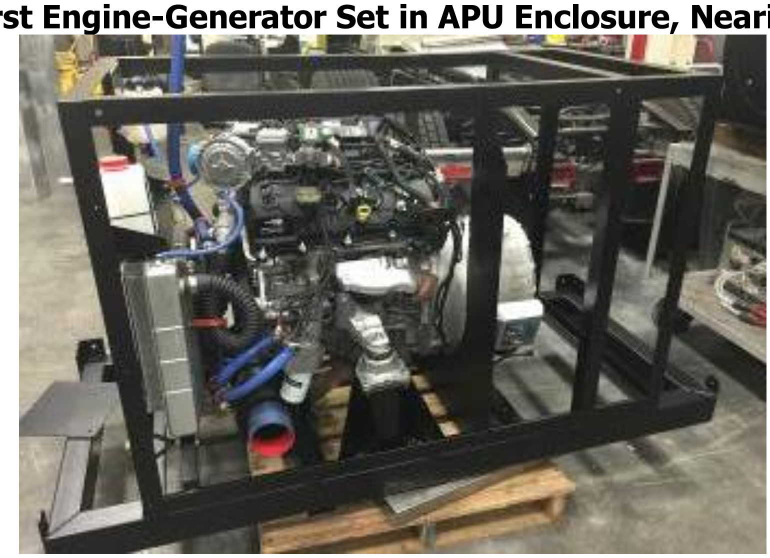
Figure 26: First APU Enclosure, Partially Assembled

Source: TransPower

APU Subsystem Assembly

By October 2015, integration of an engine-generator set into the first enclosure was nearly completed, as illustrated in Figure 27. This APU was subsequently installed onto the hybrid catenary test truck, which was physically completed in November 2015.

Figure 27: First Engine-Generator Set in APU Enclosure, Nearing Completion



Source: TransPower

Figure 28 is a photo of the first natural gas APU subsystem following the installation into the hybrid catenary truck. The single CNG fuel tank is visible near the top of the photo, directly above the enclosure containing the APU itself (engine, generator, and related hardware). To the left of the APU assembly is the truck cab, and to the right is the power pickup system used to draw power from the catenary power line.

Figure 28: APU Subsystem Installed into Hybrid Catenary Truck

Source: TransPower

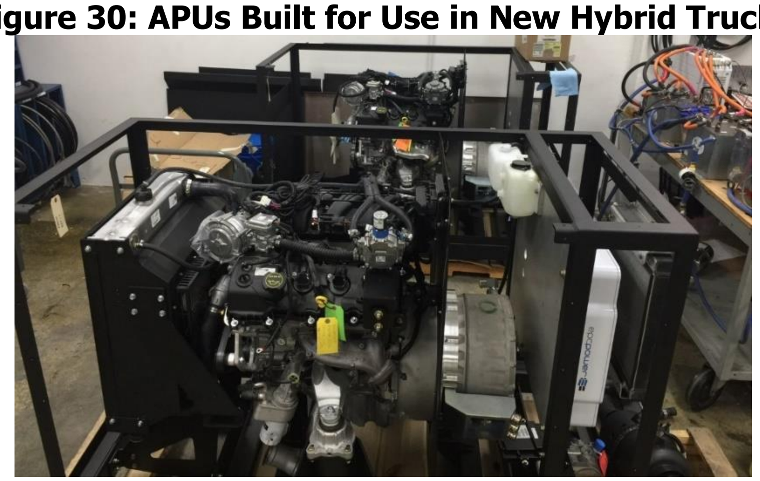
Following physical completion, the hybrid catenary truck was transported to Carson (Los Angeles County), where it underwent initial drive testing on a short catenary power line built by Siemens (Figure 29). During these tests, the CNG hybrid system was not yet functional, so the truck was operated only on battery and catenary power at the time.

Figure 29: Hybrid Catenary Truck During Initial Testing on Battery and Catenary Power

Source: TransPower

Following installation of the APU subsystem into the catenary truck, three additional APU subsystems were built, one for installation into TransPower's newly constructed dynamometer lab for testing, and two for installation into the two new natural gas hybrid trucks to be built under this project. A photo of the APU installed into the dyno lab is shown near the end of Chapter 5, Hybrid System Testing and Operation. Figure 30 shows the APU engine-generator sets built for the two new natural gas hybrid trucks, as they neared completion in the spring of 2017.

Figure 30: APUs Built for Use in New Hybrid Trucks



Source: TransPower

The unit in the foreground is complete, and the one in the background is complete with the exception of the radiator and a few other ancillary items.

CHAPTER 5: Hybrid System Testing and Optimization

Testing and optimization of the natural gas hybrid system were planned to be performed in several stages. The first stage began with testing of a Ford 3.7 liter engine running on gasoline to develop and validate basic engine controls, followed by operating the hybrid catenary truck using natural gas with basic engine controls, and culminating in operating natural gas hybrid systems using advanced engine controls – first in TransPower's dynamometer facility and finally in the three hybrid trucks. During the performance period, all these objectives were achieved through the stage of testing advanced controls in the dyno facility, enabling the project to achieve the principal goal of developing and validating a natural gas hybrid system with advanced controls. The objective of further validating the advanced controls in operational trucks was not achieved due to delays in completing the controls work and in manufacturing the two new natural gas hybrid trucks. However, transfer of the advanced engine controls to the hybrid catenary truck and the first of the two new natural gas hybrid trucks was in process as of the end of the grant period of performance, so demonstration of the advanced hybrid system and controls in fully operational trucks is expected to be achieved within a few months of the date of this report.

Basic Engine Controls Testing

Basic testing of engine controls was initiated in late 2015, using a Ford 3.7 liter engine fueled by gasoline in a test setup with a water brake dynamometer. This testing was performed before TransPower completed construction of its dynamometer facility, so the test articles were mounted to pallets within TransPower's Poway facility and engine exhaust was vented outdoors. Figure 31 illustrates this test setup.

Figure 31: Initial Engine Control Test Setup

Source: TransPower

These components were eventually transferred to TransPower's dyno facility and discussed in more detail.

Initial Testing with Natural Gas

Following testing of an APU using gasoline, the next step was testing of an APU with natural gas, using the APU subsystem installed into the hybrid catenary truck. Commissioning the first natural gas hybrid APU on this truck took several months during the first half of 2016. Figure 32 shows the initial hybrid catenary commissioning setup. The box labeled "EPC Power" is the inverter used to control the JJE permanent magnet generator, which has a continuous power rating of 100 kW and a peak power rating of 150 kW.

Figure 32: Hybrid Catenary APU Commissioning Setup

Source: TransPower

A list of commissioning tasks was maintained throughout the process until the natural gas APU system on the hybrid catenary truck was operating properly. Table 4 is the commissioning task list used on the dyno test cell. A subset of this was used on the catenary test truck.

Table 4: APU Test Cell Commissioning Task List

APU Test Cell System Commissioning Plan

Design Planning	**People**	Design leader		Jim Burns
	Time	Planned completion date for design actions		31-Mar-17
Design Actions (Customer)	**Step**	**Action**		**Status**
	1a	Submit mechanical design and layout diagram		Done
	1b	Submit cable tray and wiring routing drawing		Done
	1c	Submit wiring diagrams		Done
	1d	Confirm that all chiller to APU plumbing can be implemented as per cooling loops drawing		Done
	1e	Confirm that all CNG tank to APU plumbing can be implemented as per fuel loop drawing		Done
	1f	Submit plan for provision of remote data connection to test cell system		Done
	1g	Submit APU design to allow bill of materials validation		Done
Installation Planning	**People**	Installation leader		Terry Green
	Time	Planned completion date for Installation actions		Done
Installation Actions	**Step**	**Action**	**Required Equipment**	**Status**
	1h	Complete construction of test cell container, including attachment of plumbing manifolds		Done
	1i	Complete power cable routing between battery simulator and APU		Done
	1j	Install suitable ground points		Done
	1k	Install cooler plumbing and connections to the plumbing manifolds		Done
	1l	Build APU cradle assembly (engine, coupler, motor)		Done
	1m	**[Requires two people]** Install APU cradle assembly on rails and fasten **with metal clip.**	APU cradle assembly, metal clip assembly	Done
	1n	Install Liquid-Cooled plumbing connections from the manifolds to the modules		Done
	1o	Build APU controller backplane assembly (inverter, GFI, contactors, sensors)		Done
	1p	**[Requires two people]** Install APU controller backplane **including DC power cables.**	pack controllers, slides, bolts, wrenches	Done
	1q	Complete insulation test of DC power cables		Done
	1r	Install, label (on both ends), terminate and connect (on customer end) communication, control and power harnesses from customer equipment to Pack Controller.	termination kits, crimpers, labeller	Done
	1s	Confirm availability of ethernet network connection for transmission of data logs over Internet to Transpower.		Done
	1t	Charge the liquid cooling loop with coolant, circulate coolant, check for leaks, and record the flow rate.		Done

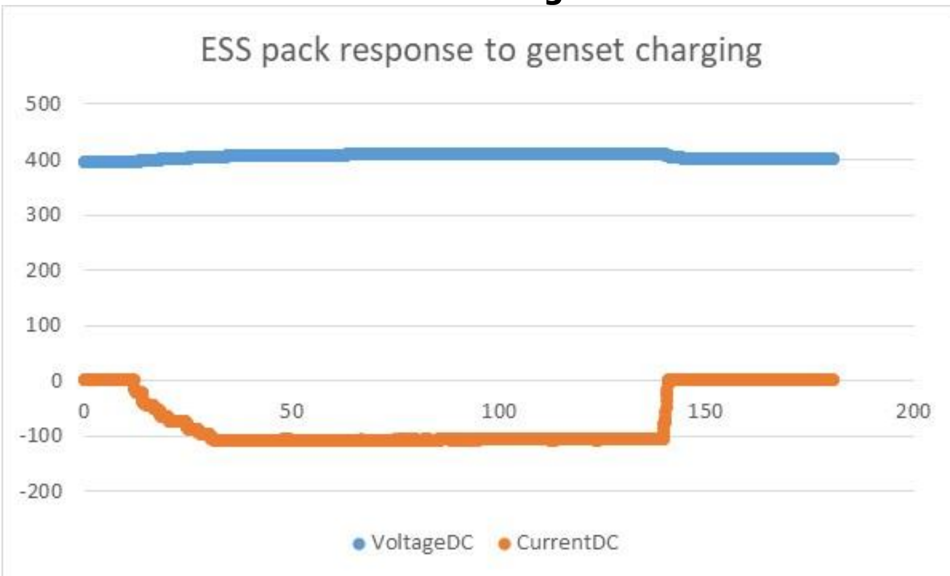
Connection Planning	**Time**	Estimated person-days of effort for Connection actions, excluding travel		22
		Requested start date for Connection actions		2/19/2017
		Planned completion date for Connection actions (based on daily working limits		3/12/2017
	Conditions	All remaining Transpower-supplied equipment and supplies will be on-site.		Done
		SAFETY: Confirm that Transpower personnel will have exclusive and		Done
		SAFETY: Confirm that working conditions in power room meet all appropriate		Done
	People	Supervisor		Ameya Jathar
		Transpower personnel for Connection actions		Terry Green
Connection Actions	**Step**	**Action**	**Required Equipment**	**Status**
	2a	Confirm Apu cradle assembly and connections layout.	label stock, label machine	Done
	2b	Connect AV900 for high voltage powe rto inverter start-up circuit	tie wraps,	Done
	2c	Check polarity of DC bus connections to precharge/gfi module	Gloves, DMM, Megger	Done
	2d	Inspect liquid-cooled plumbing for any possible problems (misplaced components, possible open valves, or uncapped tees, …etc).		Done
	2e	Install module, pack controller and all other bonded ground cables.	lugs, cable, heat shrink, screws, washers, cable cutter, strippers, crimper, heatgun,	Done
	2f	Install motor/inverter LV control wiring	cables, tie wraps, tie wrap tool	Done
	2g	Install SCADA to inverter/controller and smart se	cables, tie wraps, tie wrap tool	Done
	2h	Install all safety sensor and wiring harnesses	cables, tie wraps, gloves, mallet, tie wrap tool	Done
	2i	Install CAN hub and links for external calibration equipment	USB AA cable, Ethernet cable, pc, code	Done
	2j	Confirm operation of data log transmission		Done
	2k	<additional actions (eg. equipment retrofit, etc.)>		
Commissioning Planning	**Time**	Estimated person-days of effort for Commissioning actions, excluding travel		16
		Requested start date for Commissioning		15-Mar-17
		Planned completion date for Commissioning (based on contractor schedule)		15-Mar-17
	Conditions	All remaining Transpower-supplied equipment and supplies will be on site.		Done
		All equipment and supplies necessary to complete the defined Acceptance		Done
	People	Customer contact for Commissioning actions		Terry Green
		Transpower personnel for Commissioning actions		Wayne Beech, Rod Lindsey, Ryan Solberg
	Step	**Action**	**Required Equipment**	**Status**
	3a	Verify communications over ethernet	CAN transceiver and calibration laptop	Done
	3b	Verify communications over CAN	CAN transceiver and calibration laptop	Done
	3c	Leak check and verify CNG controls functions	Mist bottle and CNG sensors	Done
	3d	Verify inverter operation	CAN transceiver and calibration laptop	Done
	3e	Verify engine operation - sensor verification, actu	CAN transceiver and calibration laptop	Done
	3f	Validate the methane sensor safety operation	Mist bottle and CNG sensors	Done
	3g	Validate the smoke sensor safety operation	Operating engine	Done
	3h	Verify the gas flow meter operation	CAN transceiver and calibration laptop	Done
	3i	Verify e-stop control of low-voltage systems	CAN transceiver and	Done
	3j	Verify safe shut-down logic	CAN transceiver and calibration laptop	Done
	3k	Verify system alarms and interlocks	CAN transceiver and calibration laptop	Done
	3l	Verify engine cooling loop operation	CAN transceiver and calibration laptop	Done
	3m	Verify motor/inverter cooling loop operation	CAN transceiver and calibration laptop	Done
	3n	Verify safety camera set operation		Done

Commissioning Actions (w/contractor)	3o	Verify the watchdog sensor	CAN transceiver and calibration laptop	Done
	3p	Verify current sensor operation	CAN transceiver and calibration laptop	
	3q	Verify ground fault sensor functionality	CAN transceiver and calibration laptop	Done
	3r	Verify engine start logic	CAN transceiver and calibration laptop	Done
	3s	Verify engine E-stop logic	CAN transceiver and calibration laptop	Done
	3t	Verify phase wiring and rotation with resolver fee	CAN transceiver and calibration laptop	Done
	3u	Calibrate throttle	CAN transceiver and calibration laptop	Done
	3v	Calibrate ECU low voltage compensation	CAN transceiver and calibration laptop	Done
	3w	Calibrate AFR sensors	CAN transceiver and calibration laptop	Done
	3x	Calibrate MAF sensor	CAN transceiver and calibration laptop	Done
	3y	Tune spark timing	CAN transceiver and calibration laptop	Done
	3z	Calibrate fuel curves for the chosen dry gas injec	CAN transceiver and calibration laptop	Done
	3aa	Verify operation of the varaible valve actuator	CAN transceiver and calibration laptop	Done
	3ab	Verify operation of the engine temperature senso	CAN transceiver and calibration laptop	Done
	3ac	Verify feedback control near-stoiciometric comb	CAN transceiver and calibration laptop	Done
	3ad	Verify idle operation	CAN transceiver and calibration laptop	Done
	3ae	Verify low-load operation	CAN transceiver and calibration laptop	Done
	3af	Verify high-load operation	CAN transceiver and calibration laptop	Done
	3ag	Verify Closed loop ARF control	CAN transceiver and calibration laptop	Done
	3ah	Verify 60kW min generation	CAN transceiver and calibration laptop	Done

Source: TransPower

The engine on the hybrid catenary truck was expected to achieve power output levels of no more than 80 kW due to limitations in the OEM controller and the flow limits of the manifold fuel induction system. Initial testing, performed in June 2016, resulted in electrical power output up to about 45 kW. Output was limited to this level due to heating issues, which were discovered to be the result of insufficient air flow in the confined area behind the truck cab in which the APU was installed. Test operations remained stable as the commanded RPM and power levels were advanced. Testing was stopped when temperatures in the cooling loop approached upper bounds. Figure 33 shows the charging voltage and current delivered to the energy storage system on the test truck during a typical commissioning test.

