CALIFORNIA ENERGY COMMISSION

California Energy Commission

Clean Transportation Program

**FINAL PROJECT REPORT**

# Wrightspeed Digital Drive System Retrofit Kit

**Prepared for: California Energy Commission**

**Prepared by: Wrightspeed, Inc.**

**Gavin Newsom, Governor**

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# California Energy Commission

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# PREFACE

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

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

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

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-09-605 to verify the manufacture, testing and installation of a range extending electric vehicle drive system for medium and heavy-duty trucks. In response to PON-09-605, the recipient submitted an application which was proposed for funding in the CEC's notice of proposed awards July 30, 2010 and the agreement was executed as ARV-10-025 on April 27, 2011.

# ABSTRACT

The CEC awarded a contract to Wrightspeed in 2010 to verify the manufacture, testing and installation of a range extending electric vehicle drive system for medium and heavy-duty trucks. This hypothetical system titled The Route™ (then called the Digital Drive System) was developed in 2010 and 2011 and the completion of two prototypes occurred in 2012. The Route™ consists of a retrofit kit to replace a trucks engine, transmission, axle, prop shaft and certain electronic components. The Route™ is a highly advanced Digital Drive system that relies on a set of electric motors, gearboxes, batteries, inverters and a range extending turbine generator engine that is capable of recharging the battery during driving of the vehicle. The project meets the principle goals of the CEC for research and development of the Clean Transportation Program.

The project tasks include the development of hardware and software to demonstrate the retrofit kits be installed in class 3 - 6 truck with maximum governed speed of 75 miles per hour, an all-electric range of 30 miles, hybrid electric range of 400 miles and a fuel efficiency improvement of 100 percent over a 70 mile range. The objective includes a validation that the factory processes to manufacture and configure these retrofit kits result in correct installations, with specified performance and efficiency.

**Keywords**: Digital Drive System, The Route™, compressed natural gas, range-extending, powertrains, electric motor, turbine generator engine, kilowatt-hour, inverters, alternative transportation fuels, retrofit kit, gearbox, Ongoing Reliability Test and Controls Systems.

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# EXECUTIVE SUMMARY

Wrightspeed, a California based company known for building the world's fastest street legal electric car, is focused on building cleaner and more fuel efficient drive train systems for use in high fuel consumption medium and heavy-duty trucks. Medium-duty trucks today that operate with traditional piston engines consume fuel at a rate of approximately 6 to 10 miles per gallon.

The Digital Drive System retrofit kit being developed by Wrightspeed will increase the equivalent miles per gallon in excess of 100 percent. For instance, if a diesel truck gets 10 miles per gallon, the truck retrofitted with Wrightspeed's Digital Drive System will get in excess of 20 miles per gallon. As an added operational benefit, the retrofit kit is also estimated to have a 64 percent carbon density reduction when compared to the truck with a diesel engine. Wrightspeed's Digital Drive System electric drive retrofit kit replaces the entire drive system with a minimal increase in weight and includes sophisticated integrated electronics and a software management system that provide industry leading efficiencies.

For this project Wrightspeed will verify and validate electric drive retrofit kits for use in Class 3 (10,000 pounds gross vehicle weight) through Class 6 (26,000 pounds gross vehicle weight) trucks, to ensure that the system meets the specified performance efficiency levels.

The Digital Drive System includes a range extending micro-turbine powered generator that will broaden potential end-use applications. The Wrightspeed Digital Drive System uses electric-drive power for up to the first 40 miles per day after being recharged from the electrical grid. The system then switches over to a range-extending micro-turbine generator which will supply the necessary electrical energy to charge the batteries for extended driving range.

Wrightspeed identifies commercial medium-duty trucks as the niche market for the Digital Drive System because most are used in relatively local operations. The variable speed nature of the local drive cycle with frequent stops offer good opportunities for fuel savings with the Digital Drive System retrofit.

Wrightspeed plans to manufacture Digital Drive System retrofit kits in California for use by vehicle manufacturers and commercial fleet operators. Wrightspeed is located in the heart of Silicon Valley in the City of San Jose in Santa Clara County.

# Chapter 1: Technology Background

There are limited fuel saving technologies that can be applied to conventional piston engine driven trucks. Trucks are heavy vehicles that require high power engines for adequate performance. In the normal drive cycles for local delivery trucks, most medium-duty trucks consume a considerable amount of fuel to accelerate from frequent stops and then energy is wasted when the truck brakes are applied.

