FINAL TECHNICAL REPORT

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(Part of Transportation Electrification FOA: DE-FOA-0000028
Area of Interest 1)

Award Recipient: FCA US LLC f/k/a Chrysler Group LLC
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Project Title: Advancing Transportation through Vehicle Electrification – PHEV

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DISCLAIMER

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Executive Summary

Introduction

FCA US LLC viewed the American Recovery and Reinvestment Act (ARRA) as an historic opportunity to learn about and develop PHEV technologies and create the FCA US LLC engineering center for Electrified Powertrains. The ARRA funding supported FCA US LLC's light-duty electric drive vehicle and charging infrastructure-testing activities and enabled FCA US LLC to utilize the funding on advancing Plug-in Hybrid Electric Vehicle (PHEV) technologies for production on future programs. FCA US LLC intended to develop the next-generations of electric drive and energy batteries through a properly paced convergence of standards, technology, components and common modules. To support the development of a strong, commercially viable supplier base, FCA US LLC also utilized this opportunity to evaluate various designated component and sub-system suppliers. The original proposal of this project was submitted in May 2009 and selected in August 2009. The project ended in December 2014.

Financial Overview

The total budget of the project was $97.4 million. The contributions of FCA US LLC, the DOE and eight sub-recipients are shown in Table 1 below. It is also important to note that the sub-recipients Electrovaya and MAHLE Behr were component suppliers.

Participant	DOE Contribution ($ million)	Participant Contribution ($ million)	Total Budget ($ million)
FCA US LLC	36.9	41.4	78.3
Electrovaya	6.7	5.6	12.3
UM-Dearborn	2.2	0.7	2.9
EPRI	0.5	0.5	1.0
NextEnergy	0.4	0.5	0.9
UC-Davis	0.6	0.1	0.7
MAHLE Behr USA	0.3	0.3	0.6
SMUD	0.2	0.2	0.4
MSU	0.2	0.1	0.3
Grand Totals	48	49.4	97.4

Table 1: Project contributions by project participants

Project Objectives

The objective of this project was to evaluate and demonstrate advanced PHEV technologies across a range of geographic, climatic and operating environments and to accelerate the production and market penetration of PHEVs. Transportation Electrification FOA (DE-FOA-0000028 Area of Interest 1) specified the required conditions for the PHEV vehicle development and demonstration as:

- In a fleet of 100 or more vehicles
- Across a range of geographic, climatic and operating environments
- For a period of two years
- That meet 2010 emissions standards
- With an electric range of ≥10 miles and a total range ≥300 miles
- That can be accelerated for production and market penetration of PHEVs

By gaining a better understanding of consumer usage and operational needs, FCA US LLC was able to refine specifications for PHEV platforms and attain relevant experience to apply to future production programs during and after the project's conclusion. More broadly, the project offered important economic and environmental benefits by creating U.S.-based high-technology green jobs and ultimately enabling significant reductions in petroleum consumption and greenhouse gas (GHG) emissions.

Project Timeline

The overall timeline is shown in Figure 1 below.

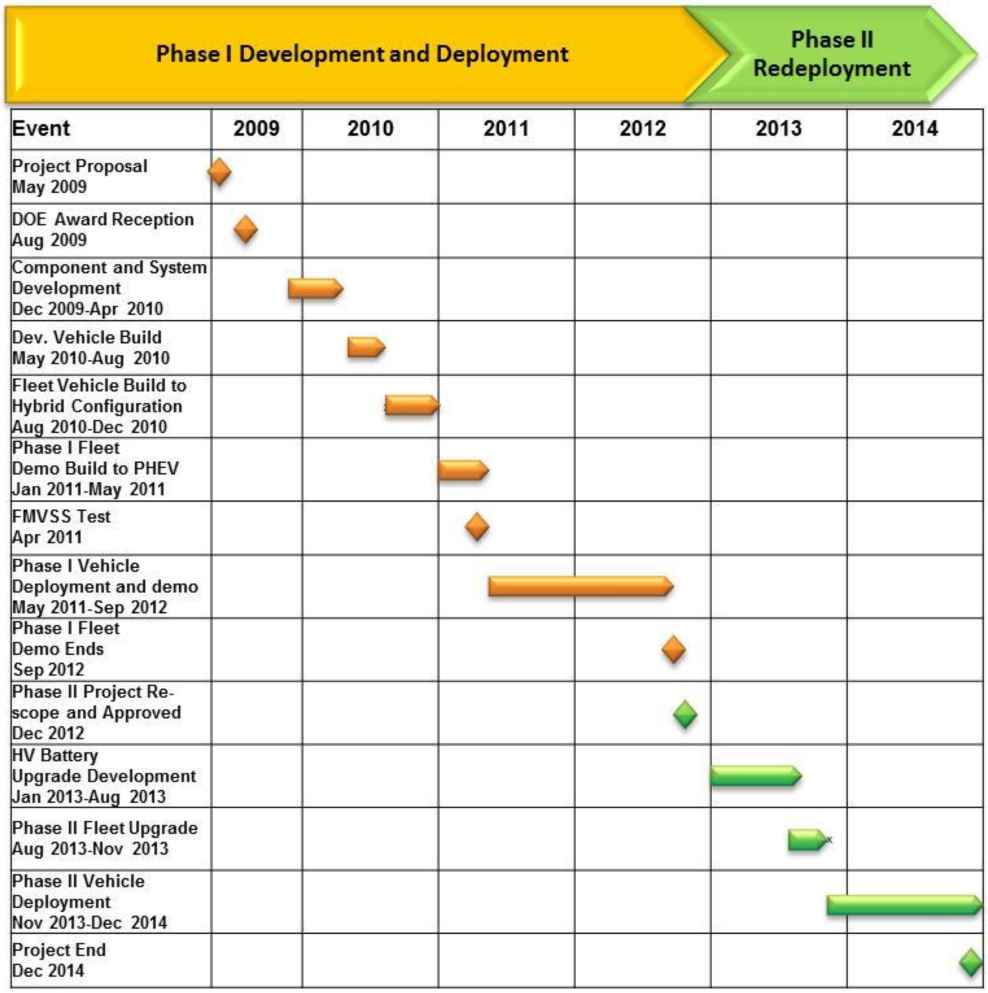

Figure 1: Project timeline

Scope of Work

The scope of work included vehicle integration and functional verification of key PHEV components and bench validation of key components and subsystems. The PHEV technology for the demonstration vehicles was developed with the intent of meeting seven key functional objectives:

1. No compromise of vehicle drivability versus customer behaviors
2. Vehicle acceleration performance in line with consumer expectations
3. Adequate power to meet the US06 drive cycle in charge-sustaining mode

4. Gradeability requirements in charge-sustaining mode
5. Optimized engine operation during charge-sustaining mode
6. Recapture the majority of vehicle kinetic energy through regenerative braking during the US06 drive cycle
7. Trailer-towing capability

During the component and system development phase, FCA US LLC successfully built one PHEV prototype concept vehicle for early development and 12 advanced-development vehicles. FCA US LLC accelerated development and validation, created supplier interfaces to finalize PHEV component and subsystem refinements and developed tooling and equipment required to build a fleet of demonstration vehicles.