Figure 33: Charging Voltage and Current During Hybrid Catenary Commissioning Test



Source: TransPower

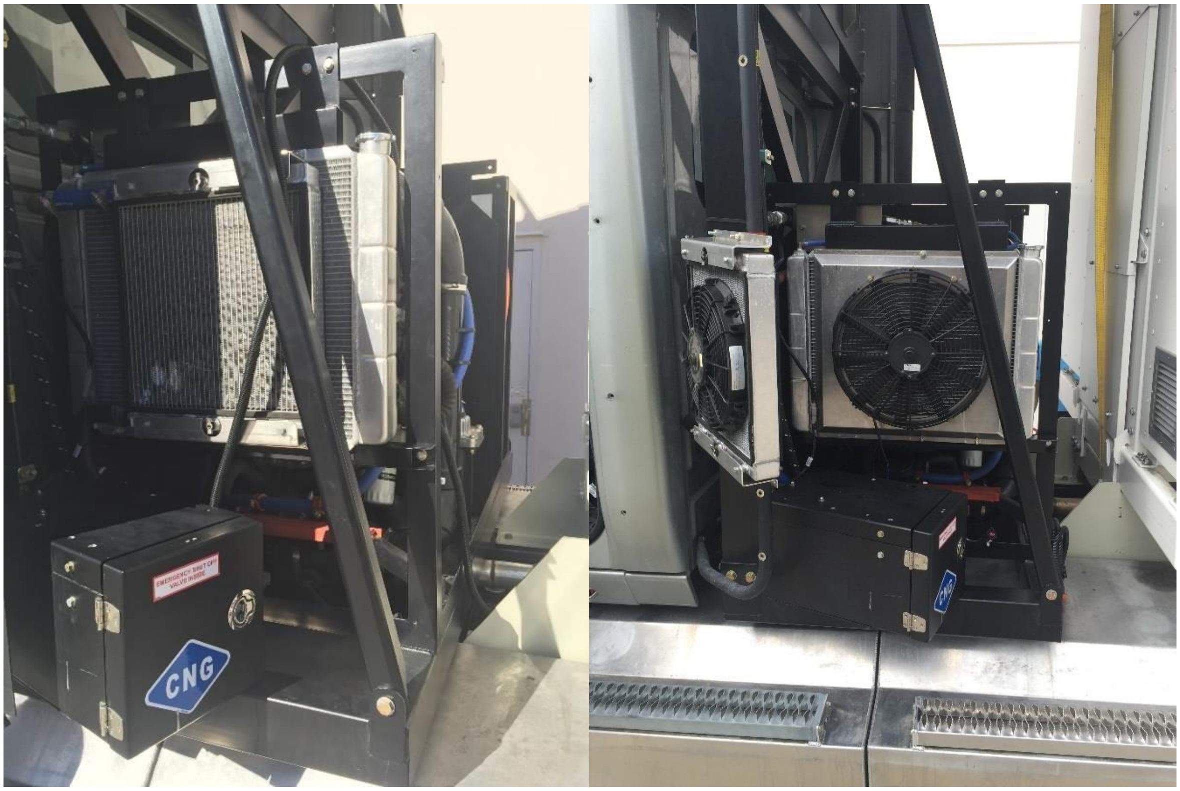
Following initial commissioning tests in June 2016, hybrid catenary APU efforts were focused on improving the cooling of the APU, so higher power levels could be achieved. The initial project goal was to achieve a continuous output of at least 80 kW. Consultations with the engine supplier during the summer of 2016 indicated that the engine design is sensitive to radiator positioning, so a modification of the plumbing was fabricated to permit entrained air to be removed from the top of the cooling loop. This design flaw was rolled into a list of design improvements that were then incorporated into the subsequent APU assemblies in construction. Improvements included:

- Relocation of the engine radiator to an elevated location relative to the engine in an attempt to eliminate trapped air in the system.
- Relocation of the radiator used for the motor/generator and inverter system to allow better airflow in the engine radiator.
- Addition of a pusher fan and shroud to increase air flow in the engine radiator.

The hybrid catenary truck provided many challenges as an APU test bed during commissioning and early demonstration of the test article APU. These challenges resulted in important lessons learned in controls integration as well as cooling approaches. A software timing discrepancy between the APU and the base truck systems at system shutdown caused a series of overvoltage conditions that led to damage of several DC-to-DC converters before the problem was identified and remedied.

Figure 34 shows the original cooling system used in the hybrid catenary APU on the left and the improved cooling system with reconfigured radiator fans on the right.

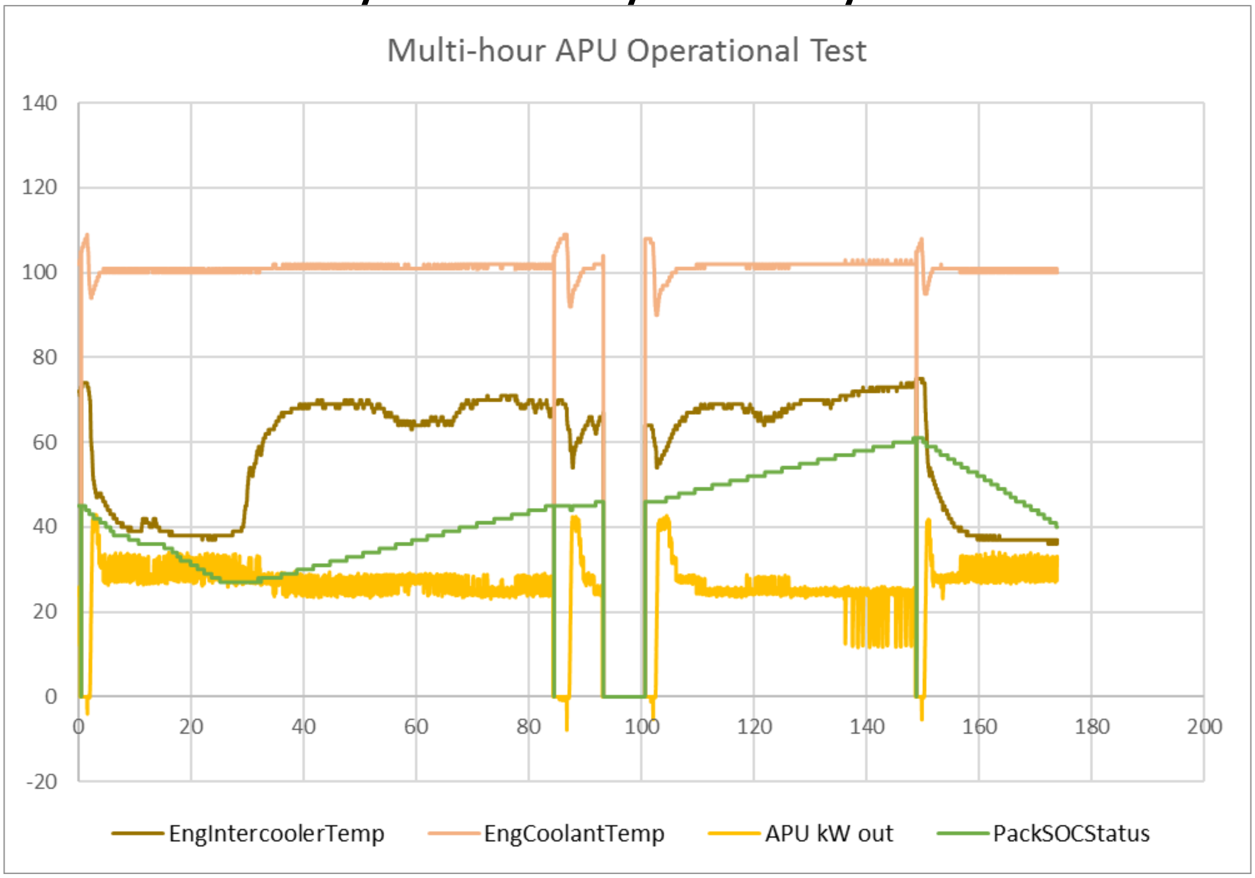
Figure 34: Hybrid Catenary APU with Initial Cooling System (left) and Improved Cooling System (right)



Source: TransPower

Data from early drive testing of the hybrid catenary truck are depicted in Figure 35. These preliminary results indicate that between 50 and 60 kW will be required to sustain unloaded cruise, and that that same 50 kW or more is a good target for providing range extension for loaded cruise. Significant control instability was observed during attempted load-following control, suggesting that more sophisticated approaches for APU operation may be required for hill climb assist operation. Only 25-30 kW of APU power generation was achieved during the drive due to inadequacies in cooling. The location of the APU behind the truck cab and away from the airstream likely contributed to this shortfall in steady generation.

Figure 35: Plot of Power, Temperature, and Battery State of Charge During Early Drive Test of Hybrid Catenary Truck



Source: TransPower

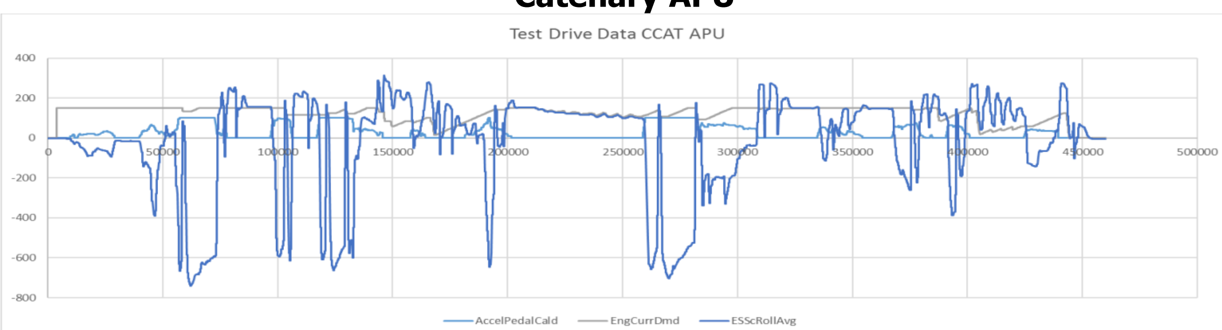
These commissioning drive results indicate that significant cooling changes, beyond those previously shown, will be required to increase the steady-state power above about 30 kW. While this power level is sufficient to prove the design premise of the project, and to add meaningful range to the test truck, several cooling enhancements suggested by work on the test truck will be implemented in the final concept:

- A larger radiator – at least as large as the one paired with this engine in the Ford F-150.
- Reuse of the much more powerful mechanical cooling fan provided by the engine.
- Heat shielding and cool-air ducting.
- Added slots in the truck side air deflectors.
- Fabrication of ducting to route slot air to the radiator.

Following addition of the larger radiator and a crank-driven mechanical fan, additional testing was performed in October 2016, consisting of a continuous run of about 30 minutes at the highest commanded power level that could be sustained at 2,900 RPM while engine coolant remained at or below 102° C. A power level of about 52 kW was reached in this worst-case test of the new cooling system improvements. This was a substantial improvement over prior tests and approached the power level determined to be required to sustain continuous driving of an unloaded truck at freeway speeds. Engine coolant temperatures in the pressurized coolant loop stabilized below the maximum target value of 102° C. Additional changes made during November 2016 resulted in another increase in continuous power, from 52 kW to 62 kW. This increase corresponds to 150 A input to the DC bus during APU operation. Stationary engine controller limits seemed to be preventing more power at this point, but subsequent custom engine controls developed in TransPower's dyno test cell were expected to overcome this limitation before the end of the project. Along with additional cooling changes still planned, these control improvements were expected to enable the APU to achieve theoretical upper limit of 80 kW of generation for steady-state operation. However, even at the 62 kW level demonstrated with the catenary truck before moving to advanced controls, 62kW would be sufficient to provide average driving power for typical drayage truck duty as performed in more than 40,000 miles of testing with EDD trucks.

Data from drive testing of the hybrid catenary truck in 2016 provided an additional opportunity to fine tune the vehicle controller response to regenerative braking events. As depicted in Figure 36, drive testing with new control rules in place was successful in retaining significant regenerative braking. Earlier curtailment of APU generation permits regen braking to be more effective. As soon as the regenerative braking reaches 10 A on the DC bus, the APU output is reduced.