For fuel efficiency reasons, larger truck engines are diesel piston engines; and, in order to meet California emission standards, they require a complex and expensive exhaust after-treatment system. The maintenance of these engines and emissions controls systems is quite expensive.

Electric drive technology is known to be efficient, clean and lower maintenance compared to piston engine drive technology. However, development and investment in electric drive systems is relatively new and investment in these technologies is just beginning to emerge. As a result, electric drive systems are expensive to manufacture.

Wrightspeed has proven the technology works and early on-road testing of the first Digital Drive System in a medium-duty truck returned fuel consumption measurements of 28 miles per gallon (MPG).

# Chapter 2: Agreement's Goals, Objectives and Milestones

## Goals

The goals of this agreement are to validate and verify (internally through manufacture, install and testing; and externally through third party kit installation) Digital Drive System retrofit kits in existing trucks, to verify that exhaust emissions meet California's standards or better, and that vehicle conversion costs are low enough that customers will realize a 3 year payback on their investment through fuel savings.

## Objective

The objectives of this agreement are:

1) Demonstrate, using Digital Drive System retrofit kits in several Class 3 and Class 5 trucks, the following:
    a. Maximum speed of 75 miles per hour, governed
    b. Grade at maximum gross vehicle weight: 25 percent or better
    c. Grade at maximum gross vehicle weight and 55 miles per hour, 5 percent
    d. Speed at maximum gross vehicle weight, zero grade, depleted battery, and sea level 55 miles per hour
    e. Range, all electric, at best conditions: 30 miles
    f. Range, hybrid electric, at 55 miles per hour: 400 miles
2) Validate and verify that the factory processes to manufacture and configure these retrofit kits result in correct installations, with specified performance and efficiency
3) Demonstrate fuel efficiency improvement of 100 percent under mixed driving conditions, 70 mile route, compared with same truck using diesel engine.

## Proposed Milestone

1) 1st Critical Project Review Meeting and Critical Project Review Report
2) 2nd Critical Project Review Meeting and Critical Project Review Report
3) Build three Retrofit Prototypes
4) Install and Test Retrofit Kits in Vehicles
5) Build to Order 1 kit for third-party
6) Observe, Test & Validate third party Install
7) Data Collection and Analysis

# Chapter 3: Objective, Milestone and Test Results

## Objective Results

Wrightspeed did successfully demonstrate the performance of the Digital Drive System retrofit kits in two Isuzu NPR-HD medium-duty trucks. Figure 1 shows one of the Isuzu models performing a test run using the Test Platform constructed. The effort involved removing the existing engines, transmissions, rear axles, fuel and cooling systems, instrument cluster and related electronics and retrofitting the Isuzu trucks with a turbine generator, two electric drive motors, two gearboxes, cooling systems, fuel systems (compressed natural gas for one truck and diesel for the other) and numerous electronic replacements including the instrument cluster, which can be seen in Figure 2. The development and retrofit of the two Isuzu trucks occurred over an 18 month period between May 2011 and November 2012. The retrofitting was completed and the two Isuzu trucks have undergone a series of tests and have been used for demonstrations to potential customers, investors, vendors and employee's. The trucks have also been shown at Trade Shows and used for a promotional video. One of the trucks was turned over to a customer for an independent field trial, and monitored remotely at Wrightspeed. That trial was successful and the customer (American Media Service in San Jose) is now a positive reference for Wrightspeed. Overall the installation, fit, performance and appearance of the two trucks have impressed potential customers.

**Figure 1: Isuzu Test Platform Rifting at Bonneville Salt Flats**

Source: Wrightspeed

**Figure 2: Wrightspeed Test Platform with Digital Drive System Installed**

Source: Wrightspeed

The Isuzu trucks did experience a technical problem with the gearboxes that caused some overheating in the gearbox at higher speeds, and as a result the maximum speed of the trucks has been limited to 61 miles per hour. This is below the stated objective for maximum speed at 75 miles per hour (Higher speeds were achieved briefly). The gearboxes have now been re-designed to reduce the losses (and therefore the heating) and future versions of the retrofit kits will include the new gearboxes, and will be able to run 75 miles per hour. However, it seems that customers would like to limit the top speed to something around 60 miles per hour anyway, to improve fuel efficiency by reducing aerodynamic drag losses.