Phase I

In Project Phase I, 140 PHEV light duty demonstration trucks were built based on 2011 Ram 1500 production model vehicles that were modified and retrofitted with PHEV systems. The vehicles included data collection and remote diagnostics instrumentation for the deployment to the fleet demonstration partners. The vehicles were delivered to the demonstration partners for fleet testing, in accordance to the legal agreement regarding the defined vehicle usage and testing profiles required of the partners. During Phase I, the PHEVs were subject to routine vehicle usage across 16 different external partners, 17 U.S. locations and the FCA US LLC Technical Center from May 2011 to September 2012.

In accordance with the agreement, eight DOE project award sub-recipients performed a series of research work for the development and implementation of the PHEV technology. Of the eight sub-recipients:

- Two sub-recipients, Electrovaya and MAHLE Behr, completed research activities and subsequently supplied components as a result of that research
- One sub-recipient, SMUD, completed research activities and participated as a fleet deployment partner
- The remaining sub-recipients provided research activities lending strong support of the project development objectives

During the Phase I deployment, several field issues were observed with the high-voltage energy storage system that impeded research work progress by the fleet partners. These included:

- Insufficient cell balancing, resulting in cell-to-cell voltage variation
- Thermal management and voltage control strategy not robust enough to manage cell-to-cell variations
- Variable and excessive cell self-discharge, leading to performance degradation

To overcome these issues, FCA US LLC took the demonstration program to the next stage by upgrading the energy storage system on select fleet vehicles and redeploying them in Project Phase II. In addition, several new features were also introduced and validated at FCA US LLC and across demonstration fleet partners. These features included optimizing the following functionalities:

- Reverse Power Flow (RPF)
- Smart Charging
- Continued Map-Based Fuel Economy Optimization

In Phase I, the overall MPG of the fleet partners with active map based fuel economy system was 24.1 MPG, a 39% increase over the fuel economy of non-active system, which is 17.3 MPG.

Phase II

For Phase II demonstration, 34 vehicles were fitted with the upgraded energy storage systems. The rationale behind the decision to reduce the fleet to 34 select vehicles was that Phase I targets had been achieved and Phase II focused more on resolving field issues and demonstrating new features. The trucks were then redeployed to the demonstration partners for advanced technology investigation. The PHEVs were subject to routine vehicle usage across 16 different external partners, 17 U.S. locations and the FCA US LLC Technical Center from October 2013 to December 2014.

The objectives of Phase II include the following activities:

- Finalize the development and verification of the upgraded high-voltage energy storage system

- Continue calibration/controls development and optimize fully integrated systems
- Complete vehicle durability and validation with the upgraded high-voltage energy storage system
- Optimize the following functionalities:
    - Reverse Power Flow
    - Smart Charging
    - Map Based Fuel Economy Optimization

Reverse Power Flow (RPF) was utilized and monitored to obtain more relevant field data. Moreover, Smart Charging and DC Charging were developed and introduced as new charging approaches, in addition to the manual and scheduled charging in Phase I:

- Smart Charging (In a scheduled charging period, customers can choose the charging process to be one of three options: Cheapest, Fastest or Optimized.)
- DC Charging (Utilize DC wall power to achieve a faster charging process)

The ultimate goal of charging systems is to combine Smart Charging, Reverse Power Flow and DC Charging capabilities. The synergies that can be realized from this combination are reduced costs for the customers and improved grid management for the electric utilities.

During Phase II, the overall MPG of the fleet partners with the active map-based fuel economy system was 24.5 MPG, a 22% increase over the fuel economy of non-active system (20 MPG).

Project Lessons Learned

All of the lessons learned in this project are being applied to current and future electrification applications. These fall into four categories:

- Thermal systems
- Charging systems
- High-voltage energy storage systems
- Vehicle drivability and fuel economy

In addition to the lessons learned at FCA US LLC from the fleet demonstration deployments, the sub-recipient research created additional benefits. All project sub-recipients are well-known public institutions (e.g. utilities, municipalities, research entities or universities) or commercial suppliers capable of managing large-scale projects. Furthermore, their extraordinary credentials in terms of research capability, industrial and technological knowledge and academic rigor made them well qualified development and demonstration partners in this project.

PHEV Technology Commercialization and Benefits to the Public

FCA US LLC's commitment to electrification is manifested in its investments in offering vehicles that use advanced powertrains, including the PHEV and Battery Electric Vehicle (BEV). FCA US LLC's technology strategy is built around developing significant capabilities in powertrain platforms and a diverse powertrain portfolio. The objectives are to meet customer needs in PHEVs and BEVs, as well as to reduce non-renewable energy consumption and GHG emission. The electrification technology developed and demonstrated in this project has been leveraged for FCA's future programs.

In addition to the public economic benefits derived from the PHEV vehicle, FCA US LLC and the sub-recipient organizations created FTE (Full Time Equivalent) engineering U.S.-based high-technology green jobs, including FCA US LLC engineers, program management and technical support resources, as well as sub-recipient resources. The year-over-year FTE jobs are shown in Table 2 below.

	2009 Pre-Award 4 Months	2010 Pre-Award 3 Months	2010 9 Months	2011 12 Months	2012 12 Months	2013 12 Months	2014 12 Months	2015 3 Months
FCA US LLC	30	84	91	76	47	26	21	2
Sub-recipients	-	5	3	6	9	8	-	-
Total FTE	30	89	94	81	56	34	21	2

Table 2: Year-over-year FTE engineering jobs

The fleet partner staffs, FCA US LLC dealer service network and component suppliers also added positions that are not reflected in the table.

Power Grid Management Opportunities

With the introduction of PHEV vehicles as a means to reduce national fuel consumption and GHG into the atmosphere, the effect on the U.S. electric grid system needs to be minimized.