Figure 36: On-Road Test Data from Drive Commissioning of the Hybrid Catenary APU

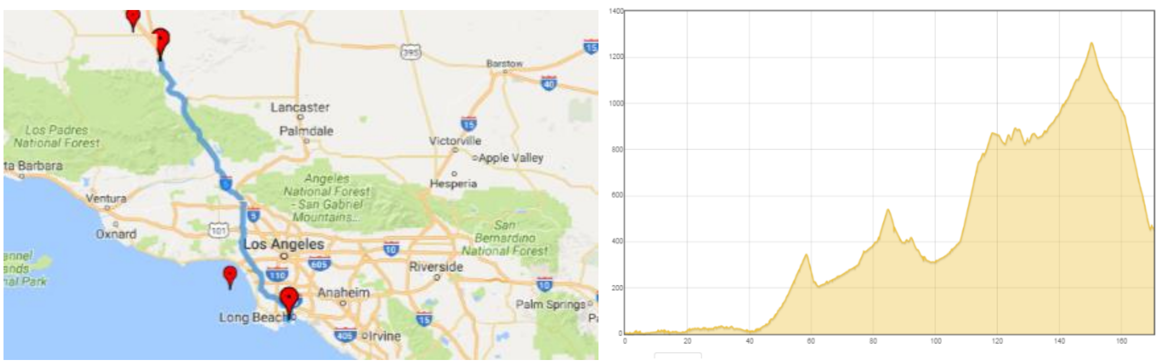


Source: TransPower

The rate of regenerative braking capture and the management of SOC are not considered critical in standard port drayage. Future scenarios with long hill climbs and significant down-slope energy recovery may be more mission-critical. In a battery-electric truck, regenerative braking can be counted on as a suitable substitute for a standard engine braking function, provided a truck with full battery is not deployed directly from the top of a long grade. Control of battery state of charge on routes in hilly regions is needed to maintain predictable downhill braking support in regeneration. To this end, TransPower has continued to evolve its contextual hybrid controls to include capabilities for CAN communication, road grade sensing, and load-estimation abilities to better estimate vehicle dynamics and permit the vehicle to more effectively act as its own test dynamometer. Such capabilities are being developed in-house from open-source software and hardware resources.

An example of a route with significant hill energy recapture potential and one that requires predicable regenerative braking is one containing the "Grapevine" hill on the Interstate 405/Interstate 5 corridor north of Los Angeles and into the Central Valley (Figure 37). This hill contains an altitude gain of 1,250 m in 110 km and then an immediate downhill section of 800 m in just 20 km.

Figure 37: Grapevine Route North of Los Angeles



Source: TransPower

From TransPower's analyses, it was observed that even in this worst-case hill descent condition, the vehicle power requirement is on par with the power returned to the truck by gravity. This indicates that modest amounts of regenerative braking should have the desired effect of keeping speed under control on the descent. From the perspective of contextual SOC control, it can be noticed that this hill requires a substantial energy expenditure. Adding estimates derived from electric drayage over flat terrain with those required just to meet the hill potential indicates a required expenditure of 314 kWh even in an ideal case. Such hills, then, are beyond the reach of even TransPower's largest battery capacity (311 kW) battery-electric trucks but easily met by modest amounts of on-board CNG storage. APU generation control up the hill, to help maintain speed on the steepest parts of the hill and to initiate high-power generation to bank electric energy in anticipation of such long hills, are continuing topics of exploration. Route data and GPS location information was combined and added to the geo-fencing capabilities for on-road testing in 2017.

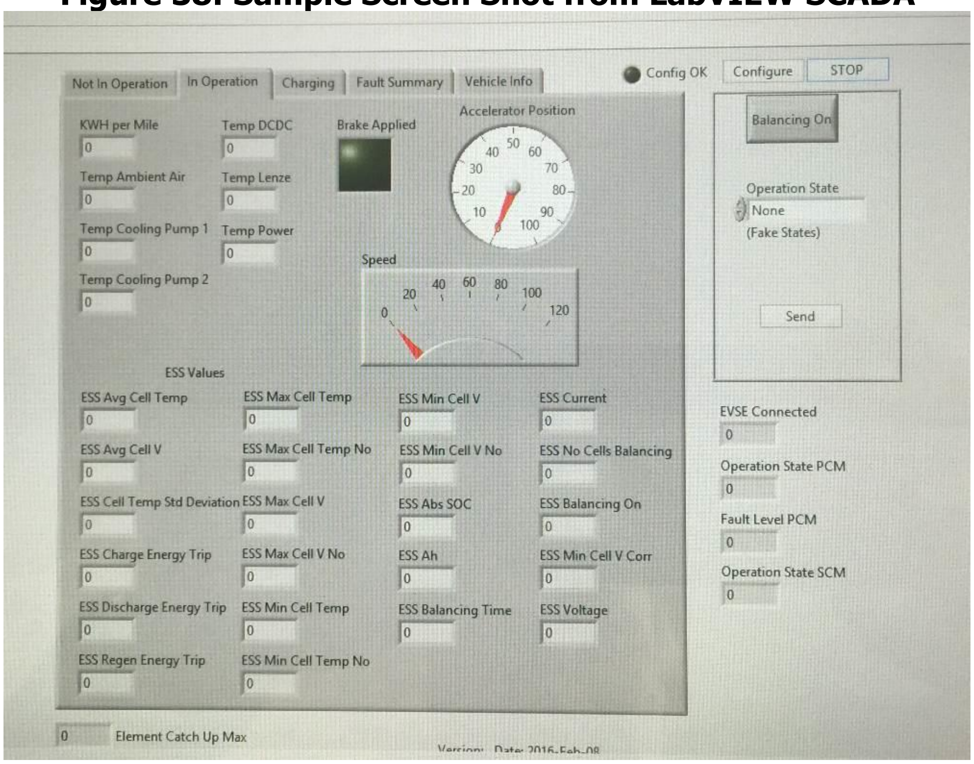
Dynamometer Testing

TransPower pursued the use of a dynamometer test cell to optimize the automotive engine to enable a higher level of engine control authority, which is expected to result in improved performance and fuel economy and lower emissions, compared with the limitations of using a stationary engine as the APU prime mover.

Development of TransPower’s dynamometer lab required a substantial amount of software as hardware development. Procurement of dynamometer lab parts was initiated in early 2016, shortly after initial testing of the Ford engine using gasoline was completed. Completion of the dyno lab was delayed during the summer of 2016 due to design challenges and parts shortages, then delayed in the fall of 2016 due to TransPower’s move from Poway to Escondido. As a result, construction and setup of the dynamometer lab took more than a year to complete, and the dyno was not ready for engine testing until well into 2017.

One of the early software preparations for the dyno facility was development of a supervisory control and data acquisition (SCADA) design in LabVIEW computer software for monitoring of tests. A sample LabVIEW screen is shown in Figure 38.

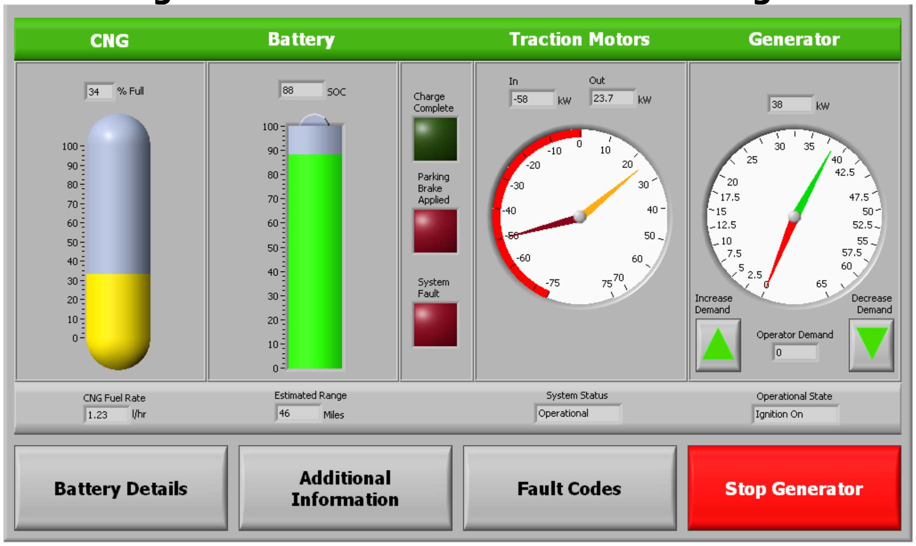
Figure 38: Sample Screen Shot from LabVIEW SCADA



Source: TransPower

A less detailed and more user-friendly SCADA design was ultimately adopted. A sample screen shot of this later design is presented in Figure 39. This design is clearly more customized for operating and evaluating a natural gas hybrid system.

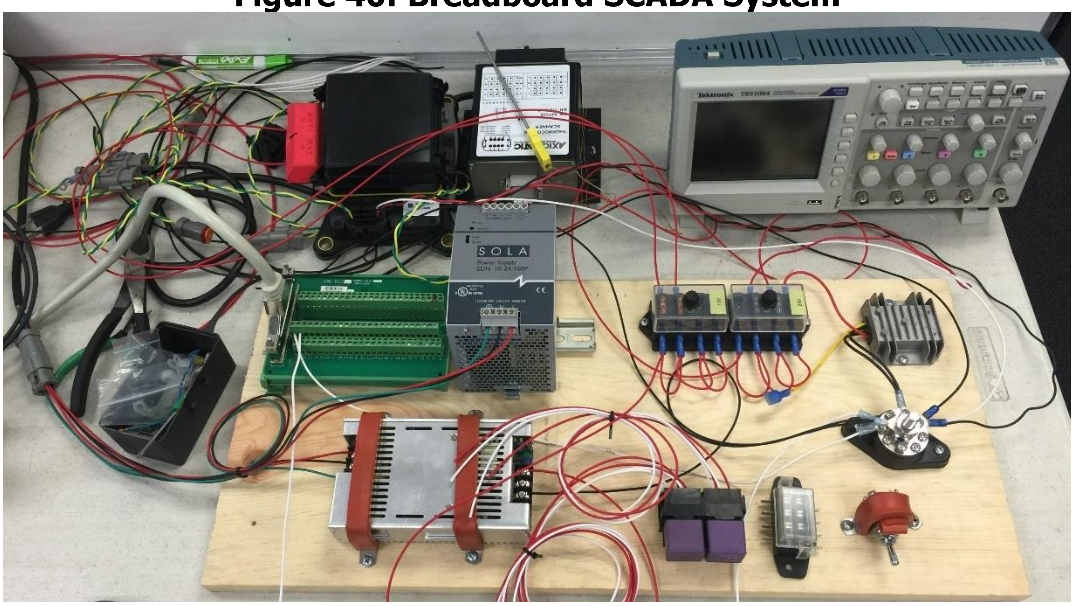
Figure 39: More Advanced SCADA Design



Source: TransPower

Figure 40 shows a breadboard system for the SCADA that was completed in April 2016.

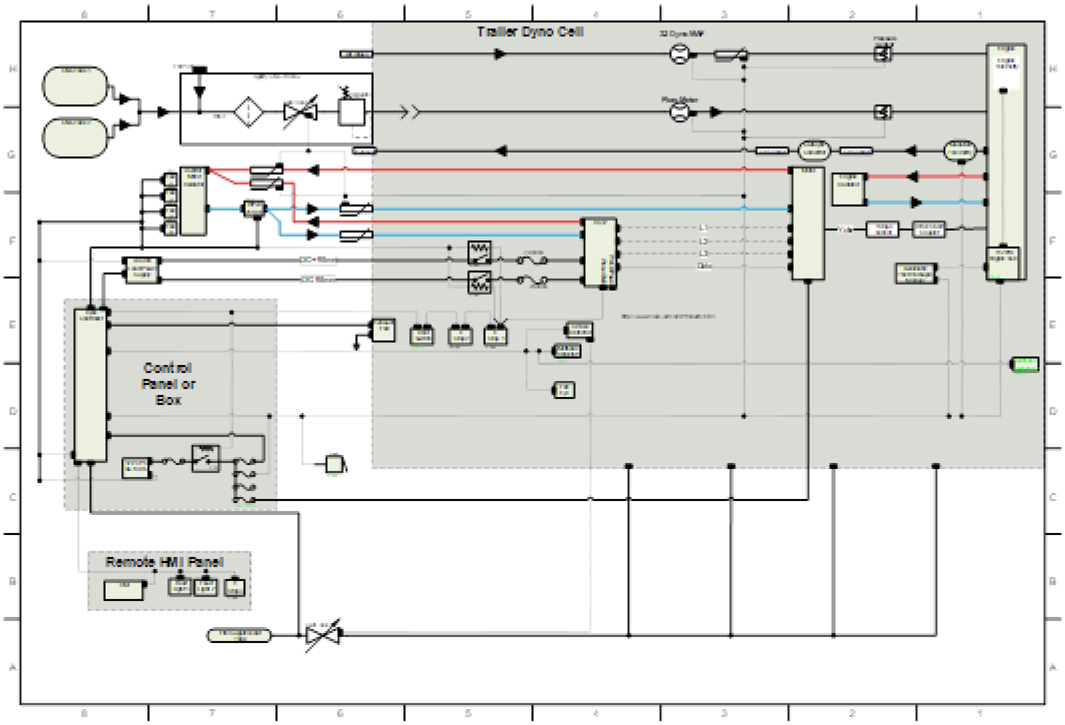
Figure 40: Breadboard SCADA System



Source: TransPower

By the end of the first quarter of 2016, system planning for dyno integration was completed. Figure 41 is a block diagram outlining the functions and subcomponents required to run controlled tests on the gen set in an off-truck or uninstalled manner.

Figure 41: Block Diagram Showing Dynamometer Functions and Subcomponents



Source: TransPower

TransPower elected to install the dynamometer equipment into a refrigerated 20-foot trailer. Figure 42 shows the trailer next to TransPower's Poway facility, illustrating the safe separation between the trailer and the building and the fixed connections for power management of the generator in test. This trailer was used to add a level of safety, containment, noise abatement, security, and flexibility to the test and engine control software development. The SCADA system was designed to permit operation and monitoring of the test cell from within the building. The function normally provided by the high-voltage battery of the vehicle was supplied instead by TransPower's AV-900 battery simulator from within the building. Cooling systems previously installed into the trailer provided a range of environmental test conditions for future exploration.

Figure 42: Trailer Used to House Dyno Lab at TransPower's Previous Poway Facility

Source: TransPower

A few months after the photo in Figure 42 was taken, TransPower moved its base of operations from Poway to a dedicated 28,000 square foot building in Escondido. This required relocation of the trailer, which interrupted dyno setup for several weeks. The dyno was completely moved to the new Escondido facility and reconnected to the AV-900 power supply by the end of 2016. An existing concrete pad was cleared for siting the trailer holding the test cell, and existing wall openings were modified to accommodate power and data connections to the computerized test equipment and the AV-900 power supply in TransPower's new power and battery laboratory inside the building (Figure 43).

Figure 43: Trailer at the New Location at TransPower's Escondido Facility

Source: TransPower

Figure 44 displays the interior of the dyno trailer during the latter stages of assembly in late 2016, highlighting the custom-built test cell exhaust system. Modification to the trailer roof required to pass hot gases, as well as the stainless-steel piping assembly that consisted of the tubing, vibration isolation, muffler and catalyst, is depicted in the photo.

Figure 44: Interior of Test Cell

Source: TransPower

During the second half of 2016, safety features were added to the dyno control application, in the form of a fault handling with safety-related sensors in the test trailer. The application allows scheduled control of the engine and motor by applying an RPM command or torque command, respectively. Data logging is provided for the user by button click and will automatically begin during faults above a certain level. High-voltage startup, shutdown, and emergency shutdown sequences were implemented to protect both equipment and personnel. The engine may be started by the motor or by the starter unit. Both start-up sequences are controlled programmatically. The application alerts the user to the current status and component availability at all times, and controls functionality based on these availabilities. Access to the system will require a password to log into the PXI, a platform for measurement and automation, remotely on an isolated network. The PXI will be treated as a headless system, allowing access only through this remote connection.