The program timeline was extended approximately 1 year from the original *schedule of products and due dates*. The original goals of the project remained in place, yet some of the key milestones where changed and as a result not completed.

In January 2013, Wrightspeed conducted a series of test to measure the fuel efficiency and energy consumption of a retrofitted Isuzu truck. A summary of the test results follows. The result of the test drive over a 63 mile range was that the Isuzu truck traveled 32 miles on battery power alone, and an additional 31 miles with the turbine generator running. The analysis concludes that the truck delivered 28.4 MPG on a cost equivalent basis, using $0.1 kWh for grid electricity, $2.20 per gallon (gal) for compressed natural gas and $4.00/gal for diesel. The same truck before conversion delivered approximately 12 MPG. Total range would be approximately 400 miles with a 30 gallon diesel fuel tank.

The retrofit kit includes an onboard 6.6 kilowatt charger that can fully charge the batteries in approximately 4 hours utilizing a 208 volts per 30 ampere electric vehicle charger that pulls electricity from the grid. This timeframe becomes shorter depending on remaining battery power when charging begins. The batteries are charged when the turbine generator is running and the time-frame to fully charge the batteries from the turbine generator is approximately 45 minutes.

The current cost of The Route™ kit is for very small prototype volumes and is significantly higher than the anticipated cost when Wrightspeed ramps up production. Higher purchase quantities will drive volume purchase discounts that will reduce the cost dramatically. Wrightspeed also intends to invest in tooling and set-up costs for molds and castings to lower the cost for major components like the gearbox. As an example, the current cost of a large component from our suppliers is $43,000 each. The supplier has quoted Wrightspeed a cost for volume purchases that is less than $2000 each; the lower pricing requires a one-time investment of approximately $1.0 million for castings, tooling and set up costs.

The current material cost for The Route™ is as expected for this stage of the development and on-going cost reductions are anticipated when Wrightspeed ramps production.

## Milestone Results

Wrightspeed was successful in retrofitting two prototypes opposed to three prototypes as identified in the key milestones. A series of checklist and test that have been performed by Wrightspeed include the following tests:

1) Document Test Plan Map
2) Drive Test Log Book
3) Dyno Checklist
4) Digital Drive System Geared Traction Drive Dyno Test Cases
5) Test Protocol
6) Truck Integration Task List
7) Post Power on Test List

8) Pre-Drive Test List

9) Pre-Customer Beta Validation and Test

10) Digital Drive System Beta Test Plan

11) Digital Drive System Regression Test Plan

12) Digital Drive System Test Drive Procedures

13) Software Integration Test Procedures

14) PGSSI Test Cases

## Drive Cycle Test Results

This section is intended to provide example data and analysis for a representative drive cycle using the experimental retrofit Isuzu NPR operated by Wrightspeed in accordance with the experimental permit granted by the State of California Air Resources Board on May 24, 2012.