The grid load mitigating features developed in this project related to the grid charging events include:

- Smart Charging that allows the consumer to manage the charging event during high demand on the electrical grid, with input from the utility
- Reverse Power Flow that allows the electric utility to use the PHEV high-voltage energy storage system to further smooth the peaks in power demand

NOMENCLATURE

AC	Alternating Current
A/C	Air Conditioning
ANL	Argonne National Laboratory
AT-PZEV	Advanced Technology Partial Zero Emissions Vehicle
BEV	Battery Electric Vehicle (All Electric)
BMS	Battery Management System
CAN	Controller Area Network
CIL	Controller In-the-Loop
CD	Charge Depleting
CPCP	Chrysler Product Creation Process
CS	Charge Sustaining
DC	Direct Current
DFMEA	Design Failure Mode and Effects Analysis
DOE	Department of Energy
DRLC	Demand Response Load Control
DRM	Data Recording Module
DVP&R	Design Verification Plan & Report
E85	Ethanol (85% Ethyl Alcohol)
EAER	Equivalent All Electric Range
ECM	Engine Control Module
EIA	Energy Information Administration
EoL	End of Life
EPA	Environmental Protect Agency
EPRI	Electric Power Research Institute
EV	Electric Vehicle
EVSE	Electric Vehicle Supply Equipment
FCA	Fiat Chrysler Automobiles
FOA	Funding Opportunity Announcement
FE	Fuel Economy
FMVSS	Federal Motor Vehicle Safety Standards
FTE	Full Time Equivalent
GHG	Greenhouse Gas
GPS	Global Positioning System
HCP	Hybrid Control Processor
HEV	Hybrid Electric Vehicle
HMI	Human Machine Interface

HV	High-Voltage
HVAC	Heating, Ventilating and Air conditioning
HVBS	High-Voltage Battery System
ICE	Internal Combustion Engine
IEEE	Institute of Electrical and Electronics Engineers
IHD	In-Home Display
INL	Idaho National Laboratory
IVD	In-Vehicle Display
MDS	Multi Displacement System
MPG	Miles per Gallon
MPGe	Miles per Gallon Equivalent
MY	Model Year
NiMH	Nickel-metal Hydride
NREL	National Renewable Energy Laboratory
NVH	Noise, Vibration and Harshness
OBC	On Board Charger
OBCM	On Board Charging Module
OEM	Original Equipment Manufacturer
PCM	Powertrain Control Module
PEV	Plug-in Electric Vehicle
PHEV	Plug-in Hybrid Electric Vehicle
PSAT	Powertrain System Analysis Toolkit
PZEV	Partial Zero Emissions Vehicle
RPF	Reverse Power Flow
SEP	Smart Energy Profile
SOC	State of Charge
SUV	Sport Utility Vehicle
SULEV	Super Ultra Low Emissions Vehicle
TCIN	Time Charge Is Needed
TCO	Total Cost of Ownership
TPIM	Traction Power Inverter Module
V2G	Vehicle to Grid
V2H	Vehicle to Home
VAC	Volts Alternating Current
VCT	Variable Cam Timing

1. Introduction and Background

FCA US LLC viewed the American Recovery and Reinvestment Act (ARRA) as a historic opportunity to begin the process of achieving required economies of scale on technologies for electric vehicles. The ARRA funding supported FCA US LLC's light-duty electric drive vehicle and charging infrastructure-testing activities while also enabling the company to apply the funding toward advancing Plug-in Hybrid Electric Vehicle (PHEV) technologies for future programs. FCA US LLC intended to develop the next generations of electric drive and energy batteries through a properly paced convergence of standards, technology, components and common modules, as well as first-responder training and high-voltage energy storage system recycling. To support the development of a strong, commercially viable supplier base, FCA US LLC also took this opportunity to evaluate various designated component and sub-system suppliers. The original project proposal was submitted in May 2009 and selected in August 2009. The project ended in December 2014.

Financial Overview

The project budget was $97.4 million. The contributions of FCA US LLC, the DOE and eight sub-recipients are shown in Table 3 below. It is also important to note that Electrovaya and MAHLE Behr were component suppliers as well as project sub-recipients.

Participant	DOE Contribution ($ million)	Participant Contribution ($ million)	Complete Budget ($ million)
FCA US LLC	36.9	41.4	78.3
Electrovaya	6.7	5.6	12.3
UM-Dearborn	2.2	0.7	2.9
EPRI	0.5	0.5	1.0
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UC-Davis	0.6	0.1	0.7
MAHLE Behr USA	0.3	0.3	0.6
SMUD	0.2	0.2	0.4
MSU	0.2	0.1	0.3
Grand Totals	48	49.4	97.4

Table 3: Project contributions by participant

1.1 Project Objectives

The objective of this project was to demonstrate and evaluate advanced PHEV technologies across a range of geographic, climatic and operating environments and to accelerate the production and market penetration of PHEVs. Transportation Electrification FOA (DE-FOA-0000028 Area of Interest 1) also specified the features that the developed PHEV must meet:

- In a fleet of 100 or more vehicles
- Across a range of geographic, climatic and operating environments
- For a period of two years
- That meet 2010 emissions standards
- With an electric range of ≥10 miles and a total range ≥300 miles
- That can be accelerated for production and market penetration of PHEVs

By gaining a better understanding of consumer usage and operational needs, FCA US LLC was able to refine specifications for PHEV platforms and attain relevant experience for future production programs during the project and after its conclusion. More broadly, the project offered important economic and environmental benefits by creating U.S.-based high-technology green jobs and enabling significant reductions in petroleum consumption and greenhouse gas (GHG) emissions. Specific project objectives are:

System design objectives

- Prove that the system solution is capable of:
    1. Producing controllable traction forces from minimum to maximum under different high-voltage energy storage system temperatures, ambient temperatures, altitudes and vehicle speeds
    2. Displacing fuel efficiently in all driving scenarios for all customers
    3. Achieving efficient charge-sustaining operations
- Verify plug-in charging mode performance based on charger and high-voltage energy storage system model
- Verify AC power generation mode
- Prove that the system solution represents optimal cost/benefit tradeoffs for a wide range of customers and operating conditions – e.g., across different types of commutes, variations in driving aggressiveness, road loads, high-voltage energy storage system temperatures, ambient temperatures, altitudes, variations in charging events and fuel and electricity costs

Development vehicle verification objectives

- Confirm vehicle functional objectives, including fuel economy, performance and effect compliance
- Prove emission targets can be achieved
- Demonstrate drivability and safety parameters

Fleet demonstration objectives

- Profile vehicle usage
- Profile customer expectation
- Prove product viability in “real-world” conditions
- Develop bi-directional (communication and power) charger interface
- Confirm that conditions for viable mass productions can be met
- Quantify the benefits to customers and to the nation

1.2 Scope of Work

The scope of work included vehicle integration and functional check of key PHEV components, and bench validation of key components and sub-systems. The PHEV technology for the demonstration vehicles has been developed with the intent of meeting seven key functional objectives:

1. No compromise of vehicle drivability versus customer behaviors
2. Vehicle acceleration performance in line with consumer expectations
3. Adequate power to meet the US06 drive cycle in charge-sustaining mode
4. Grade-ability requirements in charge-sustaining mode
5. Optimized engine operation during charge-sustaining mode
6. Recapture the majority of vehicle kinetic energy through regenerative braking during the US06 drive cycle
7. Trailer-towing capability

In addition to enabling FCA US LLC to apply lessons learned to improve its fleet vehicle performance in a timely manner, the project’s approach provided the opportunity to apply the latest technology and effectively gather useful information from the fleet deployments.