To assure safety during operation, a fault library and fault-level architecture were implemented. The lowest level fault, Level 1, continues normal operation and lights a warning lamp on the control panel. During Fault Level 2, the engine and motor are commanded down to an as-to-be-determined idle state. Data logging begins automatically, and a pop-up window will alert the technician to the fault. Operation can continue in this state once the technician acknowledges the fault message. During Fault Level 3, the system is having severe failure. High voltage is commanded low, and the contactors are removed. The engine start signal is removed. Fuel sources to the engine are removed, and a stop command is sent to the high-voltage supply. The application requires the fault level drop before continued operation. Fault Level 4 signifies a fire and engages the fire suppression system. This triggers a CO_2 alarm, lamps engage, and the CO_2 tanks dump into the enclosure.

Dynamometer testing as well as driving of the catenary CNG hybrid truck have confirmed production of up to 66 kW of power with the CNG-fueled APU, and eventual upgrading of the stationary trim engine configuration with automotive injectors and controls is expected to boost continuous power to 80 kW and peak power output to 110 kW. Results indicate that while this will not likely be sufficient for extended freeway operation, for extending the range of locally driven trucks, it is expected to be adequate. Costs estimates indicate that the baseline diesel truck costs is shown to be $80 at the 100-mile mark, versus $70 for a CNG hybrid truck driven at high speed and about $42 for a CNG hybrid truck driven at low speed. The low speed costs results are consistent with series hybrid trucks, which tend to run more economically at lower speeds, when wind resistance is lower and drive motors, as well as engines used to generate electricity, can operate near efficient speeds.

Longer-term operation of trucks using this technology will be required before meaningful conclusions can be reached about operating reliability, actual road performance, or total cost of ownership. Figure 45 shows the interior of the dyno trailer upon completion of the facility and initiation of engine calibration activities in February 2017.

Figure 45: Interior of Completed Test Cell

Source: TransPower

CHAPTER 6: Evaluation of Project Benefits

An important objective of this project was to evaluate project benefits. In accordance with Energy Commission procedures, this task involved completion of three Project Benefits Questionnaires corresponding to three main intervals in the agreement: (1) Kick-off Meeting Benefits Questionnaire, (2) Mid-term Benefits Questionnaire, and (3) Final Meeting Benefits Questionnaire. These questionnaires provided all key assumptions used to estimate projected benefits, including targeted market sector (for example, population and geographic location), projected market penetration, baseline and projected energy use and cost, operating conditions, and emission reduction calculations.

Targeted Benefits

Circulation of the Kick-off Meeting Benefits Questionnaire and general consultations with stakeholders early in the project confirmed TransPower's initial expectations regarding the benefits of CNG hybrid operation that would have the most transformational impact. Extending the range of battery-electric vehicles with the lowest possible emissions remained the benefit of strongest interest to fleet operators, environmental groups, and other key stakeholders. Achieving the highest possible fuel efficiency was second. The third priority was to provide equivalent performance to diesel trucks. This last area was a particular concern of fleet operators due to previous experiences with natural gas engines, which sometimes lacked the performance of the diesel counterparts. Along with the above benefits, TransPower's research also determined that this project would have substantial benefits if it could establish that natural gas hybrid trucks could be operated reliably and with a lower cost of ownership than conventional trucks. Collectively, these were the targeted benefits the project sought to confirm.

Calculated Benefits

TransPower's first step in confirming targeted benefits was to perform modeling and analyses to predict the benefits of combining a natural gas-driven generator with a large battery pack on Class 8 trucks. TransPower modeling and simulation tools were used to project the electricity and fuel consumption usage to operate a CNG hybrid truck for 100 miles. Data from TransPower's prior experience demonstrating battery-electric trucks were used to develop basic parameters such as estimates of battery energy use per mile. Table 5 summarizes the key input assumptions and results for a typical simulation. In this case study, a CNG hybrid truck was operated for 100 miles using an optimal combination of battery electricity and power generated from an onboard CNG engine-generator. As indicated in the lower left portion of the table, during this simulation, the truck traveled 56.9 miles using CNG and 43.1 miles on battery power to achieve the 100-mile total. In the lower right corner of Table 5, the calculated fuel use to achieve the CNG miles was 15.4 diesel gallon equivalents (DGE) of CNG. Hence, the truck was estimated to have an average fuel economy of 6.5 miles per DGE. This compares favorably with conventional natural gas trucks, which for the same weight class would typically get only 3-4 miles per DGE.

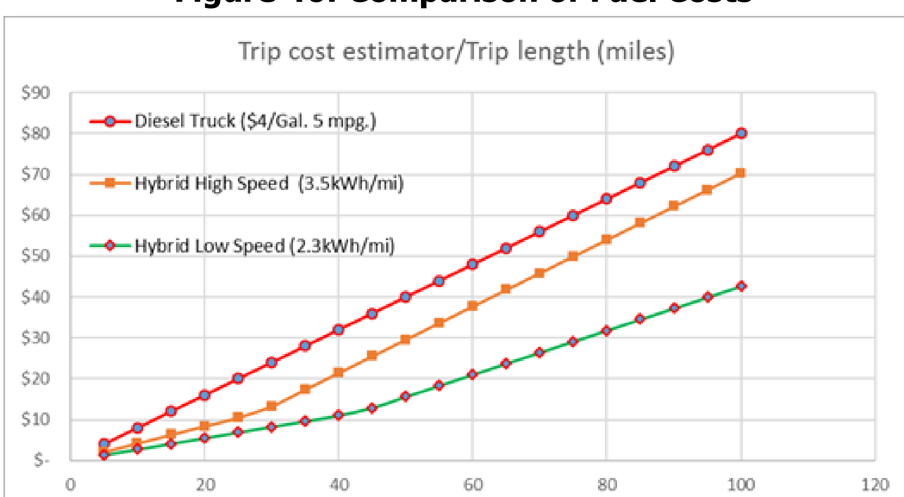
Table 5: Simulation Results

100	mile trip target		Condition		fraction	kWh/kg
2.3	kWh/mi	Low speed	1	idle	0.1	0
3.5	kWh/mi	High speed	2	22 kW	0.1	2.69
155	kWh ESS nomnal		3	60 kW	0.8	3.31
0.80	SOC avail. fraction				avg	2.92
53.9	mile range electric		Assumed			
1.00	starting SOC		Diesel MPG	5	kg CNG req	44.8
0.8	ESS DOD max.		Fuel/units	Cost/unit	scf/DGE	144
43.1	Electric miles driven		Diesel/Usgal	$ 4.00	scf/kg	49.4
56.9	CNG miles		CNG/DGE	$ 2.00	scf req	2215
131	kWh CNG required		Electricty/kWh	$ 0.12	DGE required	15.4

Source: TransPower

Other sections of Table 5 detail other key modeling parameters, such as APU power levels, battery state of charge, and assumed costs for diesel fuel, CNG, and electricity. Based on these parameters, the total cost of performing the 100-mile trip was estimated for a representative diesel truck, CNG truck, and CNG hybrid truck. The results of this comparison are summarized in Figure 46 and are sensitive to assumption.

Figure 46: Comparison of Fuel Costs



Source: TransPower

As indicated, the cost of driving the diesel truck is shown to be $80 at the 100-mile mark, versus $70 for a CNG hybrid truck driven at high speed and about $42 for a CNG hybrid truck driven at low speed. This phenomenon is not unusual for series hybrid trucks, which tend to run more economically at lower speeds, when wind resistance is lower and drive motors, as well as engines used to generate electricity, can operate near efficient speeds.

These results were largely confirmed by dynamometer testing later in the project and by the limited number of driving miles achieved with the catenary CNG hybrid truck. Further testing of this truck, as well as test driving of TransPower's two new CNG hybrid trucks, will eventually provide more definitive data on whether these kinds of benefits can be achieved in real-world operation.

Regarding the other targeted benefits, dynamometer testing as well as driving of the catenary CNG hybrid truck have confirmed production of up to 66 kW of power with the CNG-fueled APU, and eventual upgrading of the stationary trim engine configuration with automotive injectors and controls is expected to boost continuous power to 80 kW and peak power output to 110 kW. While this will not likely be sufficient for extended freeway operation, for extending the range of locally driven trucks, it is expected to be adequate. Longer-term operation of trucks using this technology will be required before meaningful conclusions can be reached about operating reliability, actual road performance, or total cost of ownership.

Future work on this architecture of CNG range extension of electric trucks will be performed near the end of Contract Number 16046 for the two range-extended hybrids funded under that program with the SCAQMD. The first of these is operational, and the second will be by the end of this year. The primary objective of the chassis dynamometer work and APU engine tuning stipulated in that contract is to make progress toward acceptable emissions, particularly NO_x, as this "small" APU design approach moves from the 3.7 L Ford CNG in stationary generator trim to that same engine sporting manifold injection and variable-valve timing, as used in the emission-compliant automotive applications. Table 6 shows measured emissions for the worst-case operation of a stationary-trim 3.7 L engine at the RPM limit on a hot day, with fixed-valve timing. These data were generated as a baseline for comparison to fully tuned emissions measurements to come, and required mobile emissions testing to be performed in the field by a UC Riverside Center for Environmental Research and Technology(CE-CERT) team.

Table 6: Base Stationary Engine Emission Results

Test Index	Test Condition			Emission Rates g/KWhr			
	rpm	%Torque	power kw	NOX		PM	
#		Nominal	Measured	AVE	STD	AVE	STD
3	1400	42%	12	4.93	0.6	0.000	0.000
4	1400	75%	24	13.9	1.6	0.001	0.000
5	2100	65%	25	12.8	0.5	0.002	0.001
6	2400	65%	31	10.6	0.3	0.001	0.000
8	2400	85%	41	0.2	0.2	0.005	0.003
16	2900	100%	62	8.4	3.6	0.004	0.002
17	2900	75%	52.7	2.9	0.6	0.000	0.000
18	2900	66%	42.7	0.9	0.7	0.004	0.006
19	2900	100%	62	12.4	3.4	0.003	0.002
20	2900	80%	54	6.9	0.4	0.001	0.000
21	2900	70%	45	5.1	1.7	0.001	0.000
22	2900	50%	32	0.2	0.2	0.001	0.000
23	1400	67%	20	12.4	1.1	0.000	0.000
24	1400	50%	15	9.3	1.0	0.000	0.000
26	2600	100%	55.7	3.9	2.1	0.009	0.003
27	2600	90%	51.5	3.8	1.3	0.001	0.001
28	2000	60%	25.6	10.8	4.3	0.000	0.000
29	2900	25%	15.7	4.0	1.0	0.002	0.001
30	2900	10%	4.4	2.9	1.4	0.002	0.001
31	2900	25%	15.7	4.1	1.2	0.002	0.001
32	2900	10%	4.4	2.0	0.7	0.001	0.000

Source: TransPower

The work completed under this Energy Commission grant led to fuel injection and spark timing control code and sensor integration that are ready for the addition of valve-train control code and a few operational protection features before the project can be refined on the dynamometer in real time using emissions values measured at CE-CERT. Such refinement is expected to greatly reduce emissions, particularly NO_x, as feedback from equipment beyond that developed and available at TransPower is used to provide calibration feedback.

GLOSSARY

Term	Definition
Automated manual transmission (AMT)	A type of transmission that uses a computer-controlled manual transmission to enable high performance across a broad range of duty cycles with a low-cost drive motor, with unprecedented efficiency.
Auxiliary power unit (APU)	The APU is an onboard power generator that augments the battery energy storage system in a hybrid vehicle. The type of APU developed under this project uses a natural gas engine mated to a permanent magnet generator to produce electricity.
Catenary power source	A catenary power source uses an overhead power line, also known as a "catenary" line, to produce power for a moving vehicle.
Commissioning	Commissioning is the process of validating the functionality of all the components in a newly built vehicle and test driving the vehicle to the point where it is roadworthy and ready for extended testing or service.
DC-to-DC converter	A DC-to-DC converter is a device that converts DC power on board a vehicle from one voltage to another. For example, a DC-to-DC converter might convert 800 volts produced by a catenary power source to the 400 volts required by the drive motors on a catenary-powered truck.
Dynamometer	A dynamometer is a piece of test equipment used to run an engine or a generator for testing. Typically, the dynamometer will include a source of power as well as a way to dissipate power from the engine or generator being tested.
Inverter-charger unit	In the TransPower electric drive architecture, the inverter-charger unit combines the functions of inverter and battery charger, allowing the truck batteries to be recharged using grid power, without a separate charger.
Regenerative braking	Regenerative braking is the process of recovering braking energy from vehicles as they decelerate and storing the energy in the battery pack of the vehicle for future use.
Supervisory control and data	A supervisory control and data acquisition (SCADA) system monitors a complex system consisting of many elements and provides a user interface that enables an operator or observer to understand the status of all the system components in real time. A

Term	Definition
acquisition (SCADA)	SCADA also generally has the capability to store data for future review and analysis.
PXI	PXI is a computer hardware designed for measurements and automated systems in rough environments.
CAN communication	Control Area Network is a wiring system that connects various devices so they can communicate
SOC	State f Charge is in reference to the energy level of an electric battery.
CE-CERT	College of Engineering - Center for Environmental Research and Technology

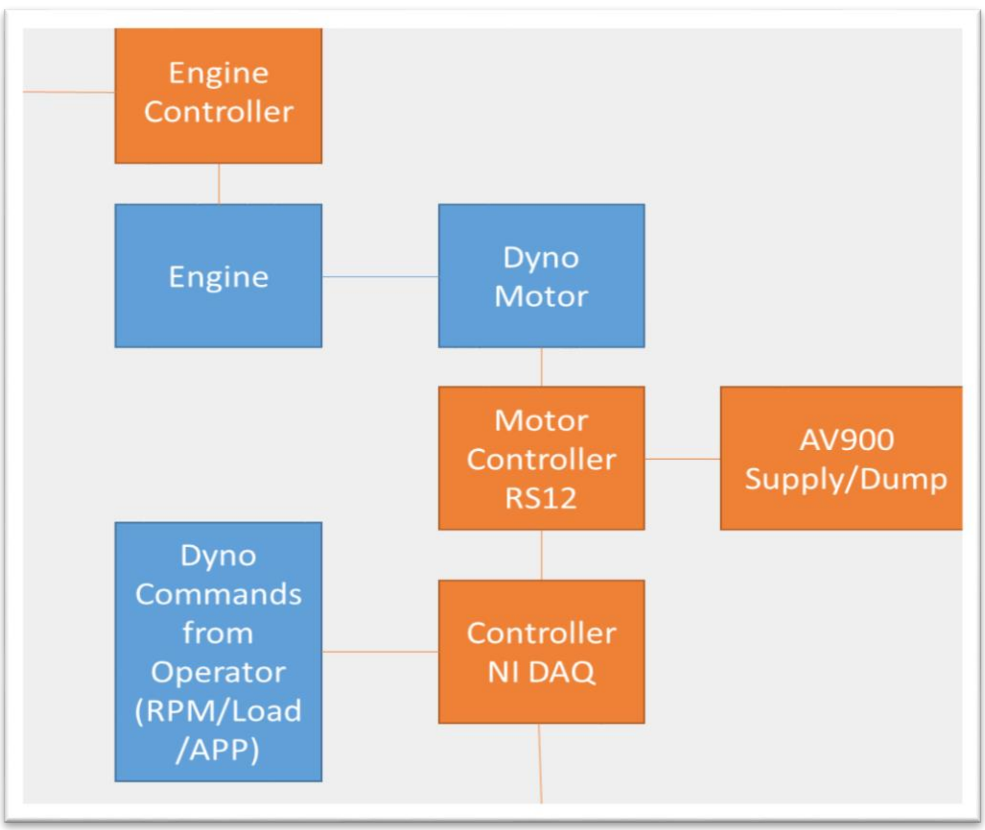
APPENDIX A:
Draft Commissioning Plan

This draft commissioning plan includes planned steps to stage commissioning from the test cell level through the level of the completed vehicle.