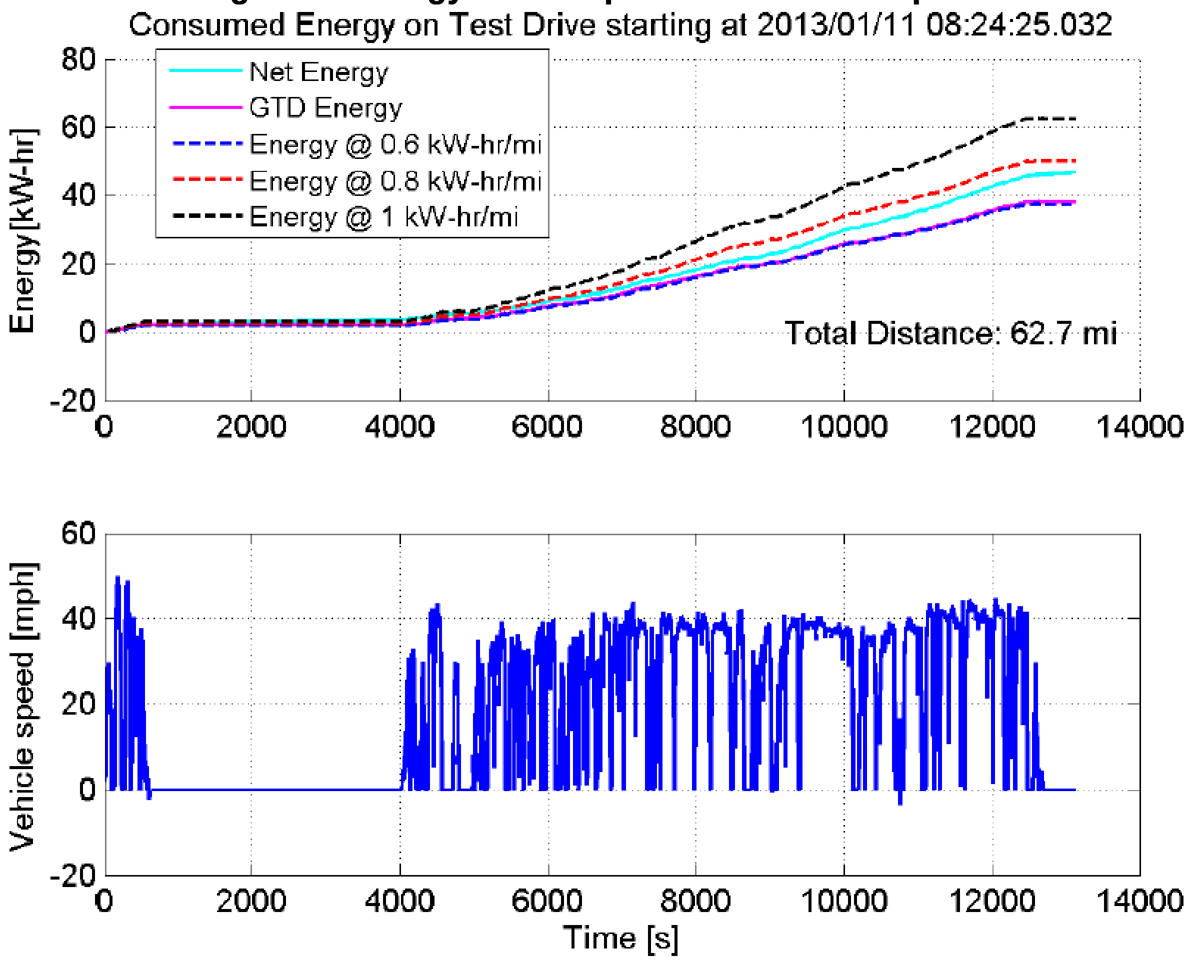
### Data and Analysis

The following data were taken from a test drive where the battery pack is initially full. Approximately half way through the drive, the turbine generator is activated to provide range-extension.

Figure 3 shows the energy consumed over the course of the test drive and vehicle speed, along with a note citing the total drive distance of 62.7 miles. A more detailed picture of the energy consumption is shown in Figure 4, with a breakdown between energy used for traction and auxiliaries.