1.2.1 Phase I Project Scope

During the component and system development phase, FCA US LLC successfully built one PHEV prototype concept vehicle for early development and 12 advanced development vehicles. FCA US LLC accelerated development and validation, created supplier interfaces to finalize PHEV component and sub-system refinements and developed tooling and equipment required to build a fleet of demonstration vehicles.

In Project Phase I, 140 PHEV light duty demonstration trucks were built based on 2011 Ram 1500 production model vehicles; these were modified and retrofitted with PHEV systems. Additionally, vehicles included data collection and remote diagnostics instrumentation for the deployment to the fleet demonstration partners. The vehicles were delivered to the demonstration partners for fleet testing, in accordance to the legal agreement regarding the defined vehicle usage and testing profiles required of the partners. During Phase I, the PHEVs were subject to routine vehicle usage across 16 different external partners, 17 US locations and the FCA US LLC Technical Center. Phase I demonstration partners are listed in Table 4 below.

Phase I Partners	**Location**	**Type**	**# of Vehicles**
Argonne National Labs	IL	Research	1
CenterPoint Energy	TX	Electric Utility	5
Central Hudson	NY	Municipality	3
City of Auburn Hills	MI	Municipality	4
City of San Francisco	CA	Municipality	14
City of Yuma	AZ	Electric Utility	10
DTE Energy (Detroit Edison)	MI	Electric Utility	9
Duke Energy	NC	Electric Utility	10
EPRI (Electric Power Research Institute)	CA	Research	1
EPRI	NC	Research	1
Idaho National Labs	ID	Research	1
MBTA (Massachusetts Bay Trans. Authority)	MA	Electric Utility	10
National Grid	MA, NY	Electric Utility	6
Nevada Energy	NV	Electric Utility	7
New York Police Dept.	NY	Municipality	5
SMUD (Sacramento Municipal Utility Dept.)	CA	Municipality	14
Tri-State Energy	CO	Electric Utility	6
FCA US LLC	MI	Development	33

Table 4: Phase I partners by location and research type

Data was collected in order to evaluate the viability of PHEV systems under typical customer usage, understand typical consumer use of PHEV vehicles, evaluate the effectiveness of HMI interfaces and assess consumer comfort with and acceptance of PHEV technologies. Findings were used to drive product improvements for planned vehicles across PHEV and HEV product lines.

1.2.2 Project Re-Scope and Phase II

During Phase I, the PHEV development and vehicle integration objectives were all achieved. In fleet deployment, however, several field issues were observed that impeded research work progress by the fleet partners. These included:

- Insufficient cell balancing, resulting in cell-to-cell voltage variation
- Thermal management not robust enough to manage cell-to-cell variations
- Variable and excessive cell self-discharge, leading to performance degradation

To address existing and potential field issues and take advantage of emerging technologies, FCA US LLC upgraded the energy storage system on select fleet vehicles and redeployed them in Phase II. For Phase II redeployment, FCA US LLC focused on the following perspectives:

- Finalize the development and verification of the upgraded high-voltage energy storage system
- Continue calibration/controls development and optimize fully integrated systems
- Complete extended vehicle durability and validation with the upgraded high-voltage energy storage system
- Continue hot- and cold-weather validation of vehicle software
- Optimize the following functionalities during Phase II of the project:
    - Reverse Power Flow
    - Smart Charging
    - Map-Based Fuel Economy Optimization
- Continue capturing fleet data to support calibration and controls development
- Continue development and calibration of Scheduled Charging

During this phase, 34 Ram 1500 PHEV trucks were deployed across eight different external partners, nine U.S. locations and FCA US LLC Technical Center. The number of vehicles deployed was reduced to 34 Ram 1500 PHEV trucks from the original 140 vehicles. The reduction marked the completion of Phase I objectives and allowed a sharp focus on the Phase II objectives noted above. A summary of the fleet partners involved in Phase II is listed in Table 5 below.

Phase II Partners	**Location**	**Type**	**# of Vehicles**
Argonne National Labs	IL	Research	1
CenterPoint Energy	TX	Electric Utility	2
DTE Energy (Detroit Edison)	MI	Electric Utility	5
Duke Energy	NC	Electric Utility	4
Duke Energy	KY	Research	1
EPRI	CA	Research	1
National Grid	MA, NY	Electric Utility	2
SMUD	CA	Municipality	5
Tri-State Energy	CO	Electric Utility	3
FCA US LLC	MI	Development	10

Table 5: Phase II partners by location and research type

1.2.3 Scope of Sub-Recipient Activities

Throughout the project, eight DOE project award sub-recipients conducted research toward the development and implementation of the PHEV technology. Among the eight sub-recipients, EPRI and SMUD were also fleet demonstration partners. A summary of their project activities and award status is shown in Table 6 on the next page.

Project Sub-recipients	Project Activity Summary
Electrovaya	Designed and manufactured the high-voltage energy storage system packs for the Phase I demonstration PHEVs
MAHLE Behr USA	Engineering R&D for the thermal systems in the demonstration PHEVs
EPRI (Electric Power Research Institute)	• Provided a test facility with infrastructure to charge and discharge PHEVs • Performed data collection, analysis and reporting • Provided Multi-Protocol Router and EVSE Com Modules for redeployed vehicles and development of Smart Grid
SMUD (Sacramento Municipal Utility Dept.)	• Provided infrastructure in the Sacramento, CA area to charge and discharge PHEVs. • Finalized data collection, analysis and reporting for vehicle to grid
NextEnergy	• Provided access to MicroGrid power test pavilion and performed charger development and verification. • Other activities included early grid integration and smart grid verification
University of California – Davis	• Assisted city of San Francisco in defining fleet applications that maximize the benefits of PHEVs and strategic placement of charging infrastructures • Collected and analyzed information from driver and fleet manager interviews and from on-board data recording instrumentation in order to recommend improvements to the vehicle design • Completed collecting and analyzing information from driver and fleet manager interviews and from data recording instrumentation onboard the PHEVs to maximize benefits of PHEVs
Michigan State University	• Derived and improved powertrain and vehicle system models • Identified system parameters using HIL models; parameters have been validated by experimental data • Completed developing an online implementation of the iterative learning predictive algorithm to estimate the desired power for a hybrid powertrain, validating it through online HIL simulations and optimizing the parameters of the proposed iterative predictive algorithm
University of Michigan – Dearborn	• Developed management tools for the State of Health and State of Charge parameters for Lithium-ion batteries • Studied soft switching that can help improve efficiency in on-board chargers • Studied the state of health estimation of lithium-ion polymer batteries for PHEV – state of charge independent method using multi-scale Kalman filtering. • Studied the high-voltage energy storage system modeling using a data-driven, bias-correction approach for electric vehicle application • Studied the efficiency optimization and loss minimization-based charging strategy research for lithium-ion battery • Completed dynamometer testing of EV motors for FCA US LLC's EV projects • Completed fabrication of back support for dynamometer testing

Table 6: Project sub-recipients summary

1.3 Project Management Cadence and Structure

Project management established a clear communications protocol, through meetings and documentation to ensure all partners were closely engaged and working toward a shared solution. There were seven key milestones during the course of the project; they were managed through a robust governance structure. Project management ensured that milestone reports, as well as minutes from working group and advisory board meetings, were communicated in a timely manner to the DOE.

