CALIFORNIA
ENERGY COMMISSION

California Energy Commission

Clean Transportation Program

FINAL PROJECT REPORT

Prototype Shuttle for Motiv Power Systems Inc.'s Electric Powertrain Control System Final Results

Prepared for: California Energy Commission

Prepared by: Motiv Power Systems

Gavin Newsom, Governor

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PREFACE

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

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

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

To be eligible for funding under the Clean Transportation Program, a project must be consistent with the CEC's annual Clean Transportation Program Investment Plan Update. The CEC issued PON-09-004 to improve medium- and heavy-duty vehicle technologies and retrofit medium-duty on-road vehicle fleets. In response to PON-09-004, the recipient submitted an application which was proposed for funding in the Energy Commission's notice of proposed awards June 10, 2010, and the agreement was executed as ARV-09-015 on October 26, 2010.

ABSTRACT

The purpose of this project is to develop, build, field, and operate a prototype electric shuttle bus that uses Motiv Power Systems, Inc.'s electric Powertrain Control System and has more than 100 miles of all electric range. The scope is to develop, create and deploy a single prototype vehicle conversion platform for the above purpose. The shuttle will support the future development of medium-duty and heavy-duty electric vehicles on traditional diesel truck assembly lines. Multiple battery packs and battery designs will be installed and operated concurrently on the shuttle.

The project resulted in the successful development of the first generation of the Motiv Power Systems, Inc. electric Powertrain Control System. It was designed, built and tested on a 20 passenger shuttle bus. This shuttle exceeded the planned engineering goals. The shuttle was operated for 1,500 miles with data collection. The project completed the scope and purpose of this Grant as shown by the above results.

The team recommends support to help pilot the technology on a traditional truck assembly line with a "Beta" fleet of varied medium-duty and heavy-duty buses and trucks. The team also recommends supporting a pilot assembly line for the manufacture of the Motiv Power Systems Inc. electric Powertrain Control System, which will create jobs in California for the manufacture of the systems and the assembly, service, and support of truck chassis equipped with the systems.

Keywords: battery, electric powertrain control system, auxiliary power unit, plug-in electric vehicle, Motiv, Motiv Power Systems, Inc. Please use the following citation for this report:

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EXECUTIVE SUMMARY

This project's goals were to develop the Motiv Power Systems, Inc.'s electric Powertrain Control System and field test it on an all-electric shuttle bus with Bauer's Intelligent Transportation. The project team would also add a second battery system to the shuttle bus and run it concurrently with the first battery system to compare their performance side-by-side and demonstrate Motiv Power Systems, Inc.'s battery-agnostic architecture.

Over the course of this project, the Motiv Power Systems, Inc. project team developed the electric Powertrain Control System, including a battery adapter, charger, motor controller, auxiliary power unit, system controller (called a powertrain control unit) and remote telemetry system. The team then field tested this system on a demonstration 20-passenger all-electric shuttle bus with 100 mile range and performance similar to its gasoline or diesel counterparts.

The team produced a zero-emissions shuttle with over 100 miles range and performance similar to non-zero emission vehicles and sufficient for use as a shuttle bus. The team also demonstrated five different battery systems on the shuttle running concurrently, four from Dow Kokam and one from Lico Technology Corp. The battery systems ran concurrently to show that the electric Powertrain Control System is battery agnostic. Battery-agnostic electric shuttles allow end-user fleets to avoid being locked in to a particular battery supplier, reducing cost and upgrade/replacement risk.

This project will likely continue to impact the future of the industry. By demonstrating a battery-agnostic system, fleet users will know that their continued requests for battery-agnostic systems are indeed possible. A battery-agnostic electric truck or bus will drive battery costs down by allowing an equal market competition. In some cases, Motiv Power Systems, Inc. customers have already seen cost reductions of up to 50 percent on battery cost, due to previous competition between vendors. This project also demonstrates the electric Powertrain Control System is compatible with legacy chassis designs. By demonstrating the system on a Ford E450 chassis, this project shows compatibility between new, all-electric trucks and buses and the existing infrastructure for manufacturing trucks. Such compatibility will save time and money in bringing electric trucks and buses to scale.

The project demonstrates an electric shuttle with a $0.57 per mile savings over its diesel equivalent. The shuttle also saves a net of 1.7 kilograms per mile of carbon dioxide equivalent greenhouse gases based on the California Greenhouse Gases, Regulated Emissions and Energy use in Transportation model. This air quality improvements and fuel use reductions are significant and economical. Currently, in California, a new all-electric truck or bus with the electric Powertrain Control System can pay for itself in about one to two years.

Upon the completion of this project, the team recommends continued support for technologies like the electric Powertrain Control System to move from demonstration into pilot pre-commercial programs. Such support would enable this technology to cross to customer revenue and adoption, thereby reducing greenhouse gas emissions, fuel usage, creating new clean technology jobs in California, and advancing the goals laid out by Assembly Bill 118.

CHAPTER 1: Project Background

Motiv Power Systems, Inc. (Motiv), in partnership with Bauer's Intelligent Transportation, Corp. proposed to integrate Motiv’s customizable electric Powertrain Control System into a prototype class-4 vehicle to demonstrate the viability and benefits of the system’s 100-mile all-electric range. Bauer was seeking to retrofit its existing diesel fleet of medium-duty vehicles with new electric-vehicle technology to increase fleet fuel efficiency, lower overall greenhouse gas emissions, and reduce adverse impacts to the environment. Motiv installed its system on a shuttle bus chassis as a test platform to illustrate the large-scale applicability of the technology. This shuttle operated along Bauer's Intelligent Transportation routes and at locations such as Stanford, Lawrence Livermore Lab and Google. One pack of a second battery supplier’s pre-production battery cells was installed during a second phase of the project and their performance and lifetime was compared against commercially-available batteries operating concurrently. This shows that a battery-agnostic electric truck or bus is possible and economical.

Project Goals

As taken from the project application, the goal of this project was to develop, build, field, and operate a prototype electric shuttle bus that uses Motiv’s power control system and has more than 100 miles of all-electric range. This shuttle the value of Motiv’s flexible electric Powertrain Control System technology for medium-duty vehicles and gathered real-time data of shuttle performance. The shuttle transported passengers over 1,500 miles during the course of the project, all while gathering field data about the performance of different components critical to electric vehicles, especially batteries. To collect data and shows the flexibility of Motiv’s electric Powertrain Control System, battery packs comprised of different cell types were tested and compared. One pack contained Lico Technology Corp.’s cells while others will contain commercially available cells from Dow Kokam. These packs all operated on the same vehicle at the same time.

By accomplishing the above goals, the project supported new technology advancement for vehicles: a battery-agnostic electric powertrain for medium- and heavy-duty vehicles.

The project also promoted the deployment of such technologies in the marketplace: an electric powertrain for medium- and heavy-duty vehicles that is compatible with truck chassis, truck assembly lines, and a wide variety of emerging battery technologies.

CHAPTER 2: Project Narrative

This chapter relates the development process for the prototype shuttle bus and the technology that went into this prototype. First, the Motiv electric Powertrain Control System Control System, which is the heart of the vehicle, is described. The system was developed for this project. Then, the shuttle chassis and installation process is described. This chapter concludes with discussion of the shuttle's operational and remote telemetry interfaces.

Description of the Motiv electric Powertrain Control System

The Motiv electric Powertrain Control System is a suite of controllers and software that easily adapts a traditional truck chassis into an electric vehicle using off-the-shelf batteries and motors. The system can be used on new vehicles and retrofits. For this project, it was shown on a retrofitted Ford 2006, E450 20 passenger shuttle bus.

The development of each of the five major power train components followed the standard process of specification, design, test, modification and retest. The design philosophy was to make each component self-protecting, and provide a generalized interface to the powertrain control unit. Each component (powertrain control unit, adaptive power converter, auxiliary power unit, Motor controller, and Charger) is described below along with a brief summary of its design.

The powertrain control unit coordinates power flows between different powertrain components (e.g., battery packs, traction motors, and onboard generators) based on each component's state and power requirements. A microcontroller in the powertrain control unit connects to the original key switch, accelerator pedal, gauges and shift lever to provide an interface between the driver and the powertrain. The powertrain control unit also provides comprehensive data collection for each component over the lifetime of the vehicle via remote telemetry. This data provides information to the fleet about performance and maintenance, and enables side-by-side comparisons of competing technologies. Figure 1 shows the powertrain control unit.

Battery adaptive power converters regulate power flows from each of the battery packs. The adaptive power converters are designed around a proprietary power regulator. This converter uses a multiphase design for scalability. This design, coupled with an ultra-wide eight to one input range, makes the converters capable of power conversation from most available energy sources. The design of this component involved power system design and specification, thermal analysis and development of an isolation system between the hazardous voltages internal to the device and chassis ground. Significant firmware design was also required to provide stable voltage and current mode operation and that could be fully controlled. Figure 2 shows the battery adaptive control unit.

The motor Controller takes control inputs and generates the switching signals to drive the power inverter and traction motor. Motor phase currents are controlled via space vector modulation and a resolver for position and velocity sensing. This algorithm was designed in house to maximize flexibility while optimizing system efficiency. Figure 3 shows the motor controller.