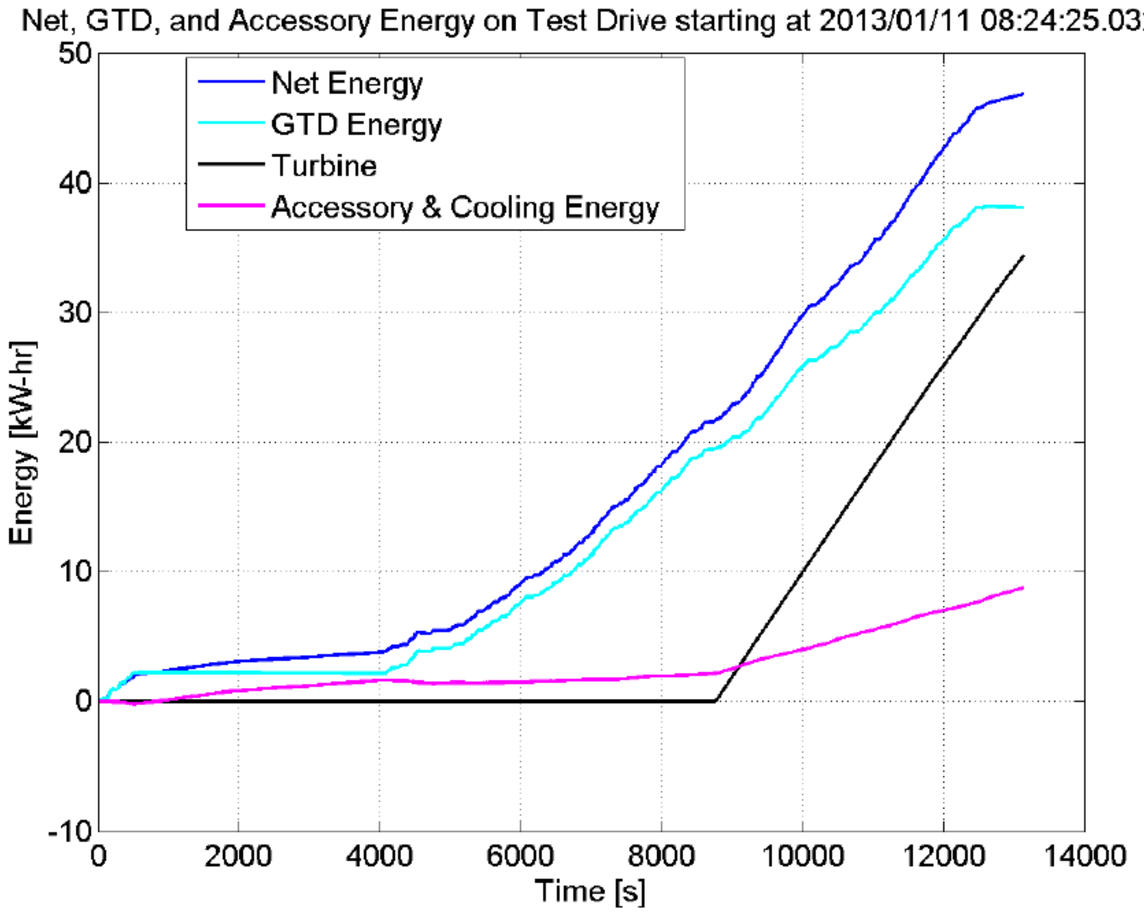
Also, the energy from the turbine generator output is shown. This shows the turbine activation at approximately 2 minutes and 26 seconds (8760 seconds) into the drive. Note the long idle time at the beginning of the drive in both of the figures.

**Figure 3: Energy Consumption and Vehicle Speed**




Source: Wrightspeed

**Figure 4: Energy Consumption by Category and Generator Energy Output**




Source: Wrightspeed

## Energy Consumption and Fuel Efficiency Calculations

These data show a total energy consumption of 46.8 kWh with the first 21.6 kWh and 32 miles of drive distance coming from the battery pack. The remaining 25.3 kWh and 30.7 miles of range come from the generator. Assuming a 25 percent efficiency for the C30, the energy used by the generator and the total energy used are, respectively,

$$\frac{25.3\ kWh}{0.25} = 101.2\ kWh$$

$$21.6\ kWh + 101.2\ kWh = 122.8\ kWh$$

Diesel fuel has an energy density of 37.95 kWh/gal, thus we can compute a MPG metric for the full drive and just the battery pack and generation stages.

$$Generator\ Only\colon \frac{30.7\ miles}{\left(\frac{101.2\ kWh}{37.95\frac{kWh}{gal}}\right)} = 11.5\ MPG$$

$$Battery\ Pack: \frac{32\ miles}{(\frac{21.6\ kWh}{37.95\frac{kWh}{gal}})} = 56.2\ MPG$$

$$Full\ Drive: \frac{62.7\ miles}{(\frac{122.8\ kWh}{37.95\frac{kWh}{gal}})} = 19.4\ MPG$$

### Cost Equivalent Fuel Efficiency Calculations (equivalent MPG)

We can also compute the cost equivalent MPG. Assuming the value \$0.10 per kWh for commercial electricity, the initial mileage driven off the battery pack cost \$2.16. Comparing the energy input to the generator and using a gas energy density of 33.4 kWh/gal and a compressed natural gas price of \$2.20 per gasoline gallon equivalent, we can compute the cost of the generation phase:

$$(\frac{25.3\ kWh}{0.25}) * \left(\frac{1\ gal\ \text{of}\ gas}{33.4\ kWh}\right) * \left(\frac{\$2.20}{\text{compressed natural gas}\ gasoline\ gallon\ equivalent}\right) = \$6.67$$

Therefore, combining the total cost of grid electricity and compressed natural gas and assuming a cost of \$4/gal for diesel fuel, the MPG on a cost equivalent basis is:

$$\left(\frac{62.7\ miles}{\$8.83}\right) * \left(\frac{\$4.0}{1\ gal}\right) = 28.4\ miles\ per\ gasoline\ gallon\ equivalent$$

### Hardware Results

Figure 5 shows The Route™ at an Advanced Clean Transportation Exposition, set up on display showing the various components that will be added to the Digital Drive System. The figure shows an encasement that holds the gearbox inside, as well as the electric motor set up from an external perspective. A close up image of the gearbox can be seen in Figure 6, specifically showing the electric motor attached.