The cadence of key project events was supported by the following activities:

- FCA Internal Cross-functional Team Meeting – Weekly
- Meeting with DOE Program Manager – Biweekly
- FCA Internal Advisory Board Review – Quarterly
- DOE Project Progress Report – Annually
- DOE VSST Annual Report – Annually
- DOE Annual Merit Review – Annually
- DOE/FCA External Audit – Annually

2. Vehicle Systems Development and Technical Effectiveness

FCA US LLC has developed and proved the concept of PHEV configuration in previous projects. Beginning in 2008, FCA US LLC built an early prototype concept vehicle for advanced-development PHEV based on the production platforms of the time. These early prototype vehicles achieved useful drivability, performance and fuel economy improvements and laid the foundation for the demonstration PHEVs developed in this project. FCA US LLC made significant progress in powertrain controls to meet the PHEV project requirements:

- Real-time optimization solutions and executions to achieve the most efficient propulsion system operations to meet driver demands, covering both charge-depleting operations and charge-sustaining operations
- Refined high-voltage energy storage system State of Charge (SOC) estimation and power limits model; refined high-voltage energy storage system voltage and temperature limit controls; refined electric drive capability and controls

The Ram 1500 pickup truck was chosen as the demonstration vehicle platform because of its versatility and capability to operate over a wide range of vehicle driving conditions. The choice was also consistent with the market's needs for commercial PHEV technologies on large vehicles, such as minivans, pickups and SUVs.

Key Innovations:

- Real-time online optimization of battery electric power and engine mechanical power
- Interactive Human Machine Interface (HMI) to help drivers maximize fuel economy
- Supply of clean on-board power for stationary power requirements
- Flexibility of plug-in charging times at grid connection
- High-voltage energy storage system thermal management to maximize PHEV benefits in extreme ambient conditions

To explore the costs versus benefit tradeoff of PHEVs in a multi-dimensional design space, a proprietary model-based system design tool was developed. The model was based on FCA US LLC's advanced propulsion technology simulation tool, similar to Argonne National Laboratory (ANL)'s Powertrain System Analysis Toolkit (PSAT). System control laws and actuator responses were implemented within the framework of FCA US LLC production. The tool was used to explore further efficiency improvements during the project.

2.1 PHEV Electrical Architecture

The network topology defines the vehicle electronic modules and data bus on which the modules communicate. The software and controls of the powertrain, chassis, and safety modules have been integrated as a system to provide seamless operation. The cabin, audio and telematics electronics provide feedback to the vehicle operator. The network topology is the blueprint of the electrical system structure. Figure 2 below illustrates the details of such topology for the demonstrated PHEV.

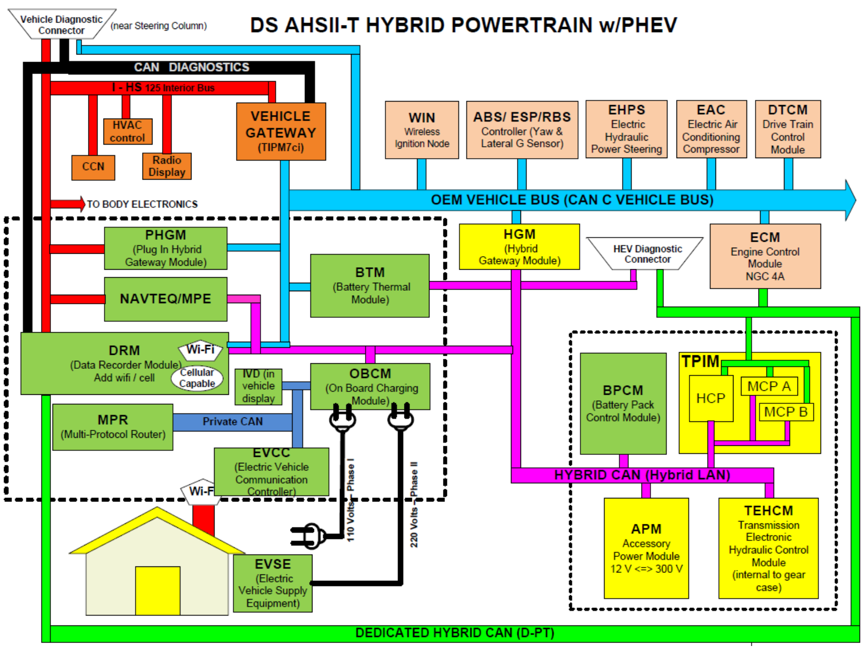


Figure 2: Network topology of the PHEV electrical network

2.2 High-Voltage Energy Storage System

Description

PHEV power and energy requirements for the high-voltage battery system were driven by functional objectives designed to meet customer and regulatory requirements. Energy storage remains a key component to the viability of PHEV. Lithium-ion batteries are the dominant chemistry for electrically driven vehicles due to their higher energy and power density and potential for lower cost. Present-day lithium-ion batteries can achieve specific power and energy levels that are much higher than those of nickel-metal hydride (NiMH) packs.

Goals and Targets

The performance goals set for the high-voltage battery system are shown in Table 7 below. The PHEV goals were initially developed from the United States Advanced Battery Consortium (USABC) Minimum PHEV requirements [1]. The high-voltage battery system was required to integrate into the existing Ram 1500 HEV, replacing the HEV battery pack, with minimal impact to the vehicle and occupant environment.

Requirements	**Units**	**Value**
Peak Pulse Discharge Power (10 sec)	kW	45
Peak Regen Pulse Power	kW	30
Max. Discharge Current (10 sec pulse)	A	300
Available Energy for CD (Charge Depleting) Mode	kWh	5.4
Available Energy for CS (Charge Sustaining) Mode	kWh	0.5
Minimum Round Trip Energy Efficiency	%	90
Cold Cranking Power at -30^oC	kW	7
CD Life/Discharge Throughput	Cycles / MWh	5,000/28
CS HEV Cycle Life	Cycles	300,000
Calendar Life	Years	15
Maximum System Weight	kg	105
Maximum System Volume	Liter	120
Nominal Operating Voltage - HV portion	Vdc	333
Maximum Operating Voltage - HV portion	Vdc	410
Minimum Operating Voltage - HV portion	Vdc	260
Nominal Operating Voltage - LV portion	Vdc	12
Maximum Operating Voltage - LV portion	Vdc	16
Minimum Operating Voltage - LV portion	Vdc	6
System Plug-in Charge Power at 30^oC	kW	1.4 (110V/15A)
Unassisted Operating & Charging Temperature Range	^oC	-30 to 52
Operating Temperatures versus Base 10 sec Peak Discharge/Charge Power		
Above 52^oC	kW	0/0
30^oC - 52^oC (100%)	kW	45/30
0^oC (50%)	kW	22.5/15
-30^oC (30%)	kW	13.5/9
-20^oC (15%)	kW	6.75/4.5
-30^oC (10%)	kW	4.5/3
No unassisted operation below -40^oC	N/A	N/A
Survival Temp Range	^oC	-46 to +66
Capacity of HV Battery Pack	kWh	12.9

Table 7: Energy storage system requirements for RAM 1500 PHEV

Design, Implementation and Integration

Electrovaya was chosen as the high-voltage energy storage system supplier for Phase I of the program due to the company's ability to meet the technical and program requirements of the high-voltage energy storage system. Electrovaya designed all parts – including cells, pack, controls and housing, in their Mississauga, Ontario facility.