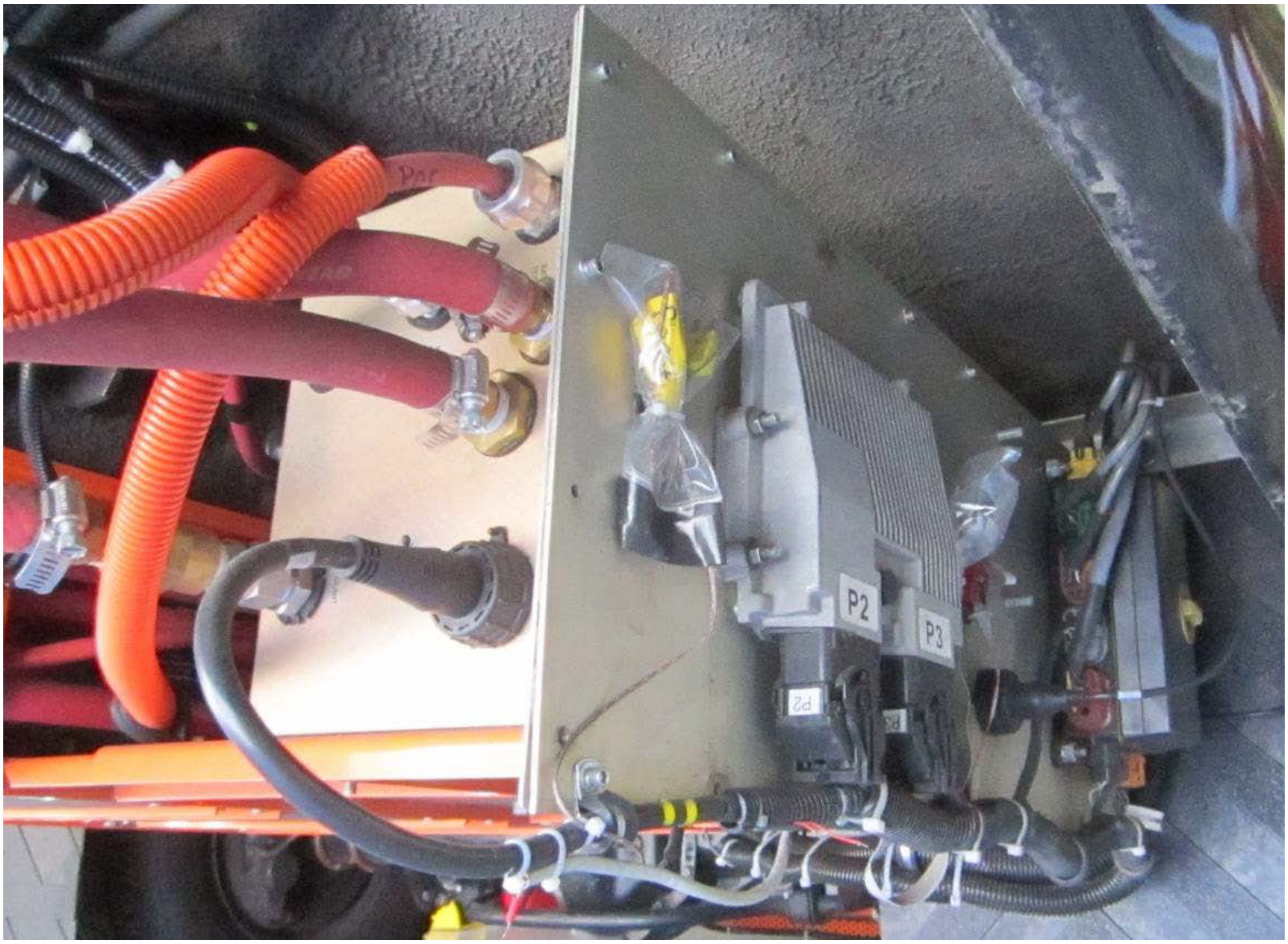
The auxiliary power unit provides 12 Volt (V) power to system auxiliaries e.g. lights, hydraulic pump, instrument panel, and pneumatic system. It replaces the alternator on the original vehicle by drawing power from the internal high-voltage power distribution bus and generating an isolated 12V output at up to 200 amperes. Microprocessor control is used for charging the 12V system batteries. Figure 4 shows the auxiliary power unit.

The 60 kW charger provides the interface from the power grid to the vehicle electronics. The charger is responsible for converting the incoming alternating current (AC) voltage to direct current (DC) and for determining ampacity of the input power. The design accommodates 120V and 240V single-phase and 208V, 480V, and 600V three-phase inputs at up to 100 ampere current capability with auto-detection of the voltage and ampacity of the line it is plugged in to. The charger communicates information about the AC line connection. Figure 5 shows the 60kw charger.

Figure 1: Powertrain Control Unit

Source: Motiv Power Systems, Inc.

Figure 2: Battery Adaptive Power Converter

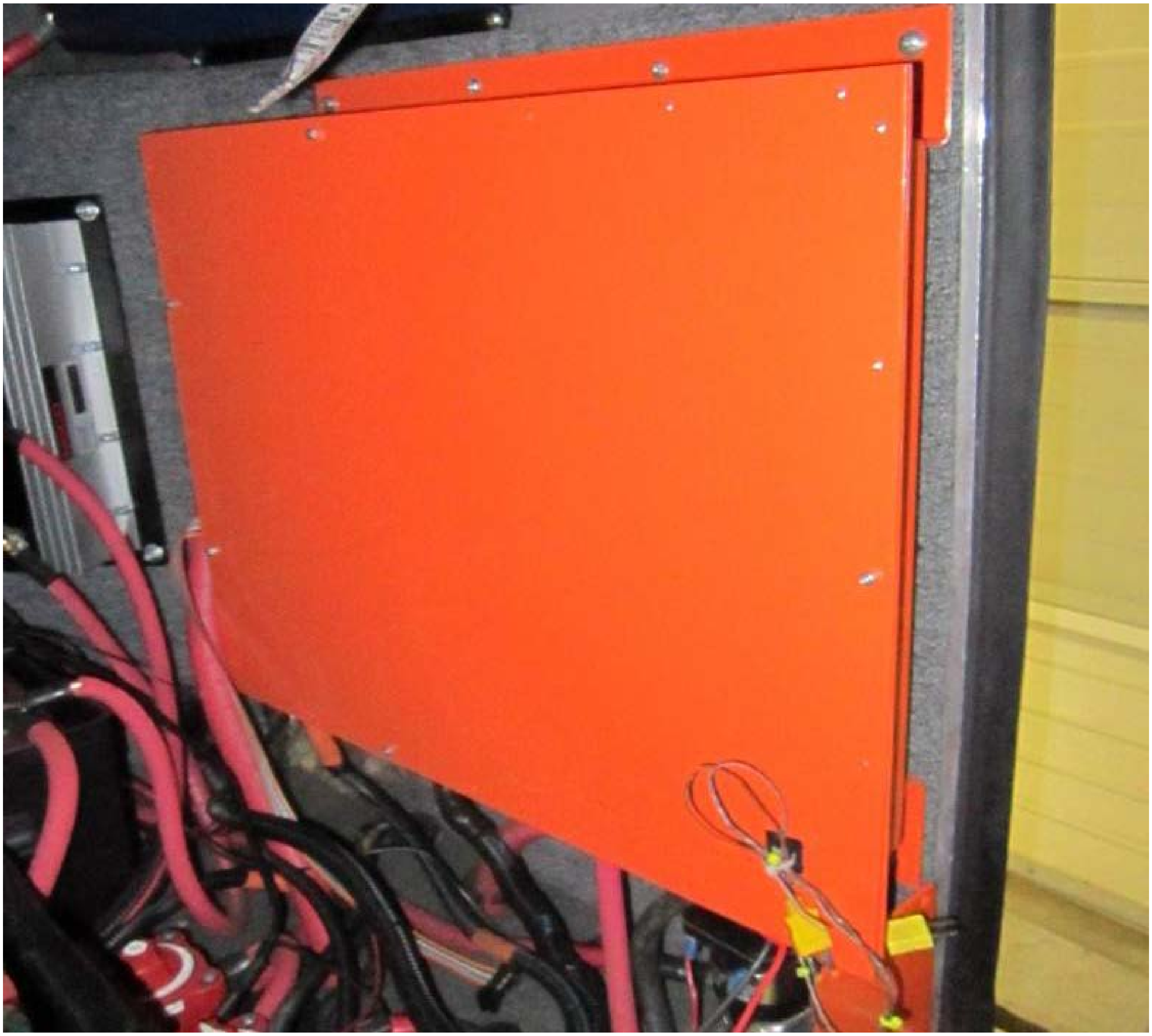


Source: Motiv Power Systems, Inc.

Figure 3: Motor Controller

Source: Motiv Power Systems, Inc.

Figure 4: Auxiliary Power Unit



Source: Motiv Power Systems, Inc.

Figure 5: 60 kW Charger

Source: Motiv Power Systems, Inc.

Shuttle Description

This section outlines the shuttle bus as it arrived to Motiv, the preparations for it, the installation of each of the Motiv electric Powertrain Control System components and associated batteries, motors, electronics and cooling system.

Shuttle bus preparations

The shuttle bus was purchased as a used Ford 2006 cutaway E450 chassis that was converted to a 20 person shuttle by Krystal Koach in Southern, California. Prior to being delivered to Motiv Power Systems, Inc., the entire original diesel drive train was removed. This was intended to give Motiv a clean chassis, stripped of all unnecessary items to allow for the design and installation of Motiv's electric Powertrain Control System, batteries, inverter, electric motor, new drive shaft and remaining components required to meet project goals. Figure 6 shows the shuttle as it arrived.

Figure 6: Shuttle as it Arrived

Source: Motiv Power Systems, Inc.

Shuttle Bus Electric Drivetrain Design, Component Fabrication and Component Installation

The installation of the prototype electric drive train in the shuttle took about 18 months from the grant project kick-off meeting to final report composition. This included driving the shuttle almost 1,500 miles for test and data collection purposes. The shuttle bus electric drive train design, component fabrication, and component installation created jobs for a dedicated team of engineers, technicians and mechanics at Motiv. This project also provided work hours to San Francisco Bay Area and Southern California specialty fabrication companies, and contributed to the California economy through the use of California commercial suppliers. The shuttle became operational in October 2011, and officially launched at the 2012 Work Truck Show in March 2012, as shown in figure 7.

Figure 7: 2012 Work Truck Show Shuttle Launch

Source: Motiv Power Systems, Inc.

Battery cradles

Each cradle of batteries includes a battery management system (BMS), electrical wiring for power transmission and control, a cooling system with pump, and a self-contained automotive style fuse and relay enclosure.

The Motiv electric Powertrain Control System can use batteries with variable physical dimensions, voltage, and power levels, while still maintaining control via the adaptive power converters.

Cooling is assembled as part of the cradle sub-assembly with pump, auxiliary battery heaters, hoses, connectors and quick disconnects for installation on the shuttle, between the frame rails for stability and protection

The fuse and relay block is a self-contained automotive style fuse and relay enclosure mounted on the lid of the adaptive power converters enclosure for easy access.

Figure 8 shows the battery cradle used in this project.

Figure 8: Battery Cradle on the bench

Source: Motiv Power Systems, Inc.

Motor cradle

The motor cradle is the structural mounting system for the motor. It also contains the cooling system, power inverter, and the motor control unit.