**Figure 5: Gearbox, Inverter and Electric Motor Floor Demo**


Source: Wrightspeed

**Figure 6: Close up of Wrightspeed Gearbox and Electric Motor**

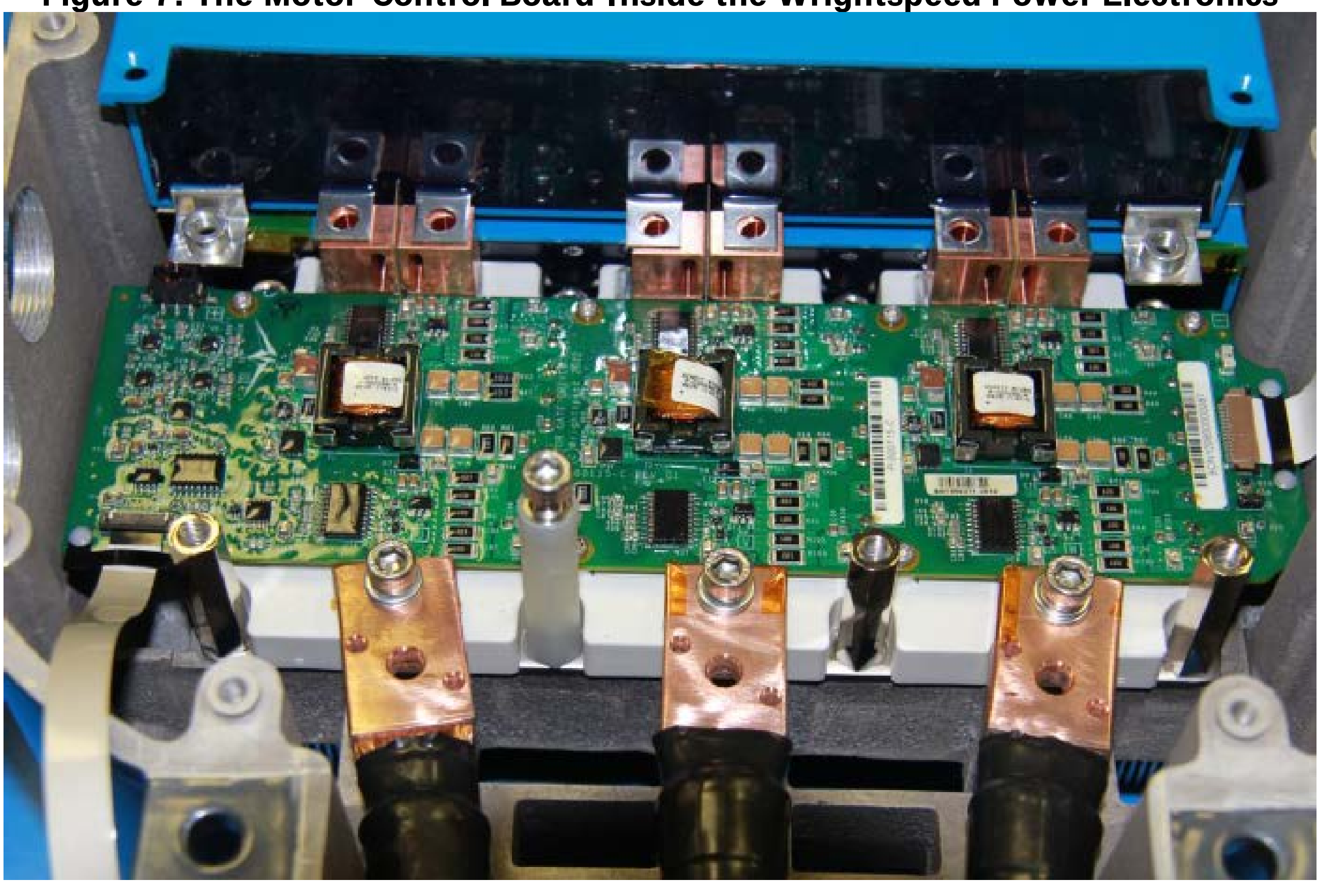
Source: Wrightspeed

# Chapter 4: Current Events

Shortly after the first two prototypes were completed, Wrightspeed received an order from a reputable parcel delivery company with a large fleet of medium-duty trucks. With this initial order, Wrightspeed learned a lot about customers' expectations and, as a result, two milestones identified in the project plan had to be modified. Milestone number 5, the build to order 1 kit for third party install and milestone number 6, to observe, test & validate third party install were de-prioritized so the organization could focus on the new customer order. The customer provided two trucks from their fleet for Wrightspeed to retrofit with the Digital Drive System. The two trucks provided were completely different platforms than the existing two Isuzu trucks already completed. Although the major components were the same, a significant amount of development work is required for the electronic interfaces, mounting hardware, plumbing, wiring and some software. The two trucks represent the first customer order for the organization and immediately became the highest priority for Wrightspeed. Figure 7 shows the motor-control board used for the Digital Drive System power electronics.

As a result, Wrightspeed focused on building the Digital Drive System kits for the trucks used by the customer (Freightliner MT45) and has been installing the first two in its own workshops.

**Figure 7: The Motor-Control Board Inside the Wrightspeed Power Electronics**



Source: Wrightspeed

# Chapter 5: On-Going Activities & Future Intent

## Successful Prototypes

Wrightspeed is extremely pleased with the results from the first two prototype trucks, is committed to the technology, and is currently working on two additional prototypes on a different platform for a fleet operator. The aforementioned gearboxes have been re-designed, with a newer enclosure seen in Figure 8, and are currently undergoing tests for performance and reliability. Wrightspeed is currently adding staff members, is re-modeling the manufacturing floor and intends to ramp up manufacturing capabilities in order to meet expected demand. Figure 9 shows the liquid-crystal display system used to check various components such as the battery/full level, speed of vehicle and energy