The housing was built with FCA US LLC oversight at Detroit-area steel stamping companies that have extensive manufacturing capability. The lithium-ion cells were built at the Electrovaya Mississauga Plant throughout the project duration. The complete high-voltage energy storage system was produced at the Electrovaya manufacturing facility in Malta, New York. All packs were assembled, tested and shipped from the Malta facility for all initial production and service pack rework throughout Phase I.

The Electrovaya high-voltage energy storage system solution offered several features [2]. Electrovaya lithium-ion SuperPolymer® MN-Series cells were among the highest energy density commercially available at project initiation. This enabled high-voltage energy storage systems to be packaged within the restrictive volume of the vehicles, and to meet the energy targets for the program. Figure 3 below shows the internal configuration of the high-voltage energy storage system comprised of four lithium-ion SuperPolymer high-voltage energy storage system modules with integrated power control management system, battery management system and thermal management system [2].

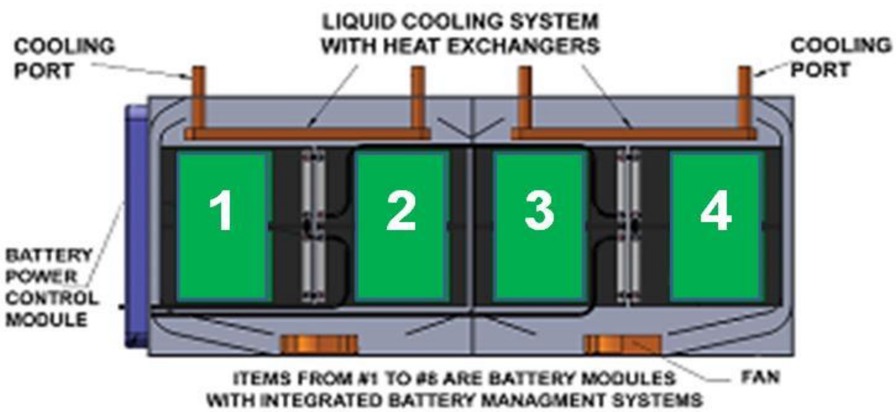


Figure 3: Internal configuration of Electrovaya high-voltage energy storage system pack [2]

Figure 4 on the next page shows the complete high-voltage energy storage system pack as installed in the Ram PHEV trucks:

Figure 4: Electrovaya high-voltage energy storage system pack as installed in Phase I

The self-contained, high-voltage energy storage system power electronics were placed in the high-voltage energy storage system case to ensure short lengths of high-voltage wiring. Thermal management featured a liquid cooling system provided cool air circulating within a closed loop. A liquid-to-air heat exchanger conditioned the air and recirculated it within the four quadrants of the high-voltage energy storage system. The pack construction was designed to protect against liquid coolant intrusion for added safety. The high-voltage energy storage system module held the cells in a proprietary “egg-carton” construction. It provided structural support to the cells with excellent vibration and shock tolerance. The thermal management was proprietary and produced minimal temperature gradient across the module. The module/cells required no stack pressure. Module-level and cell-level slave high-voltage energy storage system management was fully integrated into the module, which was designed to be easily replaceable by an automotive technician.

The battery management system optimized the high-voltage energy storage system for peak performance at the cell and module level. Additionally, it protected the system and provided system-level interface communications to the vehicle computer. Every cell was constantly monitored for optimized system performance using algorithms for equalization, state-of-charge, state-of-health and pre-charge. High-voltage energy storage system safety mechanisms included such features as a manual disconnect, thermal management and protection against over-voltage, under-voltage, over-current and over-charge.

The cells in the original high-voltage energy storage system design experienced repeated excessive variation in self-discharge, leading to difficulties in maintaining cell balance within the high-voltage energy storage system. This led to significant energy storage system performance limitations while in the field, as well as concerns with prolonged plug-in charging of the system. The cell self-discharge variation could lead to cell failures on extended plug-in charge. The replacement of the cell, with a cell not exhibiting the same root cause, was required to dramatically reduce cell-to-cell variation, as well as self-discharge variation. This led to highly predictable system performance, both in the field and during plug-in charging. This issue was addressed with the high-voltage energy storage system upgrade in Phase II of the project.

2.3 High-Voltage Energy Storage System Upgrade

As mentioned in the Scope of Work, the high-voltage energy storage systems on select PHEV trucks were upgraded in Phase II to address potential field issues and to take advantage of emerging technologies. Given a successful base vehicle with functional high-voltage energy storage management and thermal control systems, the key was to select and implement a new cell design in the same high-voltage energy storage system housing and vehicle package.

To evaluate cell supplier alternatives, FCA US LLC focused on domestic suppliers who could be viable future suppliers, preferably from the USABC development community – where sufficient information was present to evaluate and choose. The major selection criteria were cell technology with comparable controls ranges, i.e. cell min/max voltages, nickel manganese cobalt electrochemistry and cell capacity/ form factor.

Johnson Controls Incorporated (JCI) was chosen as the high-voltage energy storage system cell supplier because the company is capable of providing a high-voltage energy storage system cell that is physically and performance compatible with the energy storage system in the Ram 1500 demonstration PHEVs. The cell, while lower capacity than the Electrovaya cell, was shown to have the potential to meet and exceed the total energy of the Electrovaya, in part due to its prismatic can design. The JCI cell also exhibited superior power-to-energy ratio.

The key BMS software changes were to adjust the cell voltage versus SOC and the power versus temperature calibration tables. Modifying the thermal management system for direct liquid cooling was also identified as a key change.