Dyno Test Cell Commissioning

The dyno test cell is regulated in operation by a sophisticated supervisory control and data acquisition system developed by TransPower. The system uses LabVIEW to communicate with the TransPower-created engine controller and the attached engine state sensors over CAN, and with various digital and analog devices throughout the dyno test cell. These devices include thermocouples to monitor exhaust temperatures, CNG flow meters, HV and LV power regulation and safety systems, simple gas analyzer instrumentation, and the various safety and alert systems in the test cell. The block diagram for the SCADA portion dedicated to APU test unit control shown in Figure A-1.

Figure A-1: SCADA System Block Diagram



Source: TransPower

Engine Commissioning

Engines arrive pretested from the factory, and engines and supporting components are ready to integrate into the APU subsystem. Engine commissioning is accomplished as part of the APU subsystem commissioning process of the next section.

APU Subsystem Commissioning

This document reflects automated testing and reporting methods that TransPower is developing for the calibration, test, and reporting quality functions of current and future subsystems commissioning. The APU is one such subsystem.

Figure A-2: Commissioning Steps for the CNG APU in Test Cell

Step	Description
1	Position cradle in test area according to the marks on the floor or the position ball hanging from the cable tray. Make sure all supply and return lines reach their hook-up locations.
2	Use dispenser and fill engine with engine oil (15W40). Use dipstick to ensure proper oil level.
3	Go through the system and inspect that all electrical connectors are properly connected, hose clamps are tightened and fasteners are torque-sealed.
4	Connect the ground adaptor and the 12V adaptor to the cradle and ensure the wire doesn't touch the frame. Plug first the ground cable than the 12V cable in the adapter.
5	Connect the cradle interface connector (located next to the Busman box)
6	Connect the high voltage cable to the energy storage system interface.
7	Turn the ignition of the test stand on, the contactors on the test stand should click
8	Open the Cradle Test Software CTS, and start the application. Check if the test stand is online. The **'Test Stand ON'**-light and the **'Charger ON'**-light should be on.
9	Switch on the ignition of the cradle. Wait until the cradle wakes up. Verify that the cradle is online. The '**DNR**'-light should be flashing, and there should be temperature readings from the engine.
10	Verify the settings on the ECU.

Step	Description
11	With ignition on click on **'Connect to ECM'** wait until the prompt window…. Comes up. Quit with **'Cancel'**. The program is going to ask you if you want to safe the session. Click OK.
12	Click on **'Features and Parameters'**. It gives you a list of all Parameters.
13	Verify that the LED on the surge tank fill neck is off. Start filling coolant in the surge tank using the coolant deepener of the test station.
14	Verify that the transfer pump comes on after a couple of seconds. Keep filling.
15	Watch the **'Engine Reservoir Full'**-light. It should come on after a while. Verify that the solenoid clicks when the light comes on.
16	Watch the **'Electronics Reservoir Full'**-light. It should come on next. Keep filling the surge tank until the LED turns on.
	Switch **'Electronics Pumps'** on to circulate the coolant into the system. If the transfer pump goes on and the LED goes off fill more coolant in surge tank until system is completely filled.
18	If the system filled properly, check the box on the Inspection List.
19	Check the whole system for leaks. Check the **'Mechanical Inspection'**- check box on the Inspection List if the system is inspected and released from QA.
20	If the fuel lines are properly attached and all connections are tight, check the corresponding box on the Inspection List.
21	Fill out serial number, drive system number and operator name on the Inspection List.
22	Start Test Automation System and make sure that the ECU and the inverters are online and properly configured. If the ECU is online and CAN is working. Check the box in the Inspection List.
23	In Test Automation System check the temperature readings for generator, motor. Select the component and open up the data list. Verify that the Mot_Temp reads room temperature. Insert the value on the Inspection List.

Step	Description
24	Select motor. Watch the rpm changing as you engage the 12V starter. If it changes the motor speed feedback works. Check the box on the Inspection List.
25	Check the compartment temperature, it should read room temperature. Click '**Update Data**' to insert the next four values. Check if reasonable.
26	Check inverter error codes. Open up the diagnostic window in Test Automation System. Select the components one by one and verify that there is no error.
27	Verify the fan functionality by requesting fan power. Verify that fans spin in the right direction.
28	Switch on the exhaust evacuation blower.
29	Make sure nobody is around the cradle and then press and hold **'Engine Start'** until the engine starts up. It should take not more than a few seconds. Let the system charge up. Wait for **'System Ready'** indicator.
30	If everything works normal put the system in test mode and charge at 30 kW to warm up. Wait until the engine coolant temperature reaches 80°C minimum, then switch off test mode.
31	Stop and restart. Start the Run Test by starting the engine. Wait for the **'System Ready'** indicator.
32	Turn off ignition. Press **'Match Voltages'**. Turn ignition back on and start the engine. The generator voltage should match the energy storage voltage after a few seconds.
33	Put the cradle in test mode by clicking on the **'Test Mode'** button. Request 50kW with the power slide. Make sure the generator output power is 50kW and request 100 kW. Wait for the test mode check box to be checked than bring the power back to zero.
34	All check boxes on the Test- and the Inspection List should be checked. Press **'Print Report'**. Name file according to serial number. Adobe Acrobat should open and display a test report. Go through and verify that all items are passed. Print the report sign it and put it with the cradle documentation. Save PDF file on: C:\Quality Assurance\Test Data\Cradle\CNG.

Step	Description
35	Repeat complete test sequence two more times, then read back error codes from the inverter system in Test Automation System and check all alarms on the ECU. Finally clear all error codes.
36	Turn off the ignition and the main switch of the Test Station. Disconnect the energy storage on the energy storage side. Disconnect the 12 V and the cradle interface connector. At last disconnect ground!
37	Carefully turn off the CNG valve and then disconnect the fuel lines.
38	Disconnect the exhaust: CAUTION: The exhaust is hot, it may have to cool down.

Vehicle commissioning

Figure A-3: The Test Cell I/O Definition Table for the SCADA

NAME	UNITS	DATA	DESCRIPTION	FULL DYNO 1065 EMISSION	TRANS POWER CNG	NUMBER IN KEY	Range	Low Limit	High Limit	Location	Sensor PN
3rakePow	kW	Raw	Brake pow	X	X	21	0-160	-10	165	?	
3rakeTorc	Nm	Raw	Brake torc	X	X	27	0-25		25	?	
dCO2CVS	%vol	Raw	Dry exhau	X		99					
dCO2E2	ppm	Raw	Dry exhau	X		85					
dCOCVS	ppm	Raw	Dry exhau	X		98					
dCOE2	ppm	Raw	Dry exhau	X		82					
dCOHE2	ppm	Raw	Dry exhau	X		84					
dCOLE2	ppm	Raw	Dry exhau	X		83					
DiluteStat	Text	Raw	Dilute em	X		9					
dNOxCVS	ppm	Raw	Dry exhau	X		97					
dNOxE2	ppm	Raw	Dry exhau	X		81					
dO2E2	%vol	Raw	Dry exhau	X		86					
DynoSpee	rev/min	Raw	Dynamom	X	X	19	0-6500	-1	6700	?	
DynoSpee	rev/min	Raw	Dynamom	X	X	23	0-6500			?	
DynoTorq	Nm	Raw	Brake torc	X	X	20	0-400			?	
DynoTorq	Nm	Raw	Brake torc	X	X	24	0-400			?	
EGRdCO2E	%vol	Raw	Dry intake	X		87					
EngineHo	h	Raw	Engine ho	X		4					
FilterFlow	m³/s	Raw		X		105					
FTIR_Dire	%vol	Raw	FTIR CO2 c	X		7					
FTIR_Dire	ppm	Raw	FTIR N2O (	X		5					
FTIR_Dire	ppm	Raw	FTIR N2O (	X		94					
FTIR_Dire	ppm	Raw	FTIR NH3 c	X		6					
FTIR_Dire	ppm	Raw	FTIR NH3 c	X		93					
FTIR_Dire	%vol	Raw	FTIR NOx (	X		8					
FuelDensi	kg/m³	Raw	Diesel fue	X		10					
gAirIntake	kg/h	Raw	Intake air	X	X	70	0-1000		900	?	
gFuel	kg/s	Raw	Diesel fue	X		14					
gNaturalG	kg/h	Raw	Natural ga	X	X	16	0-100		50	?	
IntakeAirI	%	Raw	Intake air	X		67					
IntakeRH	%	Raw	Intake air	X	X	66	0-100			?	
Mode	Text	Raw	Dynamom	X		28					
pabsAirM	kPa	Raw	Laminar fl	X		69					
pabsBaro	kPa	Raw	Barometri	X	X	63	80-120			?	
PdiffAirm	kPa	Raw	Laminar fl	X		68					
pFuel	kpa	Raw	Fuel press	X	X	105	100-1200	400	1000	?	
pgAirIntak	kPa	Raw	Combusti	X	X	52	100-350			?	
pgChrgCo	kPa	Raw	Charge co	X		56					
pgChrgCo	kPa	Raw	Charge co	X		58					
pgCompO	kPa	Raw	Compress	X		53					
pgCoolant	kPa	Raw	EGR coole	X		77					
pgCoolant	kPa	Raw	EGR coole	X		78					
pgCoolant	kPa	Raw	Coolant in	X	X	89	100-350		140	?	
pgCoolant	kPa	Raw	Coolant o	X	X	91	100-350		25	?	
pgCrankca	kPa	Raw	Crankcase	X	X	45	100-150	0	25	?	
pgEGRCoo	kPa	Raw	EGR coole	X		75					
pgEGRCoo	kPa	Raw	EGR coole	X		76					
pgExhDov	kPa	Raw	Exhaust d	X	X	37	100-350		125	?	
pgExhMar	kPa	Raw	Exhaust m	X	X	35	100-350		125	?	
[illegible]	kPa	Raw	[illegible]	X		[illegible]					

Source: TransPower

Figure A-4: Commissioning Inspection for APU Generator Unit Serial #001

Inspection action		Value	Result
Mechanical inspection report		N/A	Pass
Inverter CAN communication		N/A	Pass
ECM CAN communication		N/A	Pass
ECM software version		-exp-	Pass
Generator unit temperature sensor		0-5	Pass
Generator unit speed feedback		N/A	Pass
Compartment temperature		0-5	Pass
Engine cooling reservoir level sensor		N/A	Pass
Check fuel lines		N/A	Pass
Ambient temperature		0-5	Pass
Engine temperature		0-5	Pass
Inverter temperature		CAN	Pass
Operator	Matt Vito	TransPower	

Source: TransPower

APPENDIX B: Photos of Test Cell Dynamometer

This section provides photo-documentation of the development of the engine dynamometer test cell capability developed to support engine and APU control code development and to verify CNG engine operation.

Test Cell Components

Dynamometer Test Cell Enclosure

The dyno test cell is a stand-alone, outdoor test device enclosed in a shipping container. Use of the shipping enclosure controls personnel access, provides security, and enhances safety. External views of the shipping container adjacent to the TransPower Headquarters Building are show in Figure B-1.

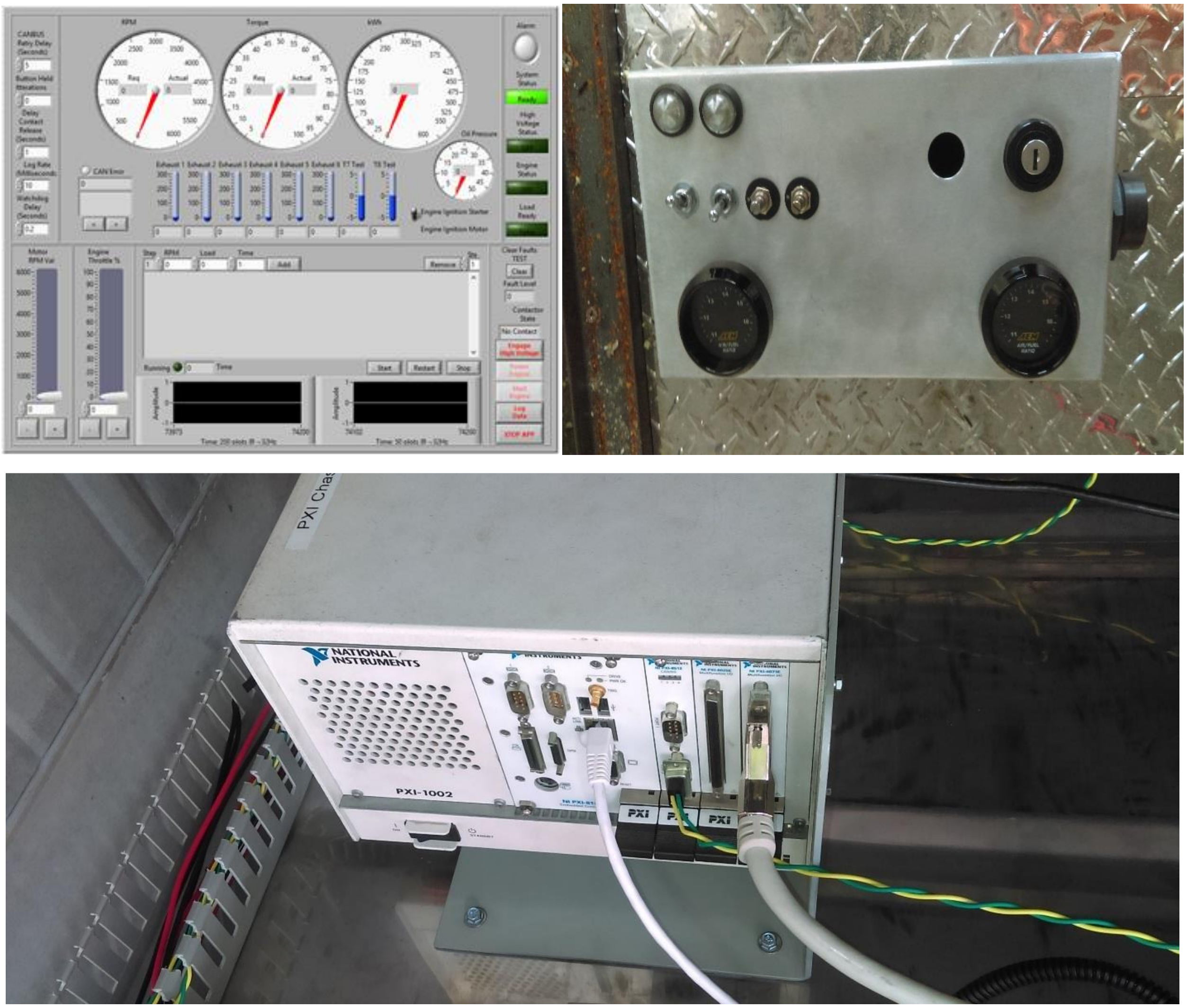
Figure B-1: Dyno Test Cell Enclosure

Source: TransPower

Dynamometer Test Cell Controls and SCADA Hardware

Controls and the SCADA system are depicted in Figure A-1 and provide for remote operation and monitoring, as well as local manual override and intervention. These both connect to a NI-PXI chassis that operates inside the enclosure, as shown in Figure B-2.