The inverter is a high power component that converts high voltage DC power from the shuttle’s electric Powertrain Control System high voltage link, to AC power that runs the synchronous motor that provides propulsion to the shuttle. The motor controller is the digital control unit supplying intelligence to the operation of the propulsion system

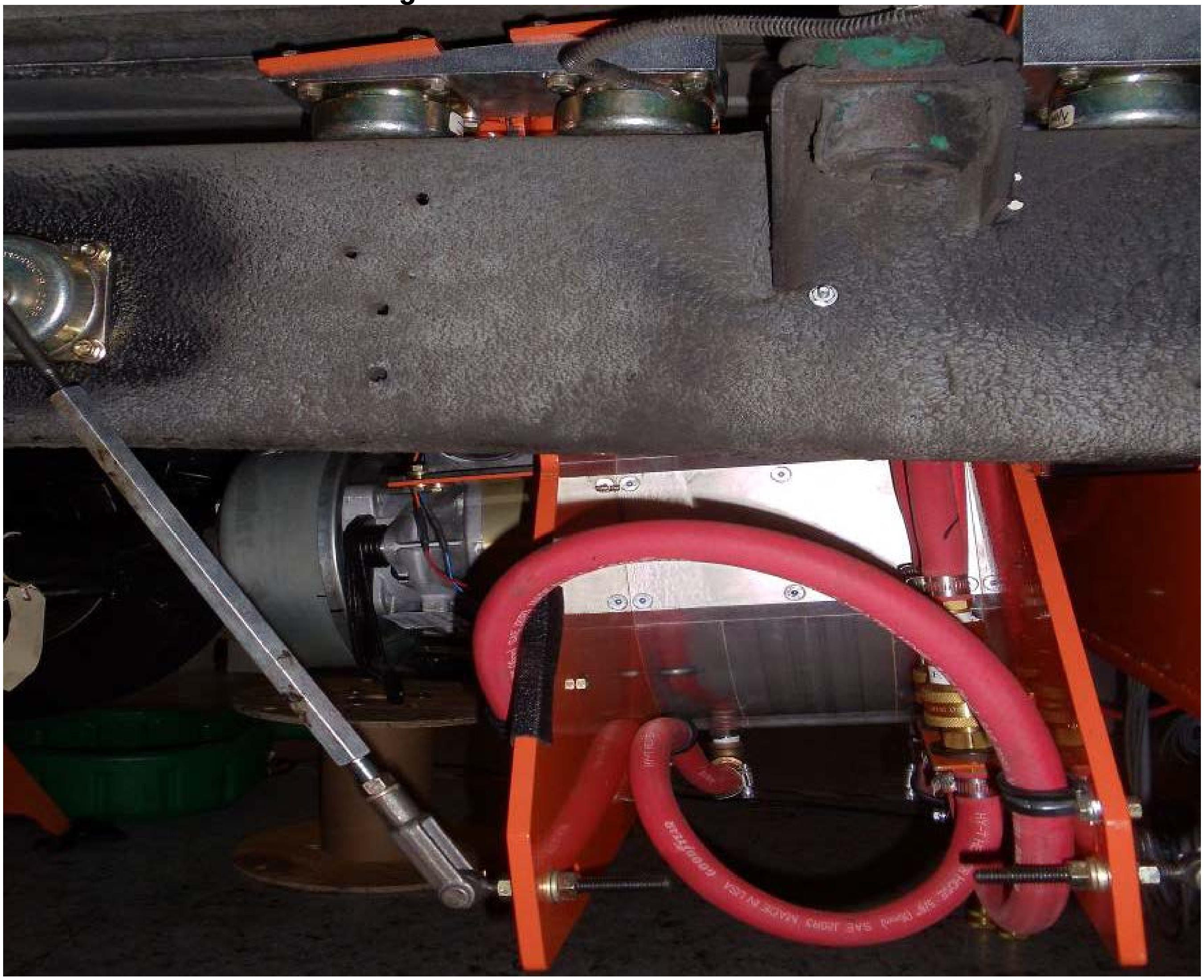
Shock and vibration mounting is accomplished through structural design with materials and fasteners made from the highest quality materials, along with structural bracing and automotive quality shock and vibration mounts sized for use on an electrified class-4 commercial vehicle.

Cooling is assembled as part of the cradle subassembly, with pump, hoses, connectors and quick disconnects for installation on the shuttle, between the frame rails for stability and protection.

Drive train alignment is accomplished by adjustable, shock mounted struts and machined angular shims, between the motor cradle mounting flanges and the shuttle frame rails.

Figure 9 shows an installed motor cradle.

Figure 9: Installed Motor Cradle



Source: Motiv Power Systems, Inc.

Auxiliary Power Unit

The auxiliary power unit converts high voltage DC power to 12 volts DC power for supplying 12V power to electric Powertrain Control System and vehicle legacy systems. The legacy power requirements are meant to feed the lighting, radio, dashboard, pneumatic pump, and so forth.

60 kW Charger

The Charger is one component within the Motiv electric Powertrain Control System. It is capable of 60 kW of power when connected to 600 volts AC 30. It can be connected to any lower voltage, single or triple phase, and will self-detect the voltage level. Motiv will supply the appropriate adapter cable for plugging into the grid as per the United States National Electrical Code, also known as the National Fire Protection Agency Document 70: Connectorization Requirements, met by National Electrical Manufacturers Association and International Electro technical Commission electrical Connectors. With this charger, the shuttle has a two-hour recharge capability without the need for an expensive separate charging infrastructure at the shuttle facility.

Shuttle primary cooling system

The primary coolant system uses the original equipment radiator, Degas bottle, and two-inch feed and return lines running 75 percent of the length of the bus, to feed each of the electric Powertrain Control System modular sections. It utilizes quick disconnect connection points and feed pumps at each branch line.

The pumps are pulse-width modulation controlled for variable speed control to maintain appropriate temperatures in the modules. Motiv uses propylene glycol as the coolant for the entire shuttle system for its reduced environmental impact and to reduce toxicity if ingested by animals.

Shuttle operation and Data logging

In general, the drive experience for the shuttle has been designed to mimic that of a traditional diesel vehicle outside of engine noise.

Operation

A user begins a route with the shuttle by unplugging the power cord. The charger detects the loss of AC power automatically, then puts the powertrain into a low power mode and charges the 12V system battery. The user then turns the key to the “on” position, putting the powertrain into drive mode and readying it for use. Once the user completes the route, the shuttle automatically recognizes when it has been plugged in and begins to charge the high voltage batteries based on the ampacity of the AC service. This is also fully firmware controlled to allow fleets to remotely schedule when plugged-in vehicles should be charged.

Data Logging

During the design process, diagnostic data logging is used to improve algorithms and optimize system performance. This is accomplished via an onboard personal computer. Logging can be initiated by running the logging program, automatically detecting connected components and saving a data stream for each component to the hard drive, along with data records for any faults that occur.

The remote telemetry system runs during all vehicle operations, shown in Figure 10. See the Appendix for details on the telemetry system.

Instruments

The legacy park, neutral, reverse, and drive gear shifter positions put the powertrain into the appropriate operating mode. The accelerator pedal is read by the powertrain control unit reads the accelerator pedal and maps it to provide an ergonomic power response profile. The legacy tachometer displays instantaneous drivetrain power, and the fuel gauge displays system state of charge.

Figure 10: Remote Telemetry System

Source: Motiv Power Systems, Inc.

CHAPTER 3:
Project Results

This section details the results from the development of the Motiv electric Powertrain Control System and its prototype demonstration on the all-electric shuttle.

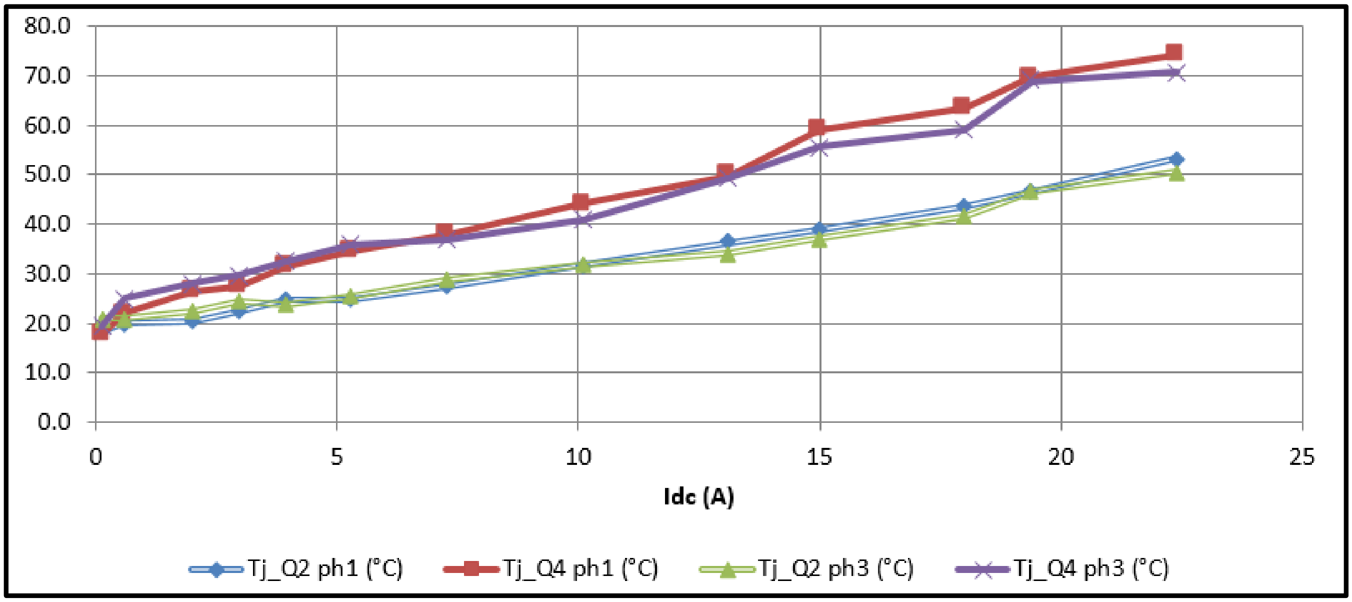
Testing

First, the project team individually bench tested components. Then, the project team tested the Motiv electric Powertrain Control System and other powertrain components together on the bench. Finally, the project team installed everything on the shuttle bus for road testing.