The Phase II high-voltage energy storage system upgrade was implemented in four steps:

1. Design, implementation and integration
2. High-voltage energy storage system manufacturing
3. Validation of the updated design
4. High-voltage energy storage system field service

Design, Implementation and Integration

FCA US LLC implemented two key design objectives after the electrochemistry change:

- Continue to maintain the existing vehicle package by reusing the existing steel high-voltage energy storage system case and vehicle interfaces
- Use a single-loop conductive thermal system as an improvement over the previous Electrovaya double-loop fan system. In the latter, conditioned fluid entered the high-voltage energy storage system to condition a second loop of conditioned air with the purpose of maintaining the thermal condition of the cells

Magna was selected as the pack/system integration provider due to its production capability and experience, as well as consideration of program timing and budget constraints. The key tasks were to:

- Understand the thermal performance of the JCI cell and develop the thermal control parameters
- Use the physical package to fit the JCI cells
- Implement a system design to be package compliant with the original high-voltage energy storage system case

The reuse of the same external case for HV battery cells eliminated the need to perform any further vehicle integration.

Magna redesigned a previously developed internal liquid-only thermal system design to the JCI cell. This liquid-only system was fully compatible with the vehicle external system and the thermal software was sufficiently adaptable. A new calibration was not required since the thermal set points were very similar. The Magna thermal modeling efforts verified that the design could maintain an even thermal cross section across each of the high-voltage energy storage system modules. It would support good cell balance during charging and discharging. This was important as cell balance is improved when all cells are charging or discharging at the same temperatures. The analysis also verified low-pressure drop across the high-voltage energy storage thermal system; the liquid thermal system already in the vehicle was not affected by this change.

Magna performed design work, verified tolerances and fit of all components. Magna then produced physical properties using components created by stereolithography, mechanical mockups, and prototype wiring and hoses to demonstrate the feasibility of design and assembly before moving to manufacture.

Figure 5 below shows the internal configuration of the Magna/JCI high-voltage energy storage system

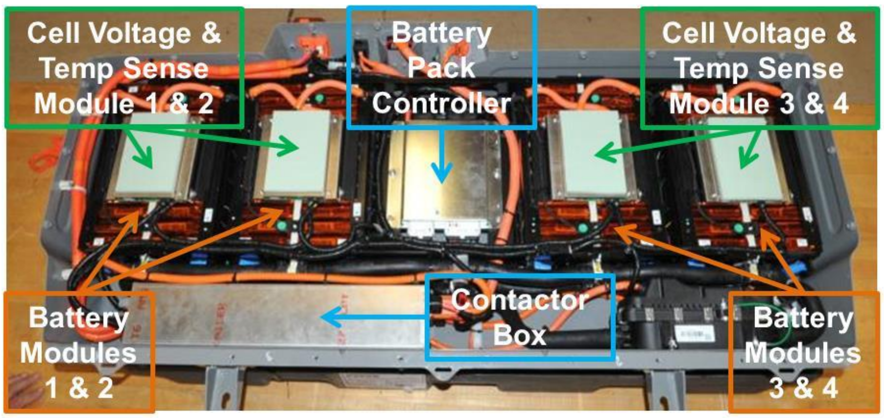


Figure 5: Internal configuration of Magna/JCI high-voltage energy storage system

Figure 6 below shows the complete Magna/JCI high-voltage energy storage system as installed in the Ram 1500 PHEV trucks.

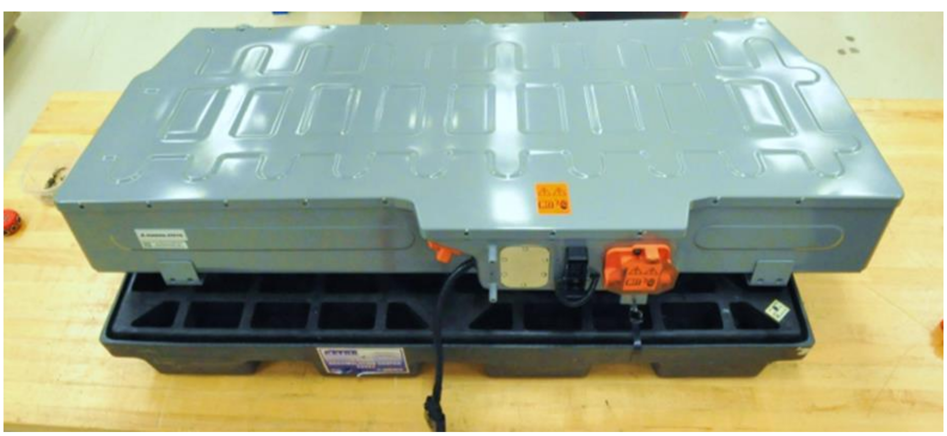


Figure 6: Magna/JCI high-voltage energy storage system as installed in Phase II

A comparison of the specifications of the Phase II Magna/JCI high-voltage energy storage system and the Phase I Electrovaya high-voltage energy storage system is shown in Table 8 below.

Properties	Magna/JCI	Electrovaya
Nominal Voltage	355V nominal	355V nominal
Energy	9.7 kWh	12.9 kWh
Power	>60 kW	> 60 kW
Mass	140 kg	185 kg
Configuration	96 cells in series	96 cells in series
Cell Capacity	27Ah	33Ah
Thermal Management	Liquid: 4 zones	Liquid-Air: 2 zones
On-Board Charger Module	Not included	Included

Table 8: Specification comparison Magna to Electrovaya

The package design reused the existing high-voltage coolant-heater and contactor box components. It created a new assembly for the high-voltage energy storage system modules, high-voltage energy storage system controller and cell sensor controller modules. This new package configuration permitted the high-voltage energy storage system to be assembled externally to the case and dropped in as a completed assembly – with only electrical wiring and coolant lines to be attached. The resultant pack was directly compatible with the existing Ram 1500 PHEV high-voltage energy storage system package.

Each Phase I high-voltage energy storage system went through a decommissioning process where all parts were either scrapped or reused. The lithium-ion cells were recycled and the following parts were reused:

- Contactor box
- High-voltage energy storage system control module
- Individual cell sensor controllers
- High-voltage coolant-heater for the high-voltage energy storage system thermal loop
- Key external interface connectors, such as high-voltage energy storage system power connector with high-voltage safety interlock
- Manual service disconnect

FCA US LLC had earlier planned to reuse the Electrovaya high-voltage energy storage management system and software. The hardware was compatible with the same number of lithium-ion cells and differed only by not connecting the air fan speed sensors and power controls. The base software transferred largely intact, since the vehicle interface had no changes and only required re-calibration of the SOC and power-available tables. Other reused hardware, such as the contactor box, used the same control boards; it was rewired to add connectors for service and the shell was repackaged for improved manufacturability and ease of service.

High-Voltage Energy Storage System Manufacturing

Magna created an in-house manufacturing plan that incorporated an automotive approach with a documented, illustrated assembly sequence. Magna controlled assembly to ensure good manufacturing practices were followed for all packs. This approach enabled an identical process to service and rebuild packs, should repair be required.

Magna also produced in-house an automotive-grade low-voltage wire harnesses that connected the high-voltage energy storage system to the vehicle and the internal controls boards. These were designed, built to automotive production standards and simplified assembly, service and trouble-shooting.

Magna delivered 39 complete pack assemblies for re-installation to a reduced Ram 1500 PHEV fleet. Four additional packs were built and held in reserve by Magna for potential field service.