**Figure 8: The Enclosure for Wrightspeed's Power Electronics**


Source: Wrightspeed

**Figure 9: Wrightspeed's Liquid-Crystal Instrument Display**


Source: Wrightspeed

## Market Prospects

The Wrightspeed system is ideal for class 3-6 trucks that operate in urban and rural routes with multiple stops. In this environment the system can increase fuel economy by a factor of 2-3 times the diesel or gasoline baseline creating a savings and incentive for its adoption by fleets.

With over 2 million vehicles operating in this "pick up & delivery" environment and an approximately 10 percent replacement cycle along with a 10 percent engine remove and replace factor, the addressable annual market is approximately 400,000 units.

Target customers would include fleet operations for FedEx, UPS, Coca-Cola, Waste Management, Cintas, Aramark, Frito-Lay, Pepsi, Bimbo, and others of similar recognition.

## Future Grants

Wrightspeed has been awarded a second grant from the CEC, Grant Solicitation PON-11-604 Advanced Vehicle Technology Manufacturing. It is Wrightspeed's intent to accelerate development and manufacturing processes of the Digital Drive System. The CEC's participation and grants are empowering Wrightspeed to accelerate these activities.

# GLOSSARY

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

1. Forecasting future statewide energy needs
2. Licensing power plants sufficient to meet those needs
3. Promoting energy conservation and efficiency measures
4. Developing renewable and alternative energy resources, including providing assistance to develop clean transportation fuels
5. Planning for and directing state response to energy emergencies.

Funding for the CEC's activities comes from the Energy Resources Program Account, Federal Petroleum Violation Escrow Account, and other sources.

GALLON (gal) - A unit of volume. A U.S. gallon has 231 cubic inches or 3.785 liters.

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

MILES PER GALLON (MPG) **–** A measure of vehicle fuel efficiency. Miles per gallon or MPG represents "Fleet Miles per Gallon." For each subgroup or "table cell," MPG is computed as the ratio of the total number of miles traveled by all vehicles in the subgroup to the total number of gallons consumed. MPGs are assigned to each vehicle using the EPA certification files and adjusted for on-road driving.