Bench Testing

The project team bench tested each of the five new components before integrating them into the shuttle. This testing included basic design verification, thermal tests, firmware debug, and control loop stability verification. The adaptive power converter required the most extensive testing due to its relative complexity and multiple operating modes. Initially, the adaptive power converter was operated from a lab supply into a water-cooled, resistive load, at various input and output voltage levels. During this testing a number of performance issues were found that required additional cooling to be added and a redesign of the control algorithm. The project team then used the adaptive power converter in conjunction with a high-voltage battery to perform full power testing. Figure 11 shows the results of thermal tests performed on the power semiconductors during this phase in the test. The project team then brought multiple adaptive power converters into operation to test elements of the control algorithm that required cooperation between multiple units. Finally, the project team then used an adaptive power converter on the bench to power the motor on the shuttle. The project team then tuned algorithm control gains to operate with the inverter as a load.

Figure 11: Junction Temperatures of Adaptive Power Converter Insulated-Gate Bipolar Transistor



Source: Motiv Power Systems, Inc.

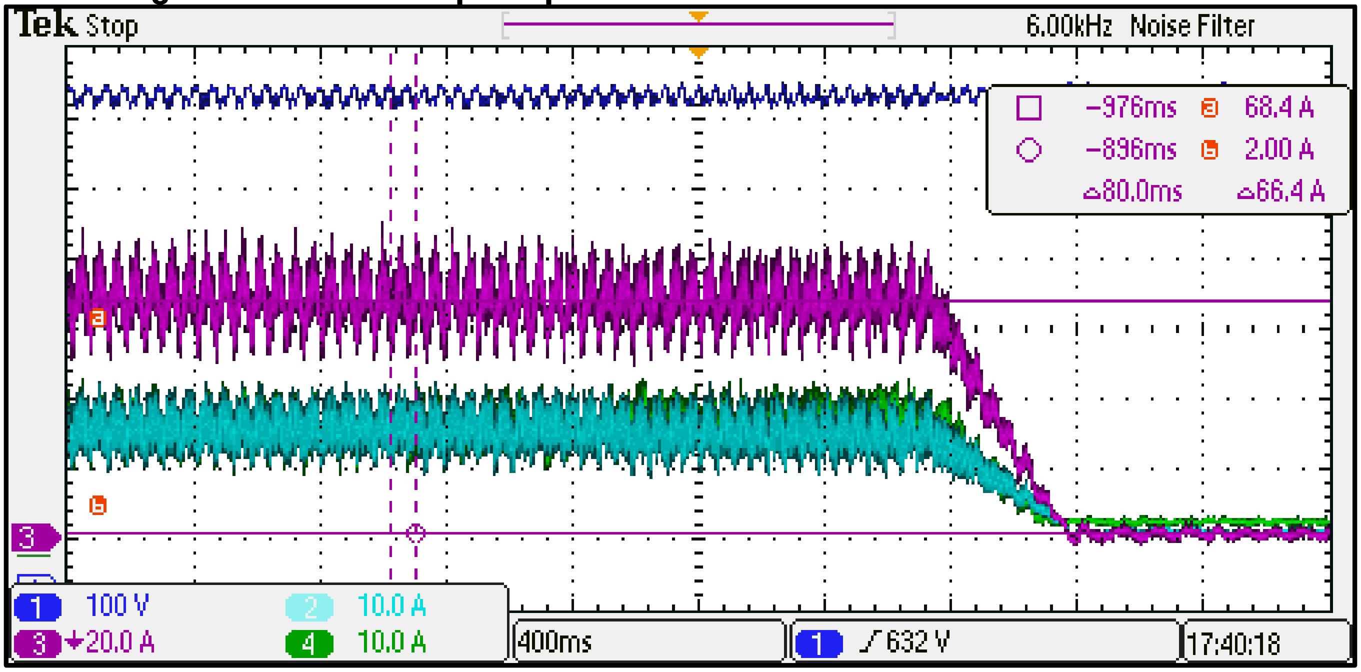
The project team bench tested the auxiliary power with a high-voltage supply to simulate the DC link from the vehicle. The load used for testing was a 12V lead acid battery and a 2,000 watt (W) power inverter to adapt the 12V output of the device to the high voltage load that Motiv had in-house. Testing resulted in minimal design modifications. The project team performed thermal testing by gluing thermocouples to the power semiconductors, power inductors and monitoring device temperatures under worst case conditions.

Bench testing for the motor controller and powertrain control unit is covered in the Nov 1, 2011, “Phase 1” report product.

Road Testing

After the project team integrated the components into the stripped chassis, they performed shuttle road testing in stages. First, the project team used exogenous instrumentation to verify component operation on a high frequency time scale. The project team performed this using voltage and current probes on relevant nodes in the system, feeding an oscilloscope in the shuttle passenger compartment. Figure 12 shows a scope capture of power flow within the powertrain.

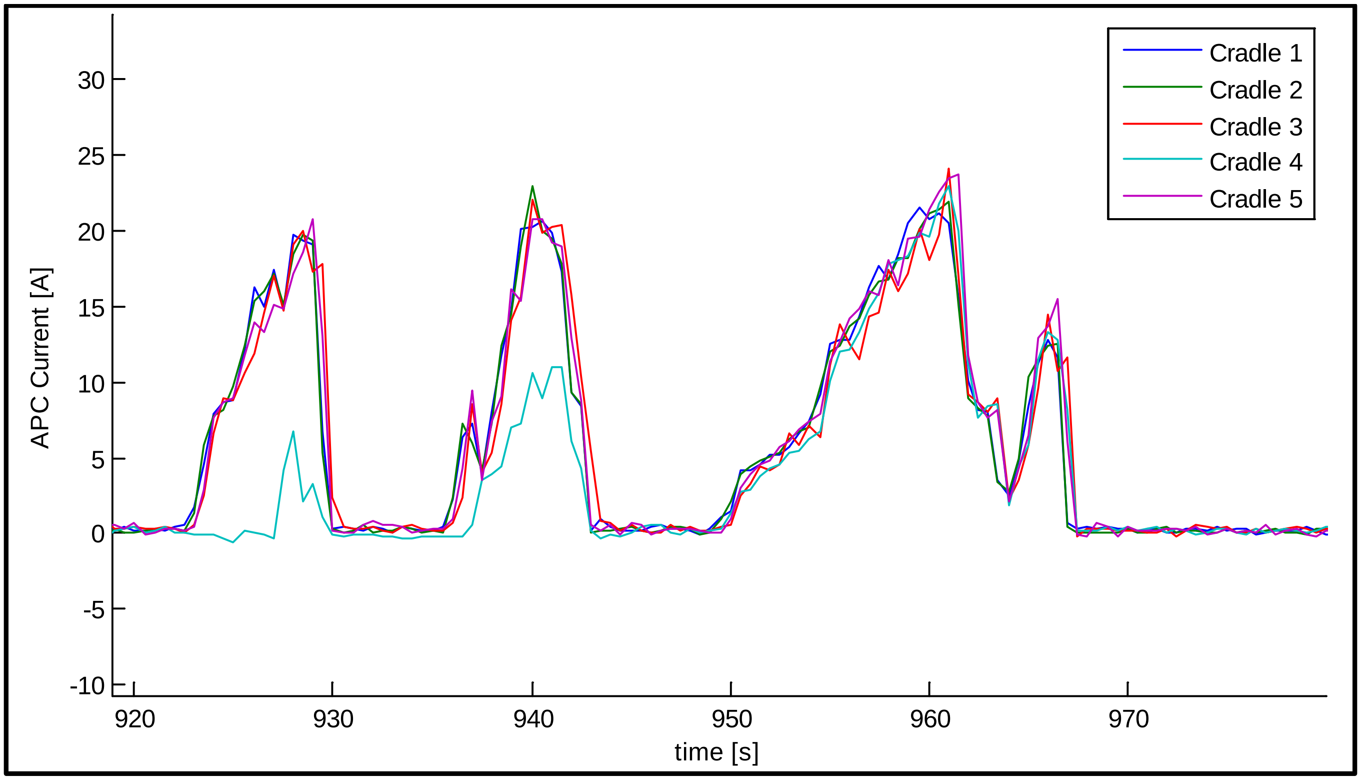
Figure 12: Oscilloscope Capture of Power Flow within the Powertrain



Source: Motiv Power Systems, Inc.

The second stage of testing used a personal computer with custom logging and visualization software to monitor and log the operation of components. This system connected to each of the power train components via universal serial bus and has the ability to capture a cycle-by-cycle log of control-loop operation during a system fault. The project team used this system to test power scheduling algorithms that distribute power flows across the battery array. For example, figure 13 shows adaptive power converter 4 being brought back into the array after a simulated fault. With this monitoring system in place the shuttle ran 50 miles a day to collect data on overall system performance. The project team captured system anomalies using this system and used the anomalies to make firmware modifications.

Figure 13: Archived Log Files Showing Cradle 4 Returning to the Array after a Simulated Fault



Source: Motiv Power Systems, Inc.

The project team tested gradability by measuring grades of a variety of hills and testing the ability of the shuttle to climb these hills from a standing start.

Motiv completed range testing by taking the shuttle on extended trips in the San Francisco bay area, while logging battery state of charge. Motive used this data to extrapolate range. The map in figure 14 below shows the shuttle on a trip to Livermore, California. The accompanying graph in figure 15 shows the state of charge of the batteries during the trip. Using the total battery capacity, the range for this trip can then be projected as 120 miles, or 1.1 miles per kWh in city driving conditions.