Figure B-2: A Physical HMI Has Been Fabricated to Supplement the Virtual HMI Control



Source: TransPower

The PXI has been mounted to the trailer wall and harnessed to the breakout board. The PXI will act as the primary controller for the dyno operation.

CNG Storage, Measurement, and Controls

Custom CNG storage was required for this project. TransPower purchased stock pressure vessels and fill port from Agility through its TAC partner Westport Cummins. In addition, TransPower installed an elite CNG gas flow meter to produce calibration data for fuel flow measurement used to verify CNG APU efficiency. Figure B-3 shows the various components of the CNG containment and metering controls.

Figure B-3: CNG Storage Measurement and Controls Components in Test

Source: TransPower

APU Assembly in Test

The APU assembly in the dyno test cell has a welded steel base feature that mimics the one used in the range extending truck designs. Figure B-4 shows the APU assembly from the radiator side, as it mounts on rails to the floor of the shipping container/test cell enclosure.

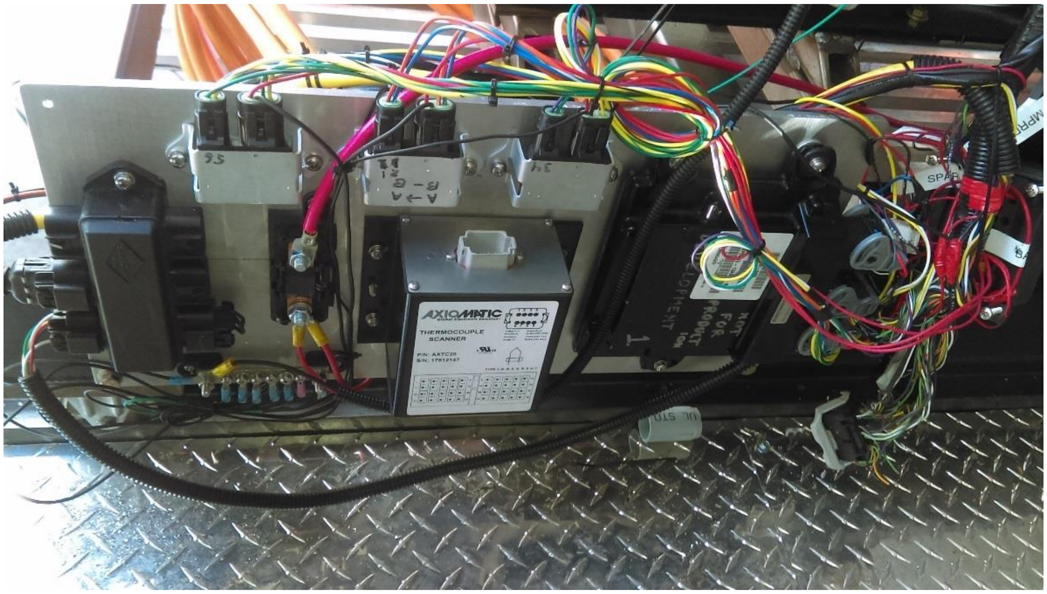
Figure B-4: APU Assembly in Test

Source: TransPower

APU Low Voltage Control Electronics

The low-voltage electronics in the dyno are assembled in a more open way than on the truck-mounted APUs that followed. These electronics provide SCADA control over the engine and CNG measurement functions. Engine control unit, APU subsystem control unit, CAN communication bus and various signal conditioning devices are shown in Figure B-5.

Figure B-5: APU Low-Voltage Electronics



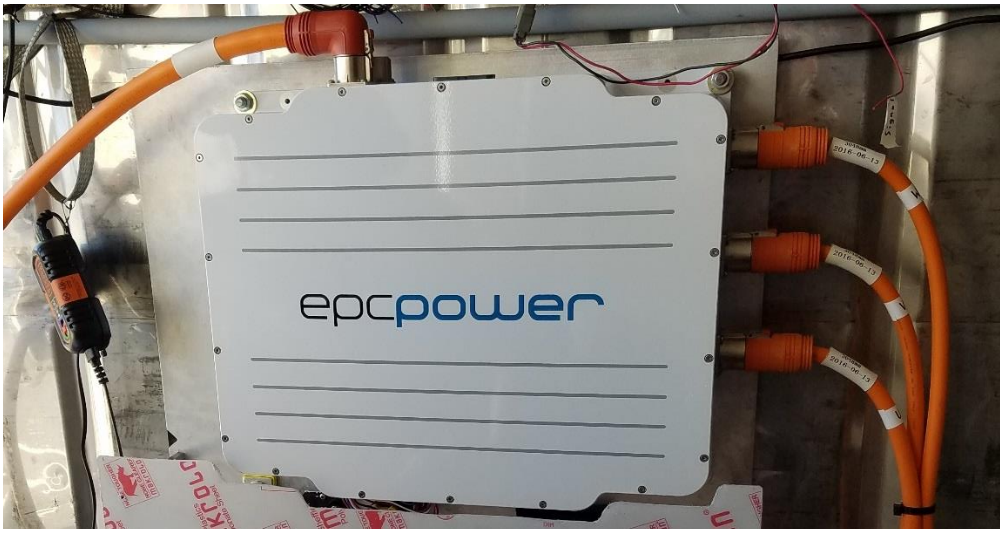
Source: TransPower

The APU control plate has been populated with controls that are better placed close to the engine. The engine harness has been attached to and tested through this control plate.

APU control inverter and power electronics

The APU inverter, used to regulate the generation of electricity within the APU, is shown in Figure B-6. Control wiring and power cabling are also shown in high-voltage orange.

Figure B-6: High Voltage Inverter and Power Electronics

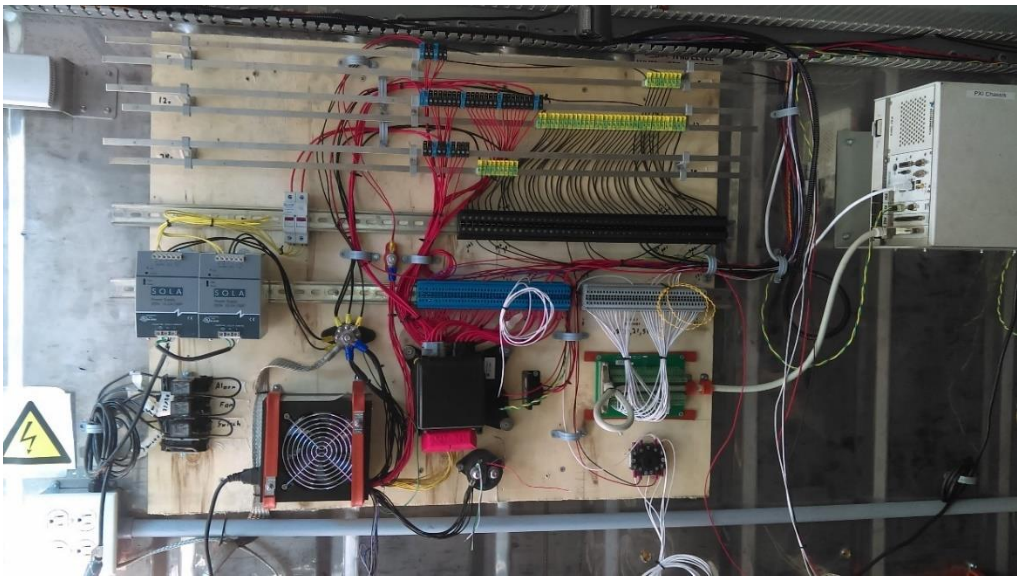


Source: TransPower

Test Cell Low-Voltage Supply and Controls

The low-voltage control features for the test cell are shown in Figure B-7. These provide for coordinated operation and safety of the various pumps, fans, relays, and power supplies needed to operate the APU logic and interlocks.

Figure B-7: Low Voltage Control of Components for the Test Cell



Source: TransPower

High-Voltage Supply and Controls

Pre-charge, ESS connect, and instrumentation are important parts of the high-voltage control. These are shown below the inverter as pictured in Figure B-8, and provide functions for the safe regulation of high-voltage power supplied to the test cell from the AV-900 industrial grade power supply TransPower has installed within the building. The AV-900 simulates the behavior and response of a vehicle high-voltage battery pack.

Figure B-8: High-Voltage Supply and Controls

Source: TransPower

Ventilation and Exhaust Routing Systems

Exhaust routing is shown through a chimney pass-through in the roof of the enclosure in Figure B-9.

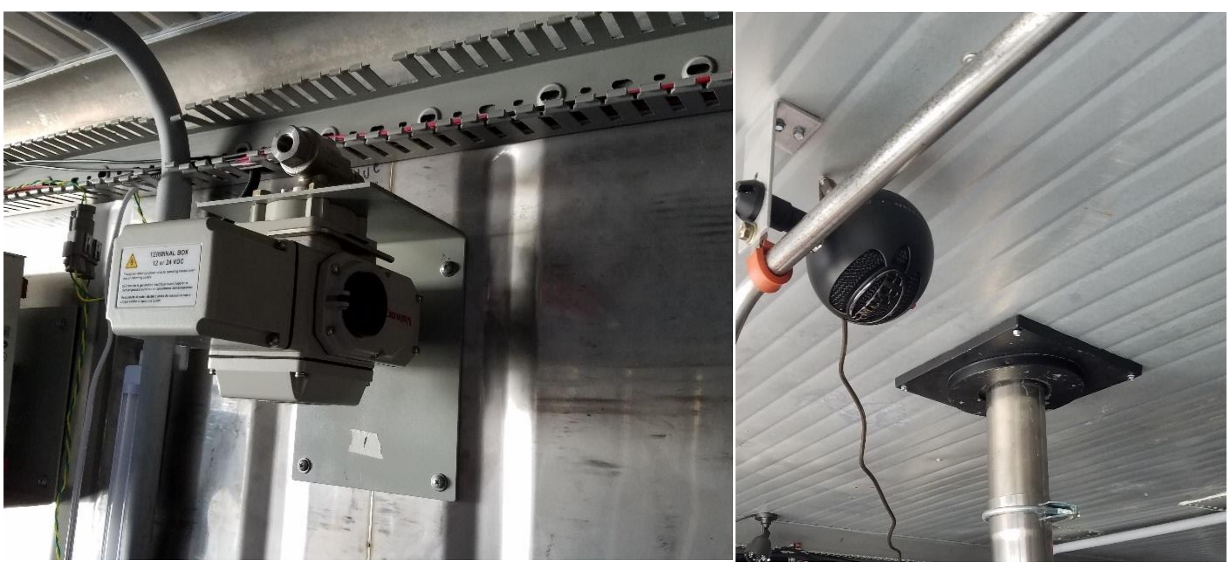
Figure B-9: Exhaust and Fresh Air Control Aspects of Test Cell Design

Source: TransPower

Safety Systems

CNG leak detector, fire sensor, fire retardant system, interlocks and other items are included in the design of the test cell. Figure B-10 shows the CNG leak sensor along with a camera and microphone unit for remote monitoring and SCADA coordination.

Figure B-10: Safety Systems Installation



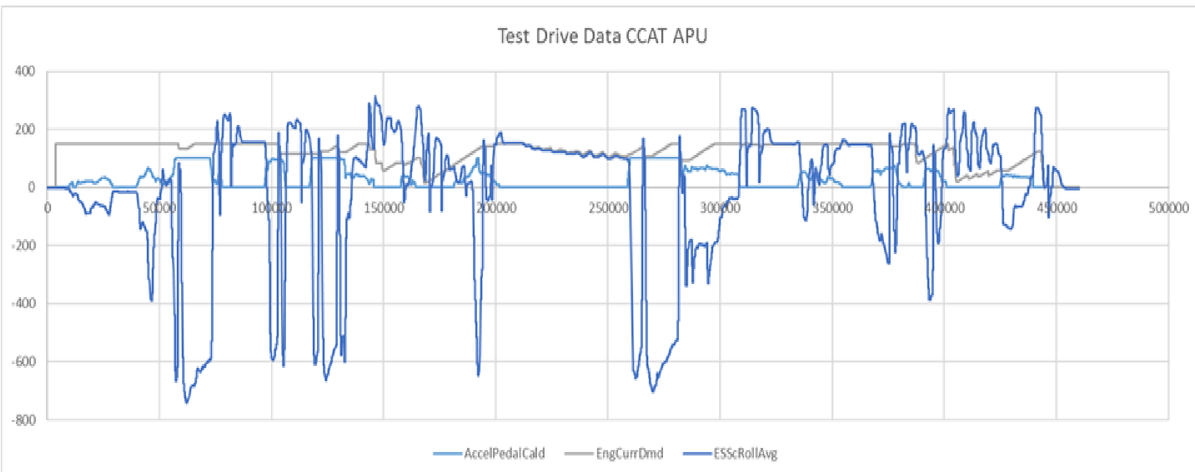
Source: TransPower

APPENDIX C: Draft Hybrid System Test Report

Drive Function Verification Testing

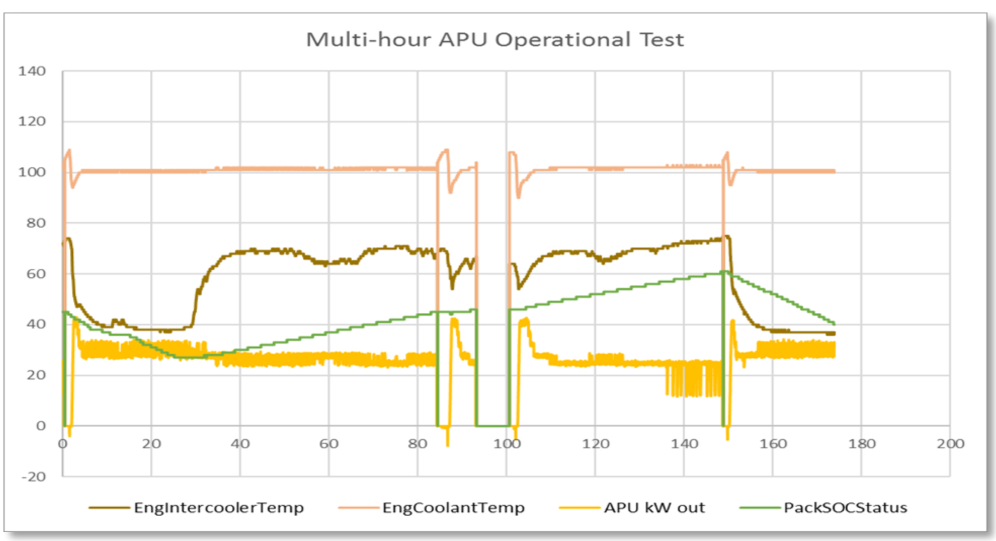
Sample raw vehicle performance data are shown in Figure C-1. This depicts a multi-hour drive from the San Diego region to Carson, CA and the DC link power in propulsion and APU generation during that drive. Thermal limit testing for the APU is depicted in Figure C-2.