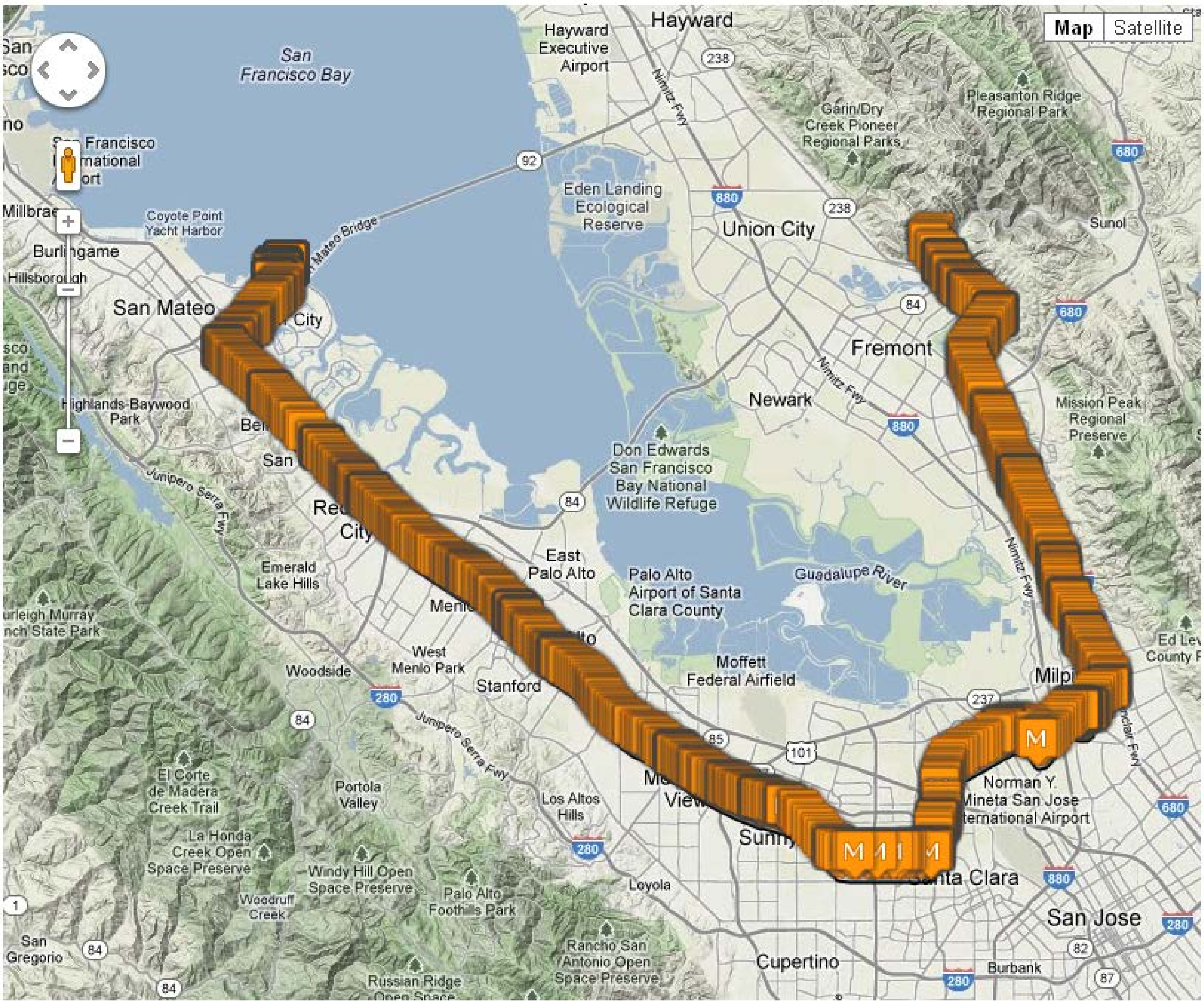
Figure 14: Data from Remote Telemetry System during a Drive from Foster City to Livermore

Motiv's Tiny WebDB Service

This web service is designed to work with Motiv's Realtime Data Logging System. It is still in testing.

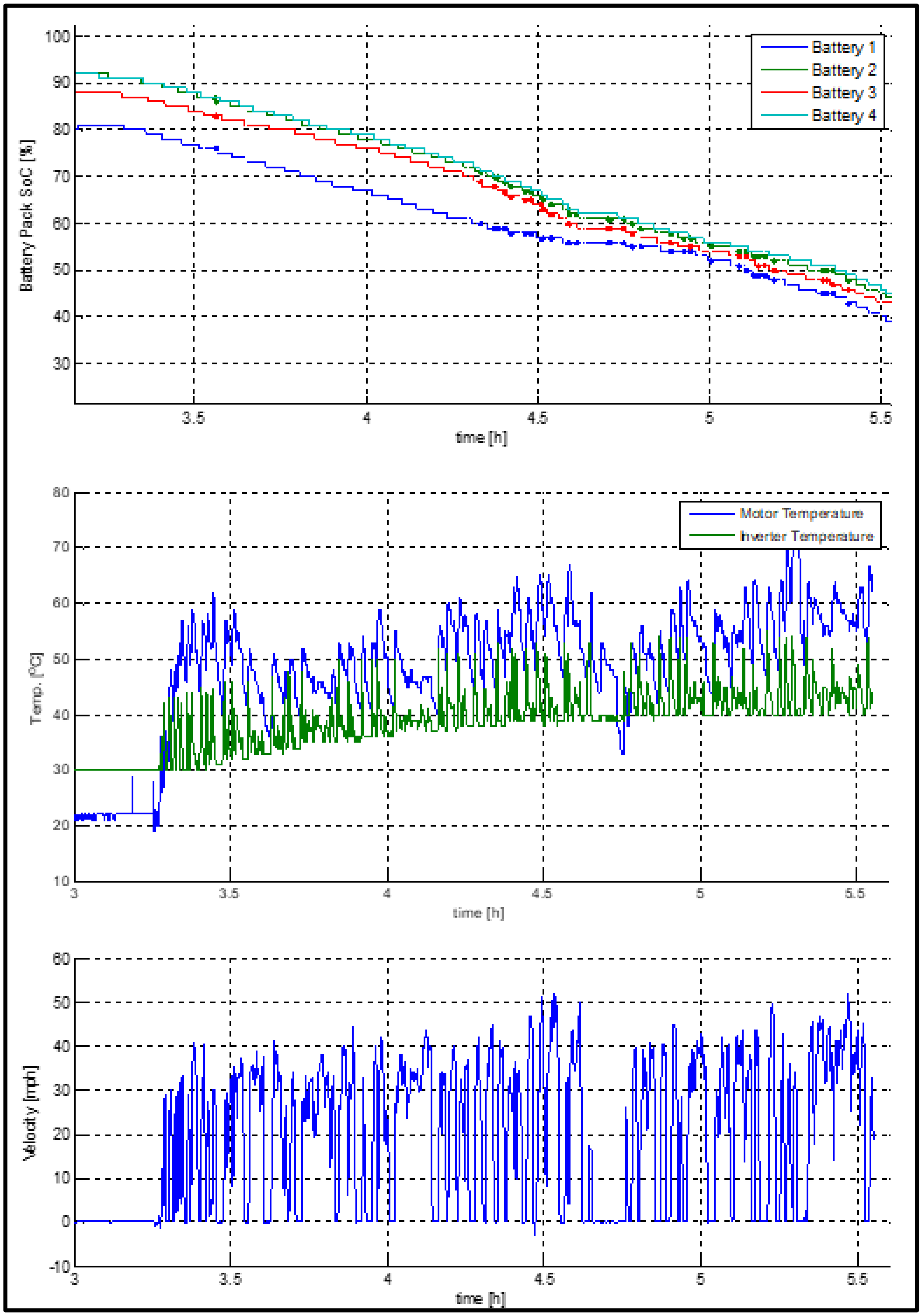
The page you are looking at shows the raw data (sans position) in list form, and shows position data on a map.

Show List



Source: Motiv Power Systems, Inc.

Figure 15: Selected Data from the Remote Telemetry System for Drive Period in Figure 14



Source: Motiv Power Systems, Inc.

The third tier of testing involved the use of the remote telemetry system to log system-level performance characteristics. This system provides information including vehicle speed and position, battery state of charge, and power electronics operating performance. This is intended to be used with a maintenance schedule to provide predictive maintenance information, statistics on component lifetimes, vehicle usage information and any other performance data required by fleets.

Shuttle Performance

Some aspects of the shuttle's performance can be quantified as follows:

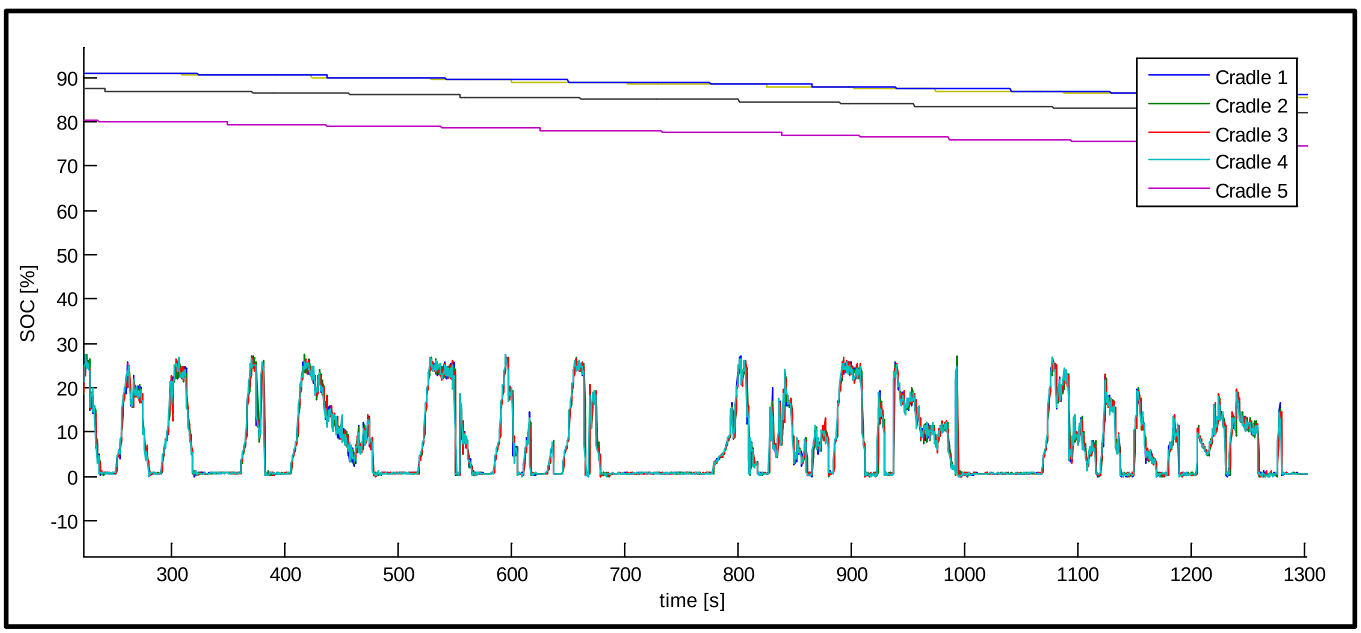
- The shuttle is capable of traversing a 10 percent grade at 35 miles per hour,
- The max sustained speed is 60 miles per hour,
- A range 100 to 120 miles, depending on loading.

The longest trip to date has been from Foster City, California, through San Jose, Fremont and Niles Canyon (California highway 84) to Lawrence Livermore Labs in Livermore, California. Data from an excerpt of this trip is shown in figure 15, figure 16, and figure 17.

Table 1 tabulates some of the longer trips the shuttle bus has made to date. The installation of a fifth battery pack resulted in a significant improvement in range as described in the project Product "Phase 2 Battery Report".

There are 1,500 logged miles to date, including 182 miles with the Phase-2 battery pack. Figure 17 shows a picture of the driving log for the shuttle bus, which served to verify the online telemetry data. After this project's conclusion, the shuttle will continue to log miles, with 2,000 planned total miles for test and data gathering before full-time hand-over to Bauer's Intelligent Transportation.

Figure 16: Battery Cradle State of Charge and Current on Trip to Livermore



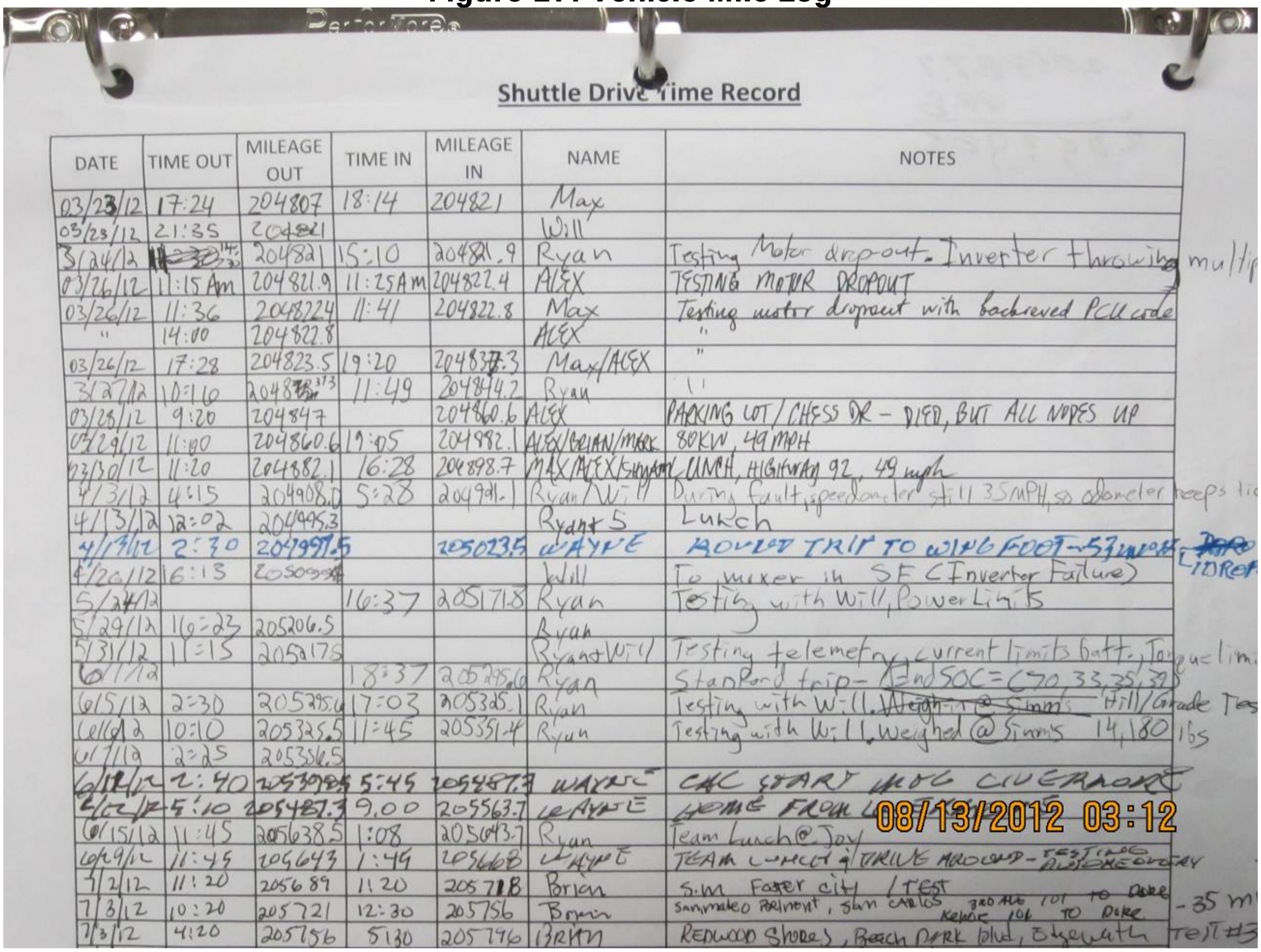
Source: Motiv Power Systems, Inc.

Table 1: Trips and State of Charge Usage

Date	Destination Address	%Δ of Charge Group 1	%Δ of Charge Group 2	%Δ of Charge Group 3	%Δ of Charge Group 4	%Δ of Charge Group 5	Avg. State of Charge change [%]	mile/ %	Estimated Range [miles]
4/13/12	240 Dollar Avenue South San Francisco, California 94080		30.5	28	23.5		27.33	0.944	94.4
6/6/12	699 Seaport Boulevard Redwood City, California 94063	31	29	26	20		26.5	0.977	97.7
6/11/12	Thunderbird Lane Livermore, California 94550	64	65	63	63		63.75	1.208	120.8

Source: Motiv Power Systems, Inc.

Figure 17: Vehicle Mile Log



Shuttle Drive Time Record

DATE	TIME OUT	MILEAGE OUT	TIME IN	MILEAGE IN	NAME	NOTES
03/23/12	17:24	204807	18:14	204821	Max	
03/23/12	21:35	204821			Will	
3/24/12	[illegible]	204821	15:10	204821.9	Ryan	Testing Motor drop-out. Inverter throwing multip
03/26/12	11:15 Am	204821.9	11:25 AM	204822.4	ALEX	TESTING MOTOR DROPOUT
03/26/12	11:36	204822.4	11:41	204822.8	Max	Testing motor dropout with backreved PCU code
"	14:00	204822.8			ALEX	"
03/26/12	17:28	204823.5	19:20	204837.3	Max/ALEX	"
3/27/12	10:10	[illegible]	11:49	204844.2	Ryan	"
03/28/12	9:20	204847		204860.6	ALEX	PARKING LOT / CHESS DR – DIED, BUT ALL NODES UP
03/29/12	11:00	204860.6	19:05	204882.1	ALEX/BRIAN/MARK	80KW, 49 MPH
03/30/12	11:20	204882.1	16:28	204898.7	MAX/ALEX/[illegible]	LUNCH, HIGHWAY 92, 49 mph
4/3/12	4:15	204908.0	5:28	204941.1	Ryan/Will	During fault, speedometer still 35MPH, so odometer keeps ti
4/13/12	12:02	204995.3			Ryan + 5	Lunch
4/13/12	2:30	204997.5		205023.5	WAYNE	[illegible] TRIP TO WING FOOT ~53 [illegible]
4/26/12	6:13	[illegible]			Will	To mixer in SF (Inverter Failure)
5/24/12			16:37	205171.8	Ryan	Testing with Will, Power Limits
5/29/12	16:23	205206.5			Ryan	
5/31/12	11:15	205217.5			Ryan and Will	Testing telemetry, current limits batt., Torque lim
6/1/12			18:37	205295.6	Ryan	Stanford trip – End SOC = (30, 33, 35, 3?)
6/5/12	2:30	205295.6	17:03	205325.1	Ryan	Testing with Will. ~~Weigh-in @ Simms~~ Hill/Grade Tes
6/6/12	10:10	205325.5	11:45	205351.4	Ryan	Testing with Will. Weighed @ Simms 14,180 lbs
6/7/12	2:25	205356.5				
6/11/12	2:40	[illegible]	5:45	205487.3	WAYNE	[illegible] START [illegible] LIVERMORE
6/12/12	5:10	205487.3	9.00	205563.7	WAYNE	HOME FROM [illegible]
6/15/12	11:45	205638.5	1:08	205643.7	Ryan	Team Lunch @ Joy
6/29/12	11:45	205643	1:49	205668	WAYNE	TEAM LUNCH & DRIVE AROUND – TESTING ALTIMETER OVERLAY
7/2/12	11:20	205689	1:20	205718	Brian	S.M. Foster city / TEST
7/3/12	10:20	205721	12:30	205756	Brian	San mateo Belmont, San Carlos 3rd Ave 101 Kehoe 101 to Dore – 35 m
7/3/12	4:20	205756	5:30	205796	BRIAN	REDWOOD Shores, Beach PARK blvd, Edgewater TEST #3

08/13/2012 03:12

Source: Motiv Power Systems, Inc.

Battery Competitive Performance Analysis

Table 2 shows a tabulated comparison of battery systems.

Table 2: Comparison of battery systems

Property	Dow Kokam Cleanbat Group	Lico Technology Corp. with Motiv BMS	Unit
Chemistry	Lithium-ion polymer	Lithium-ion polymer	
Cell Capacity	40	40.1	Ah
Cell Impedance	< 0.8	0.71	mΩ
Modules per Pack	4	6	
Cells per Module	48	32	
Pack Energy	28.4	28.4	kWh
Voltage Range	259 - 403	259 - 403	V
Peak Charge Current	150	20	A
Continuous Charge Current	80	20	A
Peak Discharge Current	300	140	A
Continuous Discharge Current	200	70	A
BMS Interface	CAN	CAN	
State of Charge Estimator	Yes	Yes	
State of Health Estimator	Yes	Yes	

Source: Motiv Power Systems, Inc.

The above table provides a performance comparison between the Dow Kokam battery packs originally installed on the vehicle and phase-2 battery pack from Lico Technology Corp. The mechanical configuration and BMS software for the two types of packs is completely different for these two systems. The electrical properties of the packs are similar because both use the same number of cells and cell chemistry. Note that it was entirely coincidental that the chemistry and cell count was the same between the two packs. The Motiv system can optimize multiple types of battery packs running at once even if voltage or cell count is different. This was shown during operation, when the state of charge of various battery packs, and by extension their actual voltage, varied. Power sharing between the packs was still successful.