Figure C-1: Select Graph of Propulsion and APU Data is Shown as Plot



Source: TransPower

Figure C-2: Select Graph of APU Thermal Limit Data is Shown as Plot



Source: TransPower

Fuel Consumption Testing

Fuel consumption testing results for the stationary-trim engine APU as measured by TransPower on the CCAT test truck in operation is shown in Figure C-3. These figures compare well with micro-turbines and other small generator sets, and match earlier modeling assumptions use in vehicle system design. TransPower's additional development of proprietary engine control software is expected to improve on these efficiency figures especially at higher power output levels.

Figure C-3: Fuel Consumption Measurement for the First Article APU

RPM	Load (%)	APU Output (kW)	Engine Temp. (.C)	Minutes	kWh/kg	Eff.
1000	0	0	16	14.13	0	0
1000	0	0	90	20.25	0	0
1400	75	22.4	89	2.48	1.85	0.14
1400	75	22.5	95	3.58	2.69	0.20
2850	90	59	98	1.68	3.31	0.25
2900	100	62	N/A	N/A	N/A	N/A
CNG diesel gallon equivalent (DGE). – 1 DGE = 6.384 pounds (2.896 kg) of CNG or CNG diesel liter equivalent (DLE). – 1 DLE = 0.765 kilograms (1.687 pounds) of CNG.						

Source: TransPower

Mobile Emissions Testing

Raw mobile emissions testing data for the stationary-trim engine APU as measured by contractor UC Riverside/CE-CERT are shown below in table C-4 and C-5. A team from UCR/CE-CERT traveled to TransPower headquarters in Escondido and performed testing on APU exhaust gases at several power levels while the vehicle was generating power for storage in its battery pack. Emissions on this hot day were higher than expected in the NOx category, and this is to be expected in the stationary trim engine at the limiting power levels dictated by its engine control software. The new software and controls approach Transpower is developing should address this excessive NOx thorough active valve control and better mixture control afforded by the port-injection included in the automotive-trim package engine.

Figure C-4: Emissions Test Conditions and Raw Data

Test Index	Test Condition				Wet Concentration NTK							
	rpm	%Torque	power kw		NOX (ppm)		O2 (%)		PM (mg/m3)		ExhaustFlow (kg/hr)	
#		Nominal	Measured	Adjusted	AVE	STD	AVE	STD	AVE	STD	AVE	STD
1		Zeroing EFM										
2	1000	0	0	6.90	5.9	8.8	2.30	0.66	0.04	0.25	31.9	5.6
3	1400	42%	12	22.02	679.8	82.5	1.12	0.21	0.12	0.12	99.7	11.4
4	1400	75%	24	34.38	1734.8	199.2	1.27	0.11	0.34	0.07	171.8	15.9
5	2100	65%	25	40.23	1716.8	73.4	0.52	0.18	0.59	0.16	186.6	5.4
6	2400	65%	31	48.48	1729.2	55.2	0.78	0.07	0.25	0.01	186.2	2.4
7	2100	85%	35	50.53								
8	2400	85%	41	58.78	28.6	20.7	-0.26	0.16	1.34	0.71	286.5	53.4
9	1400	0	0	9.66	3.6	6.5	2.02	0.09	0.20	0.02	57.3	1.0
10	1600	0	0	11.03	19.3	6.0	1.83	0.05	0.07	0.02	50.9	2.0
11	1800	0	0	12.41	46.7	6.2	1.55	0.04	0.04	0.01	53.9	3.6
12	2000	0	0	13.79	53.8	8.1	1.61	0.09	0.03	0.01	66.1	1.7
13	2400	0	0	16.55	70.2	11.6	1.44	0.06	0.02	0.01	67.1	3.3
14	2600	0	0	17.93	112.0	22.8	1.07	0.07	0.03	0.01	92.0	5.0
15	2800	0	0	19.31	142.8	11.6	1.50	2.35	0.09	0.04	100.8	18.6
16	2900	100%	62	83.86	1099.5	473.3	-0.13	0.02	0.97	0.58	401.1	60.2
17	2900	75%	52.7	74.28	353.9	69.8	-0.98	0.13	0.07	0.02	380.7	15.6
18	2900	66%	42.7	63.98	163.7	139.6	8.67	10.16	1.32	2.04	215.7	144.7
19	2900	100%	62	83.86	1616.0	443.1	0.35	0.69	0.84	0.40	402.0	19.8
20	2900	80%	54	75.62	838.8	51.0	-0.94	0.14	0.18	0.08	387.7	3.0
21	2900	70%	45	66.35	589.7	196.0	-0.71	0.14	0.12	0.01	355.8	1.1
22	2900	50%	32	52.96	18.9	23.5	0.09	0.85	0.18	0.03	285.0	2.1
23	1400	67%	20	30.26	1383.0	121.8	1.20	0.10	0.04	0.00	169.0	1.1
24	1400	50%	15	25.11	1031.6	107.5	1.48	0.13	0.06	0.01	141.6	0.8
25	1000	0	0	6.90	23.4	36.5	2.70	0.38	0.05	0.00	36.1	0.5
26	2600	100%	55.7	75.30	534.8	294.3	-0.50	0.46	2.34	0.80	340.8	11.5
27	2600	90%	51.5	70.98	466.3	159.7	-0.62	0.54	0.20	0.14	358.3	6.3
28	2000	60%	25.6	40.16	1403.3	559.7	0.46	0.42	0.03	0.00	192.5	18.9
29	2900	25%	15.7	36.17	578.9	150.8	0.19	0.23	0.65	0.24	157.0	7.7
30	2900	10%	4.4	24.53	358.3	177.1	0.54	0.28	0.37	0.32	124.2	0.6
31	2900	25%	15.7	36.17	542.0	160.6	0.17	0.26	0.62	0.25	171.9	8.2
32	2900	10%	4.4	24.53	240.7	84.4	2.92	6.26	0.20	0.05	129.1	0.6

Source: TransPower

Figure C-5: Emission Rate Results and Notes from Testing

Emission Rates g/KWhr							Comment
	NOX		PM		PN		
AVE		STD	AVE	STD	AVE	STD	
							08:42:10 warm up NTK. Time aline EFM computer with NIST time. Turn off EFM auto zero after zeroing the EFM in the morning.
4.9	4.93	0.6	0.000	0.000	2.19E+03	2.16E+03	
13.8	13.9	1.6	0.001	0.000	6.85E+03	1.34E+03	
12.7	12.8	0.5	0.002	0.001	1.09E+04	2.98E+03	
10.6	10.6	0.3	0.001	0.000	3.87E+03	1.66E+02	Engine had fault code
							Load not stable data values not reported.
0.2	0.2	0.2	0.005	0.003	2.62E+04	1.38E+04	
	0.0						
	0.1						
	0.3						
	0.4						
	0.5						
	0.9						
	1.2						
8.4	8.4	3.6	0.004	0.002	1.86E+04	1.11E+04	
2.9	2.9	0.6	0.000	0.000	1.45E+03	3.24E+02	
0.9	0.9	0.7	0.004	0.006	1.79E+04	2.78E+04	12:54:08 Stop testing due to battery issue, 13: 50 restart test.
12.3	12.4	3.4	0.003	0.002	1.62E+04	7.78E+03	
6.9	6.9	0.4	0.001	0.000	3.73E+03	1.68E+03	
5.0	5.1	1.7	0.001	0.000	2.57E+03	2.12E+02	
0.2	0.2	0.2	0.001	0.000	3.86E+03	7.33E+02	
12.3	12.4	1.1	0.000	0.000	9.77E+02	7.88E+01	
9.3	9.3	1.0	0.000	0.000	1.26E+03	1.92E+02	
	0.2						
3.9	3.9	2.1	0.009	0.003	4.25E+04	1.46E+04	
3.8	3.8	1.3	0.001	0.001	4.04E+03	2.75E+03	
10.7	10.8	4.3	0.000	0.000	4.95E+02	8.28E+01	14:24:10 stop data logging
4.0	4.0	1.0	0.002	0.001	1.14E+04	4.10E+03	
2.9	2.9	1.4	0.002	0.001	7.48E+03	6.42E+03	
4.1	4.1	1.2	0.002	0.001	1.19E+04	4.82E+03	
2.0	2.0	0.7	0.001	0.000	4.18E+03	1.15E+03	

Source: TransPower

APPENDIX D: Technology/Knowledge Transfer Plan

This Technology/Knowledge Transfer Plan is a concise summary of TransPower's plans for disseminating technology and knowledge resulting from the Natural Gas Plug-In Hybrid Class 8 Truck (NGPH-8) project. Key elements of this plan include:

- Updating the Fact Sheet submitted with TransPower's original proposal and disseminating the Fact Sheet at meetings and on TransPower's website.
- Organizing a Technology Advisory Committee (TAC) and convening periodic meetings of the TAC to obtain advice and share relevant knowledge with the TAC members.
- Identifying intended use(s) for and users of the project results.
- Identifying how the knowledge gained from the project will be made available to the public, including the targeted market sector and potential outreach to end users, utilities, regulatory agencies, and others.
- Tracking relevant activities such as technical papers published and identification of different websites containing related information.

The following subsections briefly describe planned efforts in these areas.

NGPH-8 Fact Sheet

An initial Fact Sheet was submitted with TransPower's proposal in mid-2014. At the end of the project, a Final Fact Sheet will be prepared, which will be updated to reflect the results of this three-year project. A copy of the Final Fact Sheet will be posted on TransPower's website following approval by the Energy Commission.

Technology Advisory Committee

A Technology Advisory Committee (TAC) will be formed at the start of the project. Project plans will be reviewed with selected TAC members individually as TransPower deems appropriate during the project, and conference calls will be held involving the TAC as a group at key junctures, such as to review Critical Project Review (CPR) presentations or to participate in CPRs themselves. TAC members will also be invited to review and comment on TransPower's Final Report for the NGPH-8 project in parallel with review of the report by the Energy Commission.

Intended Uses and Users of Project Results

Intended uses of the NGPH-8 project include: (i) demonstrating the viability of using natural gas as an adjunct to electric propulsion to improve the efficiency or reduce the emissions of Class 8 trucks and other large vehicles; (ii) helping to develop strategies for optimizing the performance of vehicles using natural gas; and (iii) determining the extent to which the emissions of clean-burning natural gas engines can be further reduced by using them in conjunction with electric propulsion. A key part of this activity is to understand the sensitivity of natural gas engine performance and emissions characteristics to different duty cycles in large trucks, through performance of simulations, followed by dynamometer testing, and ultimately with operation of trucks in real-world operating conditions using natural gas engines in conjunction with electric propulsion.

Intended users of the NGPH-8 project include a wide variety of stakeholders with potential interests in the viability of using natural gas as an adjunct to electric propulsion in Class 8 trucks and other large vehicles. These stakeholders include:

- Truck owners and fleet operators
- Major utilities
- CNG and CNG equipment suppliers
- Engine manufacturers
- Air quality and energy efficiency agencies
- Electric vehicle technology providers
- Research institutions involved with natural gas engine technology

The Technology/Knowledge Transfer Plan is designed to summarize the intended uses summarized above and to bring the results of these uses to the attention of the kinds of stakeholders listed above.

How Knowledge Will Be Made Available to the Public

Knowledge gained from the NGPH-8 project will be made available to the public through a variety of means, including:

- Generation of presentations and reports documenting project results as part of the project Scope of Work.
- Publication of technical papers documenting project results and findings.
- Dissemination of project Fact Sheets and other descriptive information on the TransPower website.
- Summarization of project results in proposals for funding to expand the use of natural gas hybrid technology in Class 8 trucks.
- Production of data sheets and other marketing materials to help promote awareness of the commercial availability of products resulting from this project.

The above activities are all central to TransPower's mission of commercializing technologies resulting from grant-funded research such as that targeted by the NGPH-8 project.

Tracking Relevant Activities

To the extent practical, activities related to knowledge and technology transfer during the NGPH-8 project will be tracked and documented to provide a means of measuring the success of this Technology/Knowledge Transfer Plan. This tracking process may include some or all of the following:

- Tracking the number of formal reports submitted to the Energy Commission during the NGPH-8 project.
- Tracking the number of formal presentations submitted to the Energy Commission during the NGPH-8 project.
- Tracking the amount of additional funding committed to TransPower natural gas hybrid activities, along with other key metrics such as numbers of additional trucks funded, if any.
- Documenting the number of miles accumulated on natural gas hybrid trucks during the NGPH-8 project, if any.
- Tracking business inquiries to TransPower related to natural gas hybrid technology.
- Documenting new stakeholders attracted to natural gas hybrid technology as a result of the NGPH-8 project.

The Final Report of the NGPH-8 project will be the primary means of documenting the these metrics.