Sustainability Results

So far, this project has offset 1,500 miles of driving on a 20-passenger shuttle bus. Some of these miles were testing, but many were for shuttling Motiv employees, or on routes for Bauer's Intelligent Transportation. The equivalent diesel vehicle has a fuel economy of around six miles per gallon. Therefore, approximately 250 gallons of diesel have been offset to date. Projections of the expected continued vehicle use upon grant completion are 30,000 miles per year for the next eight years, resulting in a savings of 40,000 gallons of diesel fuel. In addition, this project is responsible for additional deployment of electric trucks using Motiv's technology. Motiv estimates sales volumes of 10; 48; 600; and 2,500 vehicles over the next four years. These vehicles will all have an expected lifetime of eight years and about 30,000 miles per year. The resulting savings from the follow-on work enabled by this grant is projected to be 126 million gallons of diesel.

According to the California Greenhouse Gases, Regulated Emissions and Energy use in Transportation model, the carbon intensity for diesel of 94.7 grams of carbon dioxide equivalent CO_2e/megajoule and the carbon intensity for electricity of 124.1 grams of CO_2e/megajoule. The shuttle bus in this project averaged six miles per gallon with diesel, which equates to 2.2 kilograms (kg) of CO_2e/mile (assuming 137.8 megajoules/gallon diesel fuel). On electricity, the shuttle used one kWh or less per mile, which equates to 0.45 grams of CO_2e/mile (using 3.6 megajoules/kWh). The net carbon savings is 1.7 kg CO_2e/mile, or 10.4 kg CO_2e/gallon of diesel fuel offset. The total savings in fuel and carbon-based emissions are shown in table 3 below.

Table 3: Total and Projected Fuel and Greenhouse Gas Emissions Avoided

	Diesel (Gallons)	Carbon Emissions (kg CO_2e)
Savings to Date	250	2,600
Projected Project Savings	40,000	415,000
Projected Resulting Savings	126,000,000	1,310,000,000

Source: Motiv Power Systems, Inc.

Economic Results

This project has allowed Motiv to grow from a small, boutique consulting firm into an emerging leading supplier of electric truck components. Motiv has grown to 10 full-time employees, with plans for significant scaling in the near future. Through this project, Motiv has created the following positions: principal mechanical engineer, accounting clerk, senior mechanical engineer, principal software engineer, embedded software engineer, senior electrical engineer, power electronics engineer, senior controls engineer, and two mechanical technicians

Additionally, three California-based suppliers of Motiv will likely retain staffing increases as Motiv’s product suite sees increased piloting and commercial roll-out. These suppliers are Airtronics Metal Products, Inc. in San Jose, Suba Technology in Milpitas, and Noren Products in Menlo Park. Estimated totals for permanent, full-time job creation retention are shown in table 4. Note that Airtronics Metal Products, Inc. is located in an economic development zone, so the staffing increases there are an economic benefit to a low income community.

Table 4: New Job Creation Estimate

California-Based Company	Full-Time Equivalent Jobs
Motiv	
Engineering	7
Technicians	2
Administration	1
Airtronics Metal Products, Inc. (est.)	2
Suba Technology (est.)	1
Noren Products, Inc.(est.)	1
Total	**14**

Source: Motiv Power Systems, Inc.

In a longer time scale, Motiv expects to grow its staff to 108 people by 2015. While customer demand for electric vehicles and Motiv's products will drive this expansion, this project played an important role in the first step of this development.

This project has resulted in no negative impacts on any community, including disadvantaged communities. This project created $2.6 million in increased income in California, which has all been subject to either income tax (the labor portion), or sales tax (the non-labor portion, including materials, equipment, and so forth).

CHAPTER 4: Project Conclusions

This chapter reports cost analysis and lifetime projections. It then concludes with overall project results, conclusions and recommendations.

Cost and Carbon Analysis of Motiv's electric Powertrain Control System

Cost Analysis

An electric, medium-duty vehicle with the Motiv electric Powertrain Control System runs at approximately one kWh/mile instead of six miles per galloon diesel fuel. It saves roughly $0.57/mile in fuel costs (assuming $0.10/kWh and $4/gallon diesel). This vehicle can use any battery system, and thus gets the most competitive battery price. To field a vehicle today, the battery system for a 100-mile range (which is 100 kWh) would cost about $60,000. The Motiv electric Powertrain Control System and balance of electric drive system may cost an estimated additional $30,000. When compared to a diesel engine and transmission, which has a cost of at least $15,000, the increased up-front purchase price is $75,000. Presently, in California, there are vouchers[1] available to offset $35,000 in cost ($55,000 in the San Joaquin Valley), leaving a price differential of $40,000 ($20,000 in San Joaquin Valley). Saving $0.57/mile means that a vehicle would need to be driven 70,000 miles. With a 100 mile range, this may take somewhat over two years of operation. In the San Joaquin Valley, payback happens after just one year and one month.

Therefore, an electric truck or shuttle bus equipped with the Motiv electric Powertrain Control System in California today can pay for itself in around one year of operation. Over the vehicle's eight-year lifetime, it will have a lifetime operational savings of $97,000 ($117,000 in San Joaquin Valley).

Greenhouse Gas Emissions Reduction Economics

As shown in Chapter 3 section "Sustainability Results" above, an electric medium-duty vehicle with the Motiv electric Powertrain Control System saves 1.7 kg CO_2e/mile. This savings is free to the operator and actually saves money by operating this vehicle instead of a diesel vehicle.

By the time it has paid for itself, the vehicle has saved almost 29,900 kg of CO_2e. Over the vehicle's eight-year lifetime, it will save 415,000 kg of CO_2e.

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1 California Hybrid Vehicle Incentive Program, with "plus-ups" from San Joaquin Valley Air Pollution Control District

Vehicle Lifetime Estimates

The lithium-ion batteries are the predictive mean time between failure points in the vehicle. Their lifetime should extend to eight or more years. The useful lifetime of the lithium-ion batteries in the transportation field is approximately 3,000 charging cycles or approximately eight years. Secondary use in the fixed energy storage market should be approximately 12 years, giving the batteries a useful life of 20 years before recycling. Other than batteries, the useful life of the system will be determined by the mean time between failures of the inverter and power components in the systems

Overall Project Results

This project team accomplished all project goals. A suite of controllers and software was developed and demonstrated on a battery-agnostic all-electric shuttle bus. The shuttle bus performance was satisfactory to Bauer's Intelligent Transportation, the end user fleet. Two types of battery systems were demonstrated on this shuttle bus successfully. This project concluded on budget, and is the first project in its Project Opportunity Notice to conclude.

Project Conclusions

The purpose of the project as stated in the application manual was:

- The CEC is seeking to fund projects that develop the commercialization of advanced medium- and heavy-duty vehicle technologies.
- The intent of this solicitation is to provide funding to advance medium- and heavy-duty vehicles to significantly reduce the demand for petroleum fuels and greenhouse gas emissions in this critical market sector.

The project marked an important step towards the commercialization of the Motiv electric Powertrain Control System, which is a new technology for the electrification of medium-duty and heavy-duty vehicles. As described in Chapter 3, this technology has potential to reduce demand for petroleum fuels and greenhouse gas emissions.

GLOSSARY

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

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

CALIFORNIA 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:

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

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

KILOGRAM (kg) - The base unit of mass in the International System of Units that is equal to the mass of a prototype agreed upon by international convention and that is nearly equal to the mass of 1000 cubic centimeters of water at the temperature of its maximum density.

KILOWATT (kW) - One thousand (1,000) watts. A unit of measure of the amount of electricity needed to operate given equipment. On a hot summer afternoon a typical home, with central air conditioning and other equipment in use, might have a demand of four kW each hour.

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

CARBON DIOXIDE EQUIVALENT (CO_2e) - A metric used to compare emissions of various greenhouse gases. It is the mass of carbon dioxide that would produce the same estimated radiative forcing as a given mass of another greenhouse gas. Carbon dioxide equivalents are computed by multiplying the mass of the gas emitted by its global warming potential.

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

MOTIV POWER SYSTEMS, INC. (MOTIV) - An American manufacturer of all-electric chassis for medium-duty commercial vehicles, based in Foster City, California.[2]

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

WATT (W) - A unit of measure of electric power at a point in time, as capacity or demand. One watt of power maintained over time is equal to one joule per second. Some Christmas tree lights use one watt. The Watt is named after Scottish inventor James Watt and is capitalized when shortened to w and used with other abbreviations, as in kWh.