APPENDIX E: Technology/Knowledge Transfer Report

This Technology/Knowledge Transfer Report is a concise summary of the results of TransPower's efforts for disseminating technology and knowledge resulting from the Natural Gas Plug-In Hybrid Class 8 Truck (NGPH-8) project. As discussed in Appendix E, key elements of this plan included:

- Updating the Fact Sheet submitted with TransPower's original proposal and disseminating the Fact Sheet at meetings and on TransPower's website.
- Organizing a Technology Advisory Committee (TAC) and convening periodic meetings of the TAC to obtain advice and share relevant knowledge with the TAC members.
- Identifying intended use(s) for and users of the project results.
- Identifying how the knowledge gained from the project will be made available to the public, including the targeted market sector and potential outreach to end users, utilities, regulatory agencies, and others.
- Tracking relevant activities such as technical papers published and identification of different websites containing related information.

The following subsections briefly describe the results of planned efforts in these areas.

NGPH-8 Fact Sheet

An initial Fact Sheet was submitted with TransPower's proposal in mid-2014. Information has been compiled for updating of this Fact Sheet at the end of the project, and an updated Fact Sheet will be submitted to the Energy Commission for review concurrently with submission of this Draft Final Report. As discussed in Appendix E, a copy of the Final Fact Sheet will be posted on TransPower's website following approval by the Energy Commission.

Technology Advisory Committee

The Technology Advisory Committee (TAC) has been a helpful adjunct for meeting the goals of the NGPH-8 project. The TAC has reviewed and commented on Critical Project Review (CPR) presentations and participated in CPR #1 on May 18, 2015. Copies of this Draft Final Report are being sent to all TAC members concurrently with its submission to the Energy Commission, and comments received from TAC members are reflected in the final report.

Intended Uses and Users of Project Results

Intended uses of the NGPH-8 project include: (i) demonstrating the viability of using natural gas as an adjunct to electric propulsion to improve the efficiency or reduce the emissions of Class 8 trucks and other large vehicles; (ii) helping to develop strategies for optimizing the performance of vehicles using natural gas; and (iii) determining the extent to which the emissions of clean-burning natural gas engines can be further reduced by using them in conjunction with electric propulsion.

During the NGPH-8 project, TransPower conducted outreach with a wide variety of stakeholders with potential interests in the viability of using natural gas as an adjunct to electric propulsion in Class 8 trucks and other large vehicles. These stakeholders included:

- Truck owners and fleet operators – including Total Transportation Services, Inc. (TTSI), SA Recycling, National Retail Trucking (NRT), Heineken, Devine Intermodal, BAE Systems, Terminalift.
- Major utilities – including San Diego Gas & Electric Company (SDG&E), Southern California Edison (SCE), Pacific Gas & Electric (PG&E), Duke Energy, Southern Company, and Florida Power & Light.
- CNG and CNG equipment suppliers – including Agility, which provided the hydrogen tanks used in the two new CNG hybrid trucks.
- Engine manufacturers – including Ford and Honda.
- Air quality and energy efficiency agencies – including the ARB, SCAQMD, Texas Commission on Environmental Quality, New Jersey Department of Environmental Protection, and New York State Energy Research and Development Authority (NYSERDA).
- Electric vehicle technology providers – including Yinhe New Energy Ltd., Jing Jin Electric, Capstone Turbines, Siemens, Eaton, and Meritor.
- Research institutions involved with natural gas engine technology – including the University of California and the Gas Technology Institute.

As part of the Technology/Knowledge Transfer Plan, results of the NGPH-8 project were shared with many of the stakeholders listed. For example, the benefits of using a natural gas generator to extend the range of electric trucks was discussed with all of the truck fleet operators listed above, as all expressed concerns about the limitations of using pure battery-electric trucks on some of their fleets. The two new CNG hybrid trucks built during this project will be deployed with fleet operators such as these to demonstrate the benefits of the technology in real-world operations.

How Knowledge Will Be Made Available to the Public

Knowledge gained from the NGPH-8 project was made available to the public through a variety of means, including:

- Generation of presentations and reports documenting project results as part of the project Scope of Work.
- Publication of technical papers documenting project results and findings.
- Dissemination of project Fact Sheets and other descriptive information on the TransPower website.
- Summarization of project results in proposals for funding to expand the use of natural gas hybrid technology in Class 8 trucks.
- Production of data sheets and other marketing materials to help promote awareness of the commercial availability of products resulting from this project.

The above activities are all central to TransPower's mission of commercializing technologies resulting from grant-funded research such as that targeted by the NGPH-8 project.

Tracking Relevant Activities

To the extent practical, activities related to knowledge and technology transfer during the NGPH-8 project will be tracked and documented to provide a means of measuring the success of this Technology/Knowledge Transfer Plan. This tracking process may include some or all of the following:

- Tracking the number of formal reports submitted to the Energy Commission during the course of the NGPH-8 project.
- Tracking the number of formal presentations submitted to the Energy Commission during the course of the NGPH-8 project.
- Tracking the amount of additional funding committed to TransPower natural gas hybrid activities, along with other key metrics such as numbers of additional trucks funded, if any.
- Documenting the number of miles accumulated on natural gas hybrid trucks during the course of the NGPH-8 project, if any.
- Tracking business inquiries to TransPower related to natural gas hybrid technology.

Documenting new stakeholders attracted to natural gas hybrid technology as a result of the NGPH-8 project.

APPENDIX F: Production Readiness Plan

Establishing production readiness for manufacturing of natural gas hybrid systems at commercial scale required a significant scale-up from TransPower's operation at the beginning of the NGPH-8 project in 2014. Significant progress was made in achieving this scale-up over the three-year term of the NGPH-8 agreement, but substantial additional work will be required to support commercial scale manufacturing. This Draft Production Readiness Plan summarizes this process and details plans to accomplish the remaining tasks required to establish commercial scale manufacturing of natural gas hybrid systems and components for Class 8 trucks.

TransPower Production Capabilities at Start of Project

At the start of the NGPH-8 project in July 2014, TransPower possessed the facilities and tools required to complete the proposed R&D. All of the company's operations were based in a 21,000 square foot R&D and manufacturing facility in Poway, California. To support analytical work, TransPower had a computer network with shared data storage and software such as Matlab and Simulink. To support manufacturing and testing, TransPower possessed the equipment required for small-scale manufacturing and testing of hybrid-electric vehicles and components including truck lifts, a crane and hoist, heavy-duty forklift, air compressor, an AV-900 battery tester, and enhanced electric power infrastructure. In total, these facilities were capable of supporting the conversion of approximately ten vehicles per year to electric or hybrid-electric propulsion, and the manufacturing of perhaps 20-30 drive systems per year.

At the start of the NGPH-8 project, TransPower was in the process of employing these capabilities to put 20 medium and heavy duty vehicles into service using the company's "ElecTruck™" drive system, all of which use or will use the company's base battery-electric propulsion technologies and core components. A handful of vehicles deployed prior to the NGPH-8 project, including a Pilot Truck used for drayage and a 40-foot school bus, were operating with varying degrees of reliably but generally exceeding road performance expectations.

Evolution of TransPower Production Capabilities During Project

During the project, TransPower substantially expanded its production capabilities. The linchpin of this effort was the company's move to a new building in Escondido, which provides 28,000 square feet of space for expansion of manufacturing activities. TransPower also acquired a separate manufacturing grant from the Energy Commission in 2015, which has provided funding for acquisition of manufacturing tools and development of improved manufacturing and quality control procedures. These activities are still in process, and the manufacturing grant will continue until mid-2018. This will coincide with TransPower's completion of test driving of its initial fleet of natural gas hybrid trucks, providing an opportunity to transition into larger scale manufacturing of natural gas hybrid systems and components. Production quantities are expected to increase significantly in 2019 and 2020, potentially reaching the hundreds of units per year.

Rationale for Manufacturing Initiatives

TransPower's manufacturing initiatives are designed to address economic market barriers by providing the resources to transition key TransPower-manufactured EV components into higher rates of production, which is projected to lower component manufacturing costs by one-third, leading to subsequent reductions as economies of scale are achieved in commercial production, resulting in another cost reduction of about one-third by 2020. These initiatives will also enable implementation of improved quality management processes that will result in greater reliability. The cost reductions and quality improvements resulting from higher volume manufacturing will make heavy-duty electric trucks and other vehicles more affordable to fleet operators, serving as a catalyst for large-scale commercial adoption of heavy-duty EVs and plug-in hybrid trucks in California and elsewhere. These barriers have not been addressed by the market because most commercial investments in this sector have been focused on developing components for light-duty EVs, which have higher sales volumes than heavy-duty vehicles and are hence seen by most investors as offering a potentially higher rate of return. The technical hurdles faced by previous developers of heavy-duty EV components have also been discouraging to investors, although TransPower the Recipient's recent successes have the potential to turn around investor sentiment if commercial interest in heavy-duty EVs can be demonstrated.

With the recent demonstration of more capable heavy-duty EV components by TransPower, investors are beginning to show interest. Early in the NGPH-8 project, TransPower held meetings with about a dozen investment firms in New York and San Francisco in September and October of 2014. However, the recurring theme of these discussions was that significant private investment in heavy-duty EVs will only occur once private fleet operators start ordering such vehicles commercially. The most effective way to make this happen is to drive down the manufacturing costs of these components. Hence, TransPower has made it a high priority to transition its new EV components into higher rate manufacturing. Prudent investments of this type that are being made now are expected to lead to substantial commercial interest by 2019. This will most likely lead to substantial investor interest and availability of much larger amounts of private capital to support large-scale adoption of heavy-duty electric trucks, tractors, school buses, and other vehicles by the end of this decade.

TransPower's production readiness initiative is timely in light of the high priority the State of California has placed on reducing emissions from goods movement activities, and specific objectives the State is taking to encourage deployment of zero-emission trucks. Investments made in reducing the costs of manufacturing components for heavy-duty EVs will almost certainly produce near-term economic returns to the State in the form of reduced costs for vehicle demonstrations the State is likely to fund over the next few years, as well as longer term economic returns as a large, vibrant market for manufacturing and servicing of heavy-duty EVs takes root in California over the remainder of this decade.

Production Readiness Plan Objectives

The objectives of this Production Readiness Plan (PRP) are to implement the design refinements, manufacturing tools, and production processes required to achieve the aforementioned goals, which is to achieve significant and measurable reductions in the costs of manufacturing the key components developed by TransPower the Recipient for battery-electric and hybrid-electric operation of large trucks, tractors, school buses, and other vehicles weighing up to 80,000 lbs. Specific project objectives are to:

- Achieve the necessary refinements in the designs of "high-impact" EV and plug-in hybrid components to enable utilization of more efficient manufacturing processes.
- Successfully demonstrate new manufacturing processes to produce these components on a small scale, enabling estimates of future manufacturing costs to be updated and strategies to be adjusted as appropriate.
- Expand pilot manufacturing to higher volumes and demonstrate a one-third reduction in component manufacturing costs from current levels.
- Achieve significant commercial orders for heavy-duty vehicles using EV components manufactured under this project, and capital investments to support growth of manufacturing capabilities after 2019 to meet this demand.

These goals are measurable. TransPower has established a goal of reducing the cost of manufacturing the complete set of components required for a heavy-duty electric vehicle by one-third by 2019, based on a production volume of 100 vehicles per year. This is expected to lead to a reduction in manufacturing cost of another one-third as manufacturing volumes increase from 100/year to 2,000/year by the middle of the next decade. TransPower has also established 100 EVs as its production goal for 2019, including vehicles converted by TransPower and vehicles manufactured by original equipment manufacturers with drive system "kits" supplied by TransPower.

The PRP objectives are being pursued in a two-phase process. During the first phase, EV component design refinements for productionization will be completed and prototypes of these components will be manufactured on a low-volume pilot production line using new manufacturing tools and processes. In the second phase, after the productionized designs of the EV components and new processes have been validated at low volume, higher volume manufacturing will be initiated. In both phases, manufacturing will be accomplished using TransPower vertically integrated manufacturing (VIM) process, which was initially developed under an Advanced Vehicle

Technology Manufacturing (AVTM) grant awarded to TransPower in 2010. The PRP project will build on the success of this initial AVTM project by refining the design of key components developed under the earlier project and facilitating the important transition to higher volume manufacturing.

The first main task in this process is to identify alternative manufacturing processes capable of reducing the costs of selected "high-impact" EV components and to refine the designs of these components to enable them to be manufactured using these processes. This process, underway since late 2015, includes implementation of a new Enterprise Resource Planning (ERP) system, along with associated elements such as computer workstations, a bar-code system, and design-to-procurement software, and training of employees on its use. A key related activity is to identify new mechanical and electronic fabrication methods and tools suitable for reduction of the costs of manufacturing structural and mechanical components such as battery enclosures, driveline couplings, and Power Control and Accessory Subsystem (PCAS) support structures. The ultimate objective of these efforts is to perform design revisions to components, assemblies, and subsystems as required to accommodate new manufacturing processes selected.

The second main task in this process is to complete preparations for pilot manufacturing of structural and mechanical components such as battery enclosures, driveline couplings, and PCAS support structures. This includes development of the layout and process flows for a new pilot production line for manufacturing of structural and mechanical components. Key output of this task will include a structural and mechanical plant layout and process flows. This will then enable TransPower to acquire and set up or install electrical and electronic manufacturing tools and equipment required for initial validation of new manufacturing processes, including:

- Tools for the cutting of raw material such as hydraulic sheers.
- Computer numerical controlled (CNC) machines for final machining of structural and mechanical parts, including a CNC plasma machine, CNC mill, and CNC lathe.
- Welding machines for metal inert gas (MIG) and tungsten inert gas (TIG) welding, along with associated weld shop fixtures and equipment.
- Drill press equipment.
- Lockers for storage of dies and cutting bits.
- Cranes for lifting and moving heavy structural components such as battery enclosures.
- Structural and mechanical elements of a system test stand for final qualification of EV components.

Of particular importance is development of the layout and process flows for a new pilot production line for manufacturing of electronic components such as TransPower's inverter-charger unit (ICU) and battery management system (BMS) sensor/balancing boards. Pilot production of these components at TransPower's new Escondido facility is scheduled to begin during the fourth quarter of 2017. This will closely follow activities already undertaken, such as development of the layout and process flows for a new pilot production line for assembly of electrical subsystems such as central control modules (CCMs) and high voltage distribution modules (HVDMs).

The third main task in the PRP process is to achieve an initial production run of components sufficient for a minimum of ten vehicles, using the manufacturing processes and tools implemented on preceding tasks, and to evaluate the manufacturing test processes and components to validate cost projections and support progression to higher volume manufacturing. The components will be validated through bench testing followed by testing on fully functional vehicles integrated by TransPower the Recipient under other projects. This activity will be initiated during the summer of 2017.

The fourth main PRP task will be to expand TransPower's manufacturing capacity to levels required to produce components for at least 100 vehicles per year by 2019, with a clear path for growth to 1,000 vehicles per year by 2022. This may involve relocating some of the equipment purchased under prior tasks to a larger facility upon completion of the low-volume production run described previously.

The aforementioned manufacturing grant is providing a significant amount of funding to support these efforts, with 50-50 cost sharing from TransPower.