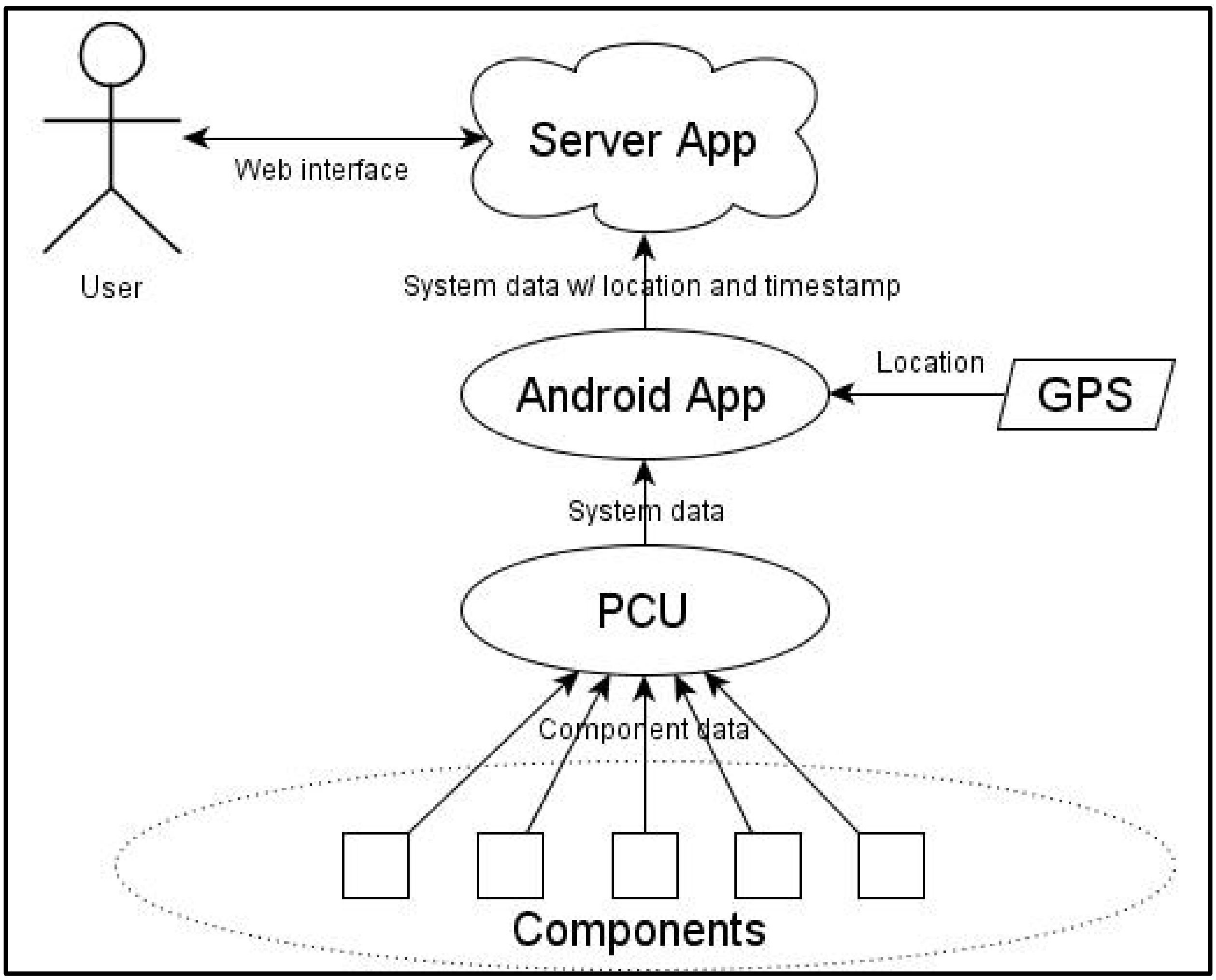
2 Motiv Power System Inc.'s Website

APPENDIX A: Remote Telemetry System Description

Overview

Motiv's remote telemetry system provides a means for real-time tracking of equipped vehicles, generation of preventative maintenance reports for fleet managers, and gathering of operational data valuable to battery and motor vendors. This system logs data from each powertrain component, stamps it with a time and location, and funnels it to a server application which manages the data and provides an interface to interested parties. A visual overview of this system is shown below in figure A-1.

Figure A-1: System Overview



Source: Motiv Power Systems, Inc.

Vehicle system

Raw data from each component is tunneled out of the vehicle system through the system controller (powertrain control unit). Data fields logged from the vehicle system include:

- System level:
  - powertrain control unit ID (serial number)
  - Accelerator pedal position
  - System efficiency
  - System faults
- For each battery:
  - Efficiency
  - State of charge
  - State of health
- For the motor:
  - Efficiency
  - Temperatures
  - Angular velocity of shaft
- For the charger:
  - Efficiency
  - Temperature
  - AC voltage
  - Ampacity
- For the 12V auxiliary power unit:
  - Efficiency
  - Power electronics temperatures
  - Voltage measured on 12V side
  - Current measured on 12V side

Android application

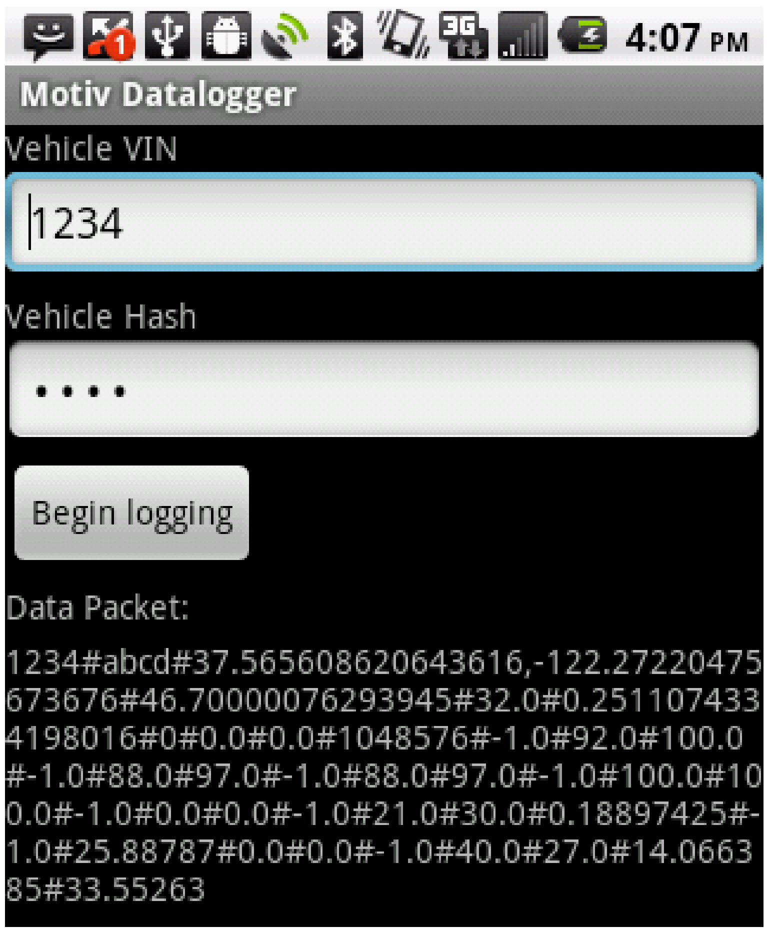
The Motiv data logger Android application receives data points sent from the powertrain control unit over a secure wireless connection. During configuration, the app obtains a vehicle identification number and alphanumeric hash from the user to identify the vehicle and authenticate the data being logged. Once a logging session is initiated, the system is ready to accept data points from the vehicle controller. When a data point is received the app appends the following fields.

- Timestamp (also serves as a unique identifier),
- Vehicle identification number,
- Location data,

- Built-in accelerometer reading.

Once these fields are appended, the data point is sent via a secure connection to a web server where it is handled by a server application. The raw data packet being sent is displayed in American Standard Code for Information Interchange format. The Android application user interface is shown in Figure A-2 below.

Figure A-2: Android Application

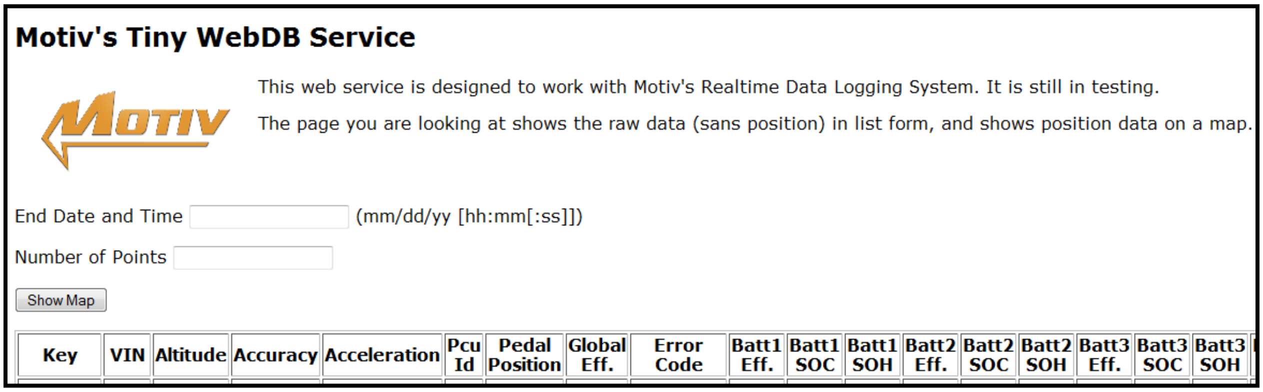


Source: Motiv Power Systems, Inc.

Server Application

The server application handles database management and data presentation. A web interface (requiring authentication) is provided to plot vehicle location and state of charge over a specified date range and display recently logged data points. Utilities allowing authorized users to perform functions such as extracting raw data sets, editing entries, and creating new vehicle identification hash pairs are also included. This web interface is located at https://www.motivtinywebdb.appspot.com. Figure A-3 shows the interface to the mapping feature.

Figure A-3: Mapping Feature Interface



Source: Motiv Power Systems, Inc.

APPENDIX B: Consolidated List of Subcontractors

The following is a list of all subcontractors funded by Motiv as the grant recipient.

Systems Consulting, Inc.

Address: 2850 SW Cedar Hills Blvd. #329, Beaverton, Oregon 97005.

Statement of Work**:** Systems Consulting provided embedded software development for this project. Work included the operating environment used on all embedded processors in Motiv's electric Powertrain Control System, sensor subsystem configuration, implementation and data processing, algorithm cradles, exerciser/test code, communications protocol definition and implementation, system administration policy definition and implementation, and other embedded programming.

Period: November 2010 through June 2012.

Value: $191,623.54 (50 percent CEC funded, 50 percent match by Motiv).

Lico Technology, Corp.

Address: 4F., NO,4, Ln.95,Anxing Rd., Xindian Dist., New Taipei City, Taiwan 23159.

Statement of Work**:** Lico Technology, Corp. provided a second battery system and support to bring that battery system up to an automotive-ready pack. This included the development of a charge and thermal management system, supplying 28 kWh of battery modules, and cell/module testing.

Period**:** November 2010 through June 2012.

Value**:** $607,000 (50 percent CEC funded, 50 percent match by Lico Technology Corp.).

Airtronics Metal Products, Inc.

Address**:** 1991 Senter Road, San Jose, California 95112.

Statement of Work**:** Airtronics Metal Products, Inc. provided fabrication of Motiv electric Powertrain Control System component enclosures and shuttle bus mounting brackets and cradles. Enclosures include charger, motor controller, battery adaptive power converter, powertrain control unit, and auxiliary power unit. Brackets include battery cradles, motor cradle, and auxiliary power unit mounting.

Period: November 2010 through June 2012.

Value**:** $33,549.68 (50 percent CEC funded, 50 percent match by Motiv).