Validation of the Updated Design

The design validation process proved that the updated energy storage system met its desired function and performance requirements. The validation process consisted of four parts:

1. Component verification
2. Prototype breadboard before initial production
3. End-of-line functional and performance testing
4. System production qualification, including functional and durability validation

Magna used a functional Electrovaya pack to verify all reused electronic modules were functional in their original environment. This included checking reported values, diagnostic scans and control commands to verify function before being reused in pack assembly. This was judged an acceptable analogue, as there were no Electrovaya component testers available for component testing before reuse.

Magna built a breadboard test pack using Magna/JCI modules, Magna wiring and Electrovaya electronics modules with software updates. In this pack, Magna tested first-article high-voltage energy storage system modules, wiring and interconnects required to complete a full pack. It was used to perform a component electrical validation program to qualify their design before committing to production builds.

Magna used the FCA US LLC diagnostics interface over CAN communications and the hardware control/power lines in the vehicle interface connector to communicate to a computer. The company also used an ABC-150 high-voltage energy storage system power cycler to exercise the high-voltage energy storage system and verify the correct software level and function. The purpose was to validate that the pack was properly assembled before packing and shipping to FCA US LLC for vehicle integration.

Pack production validation included vibration, hot and cold durability testing – including cycle life testing – to assess product quality. All tests passed, with the exception of one early cell failure, resulting in one module replacement for the completion of the test.

Energy Storage System Field Service

Four packs were held in reserve as service parts in the event of a field issue with the high-voltage energy storage system packs. No service packs were required to replace defective packs in the field.

The completed packs were installed into Ram 1500 PHEV trucks and resulted in very few integration issues. This was an expected outcome, as the interface was identical and used the same installation tools and procedures of previous pack installations.

2.4 Plug-in Hybrid Electric Vehicle Thermal Management

Description

Plug-in electrification of automotive vehicles brought some unique challenges for the vehicle thermal management system, including the addition of new systems and modifications to existing ones. Today's high-voltage power electronics components, including inverters, DC-to-DC converters and high-voltage energy storage system chargers, utilize liquid cooling systems that typically require a maximum coolant temperature of 75°C. The next generation lithium-ion high-voltage batteries require complex thermal management systems. MAHLE Behr USA was chosen as a sub-recipient to research the thermal system design to overcome the challenges outlined above. In addition, MAHLE Behr was selected to supply the components and system for thermal management.

The maximum desired cell temperature is typically 35°C, while lithium plating can occur during charging at lower temperatures. Extended operation at extreme high and/or low temperatures can significantly degrade the life of the batteries, reducing their pulse power capability and energy capacity. The general trend of temperature effects on high-voltage energy storage cells is shown in Figure 7 below.

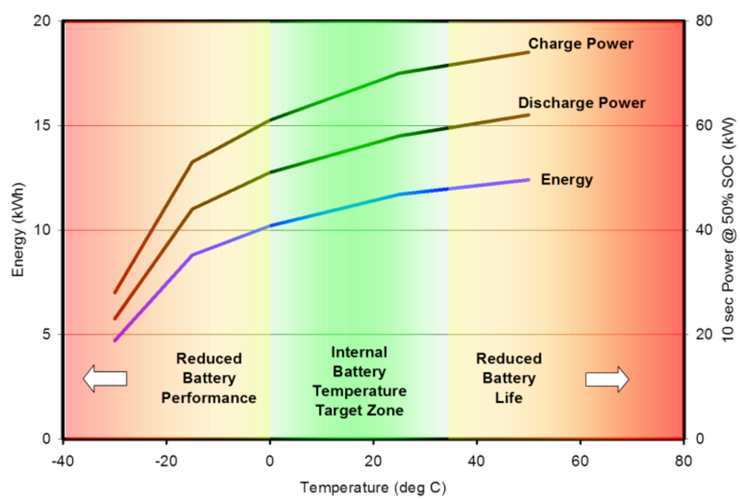


Figure 7: Temperature effects on high-voltage energy storage system cells

To meet all of the challenges discussed above, two additional and separate thermal management circuits were added to the vehicle. The power electronics components were cooled with a low- temperature coolant circuit. A second low-temperature coolant loop was used to cool the high-voltage energy storage system, using a low-temperature radiator at low ambient temperature and a chiller at high ambient temperature. The chiller is integrated into the vehicle HVAC (Heating, Ventilating and Air Conditioning) system, in parallel with the HVAC evaporator.

Figure 8 below shows the schematic of thermal management system employed.

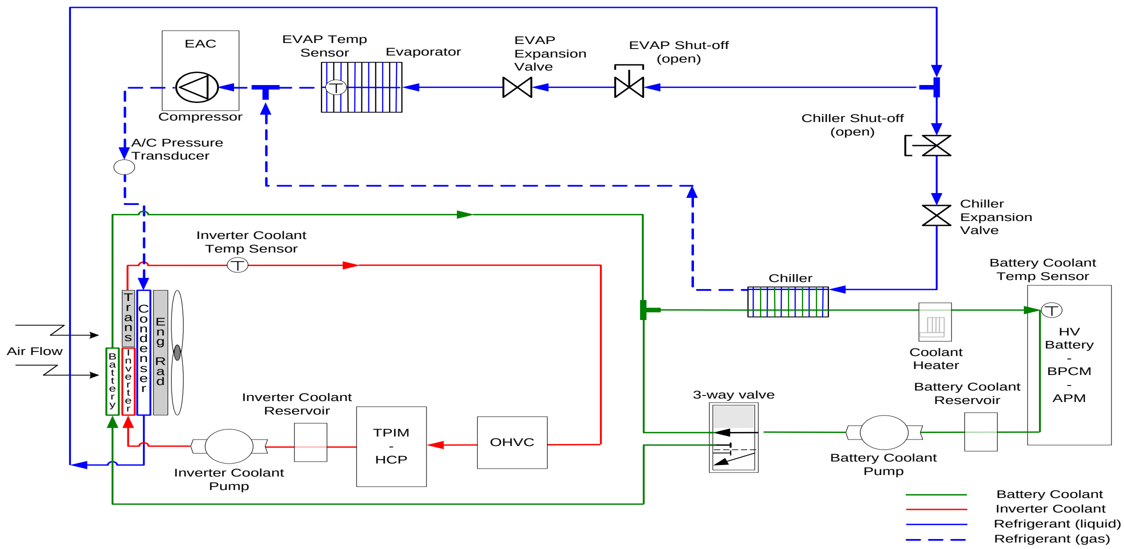


Figure 8: Thermal-management circuits

Goals and Targets

The system was calibrated to meet the following high-voltage energy storage system temperature control specification:

- Passive cooling (radiator) and active cooling (A/C chiller) were employed to target 37^{0}C average cell temperature

Vehicle Implementation

The main components relevant for the high-voltage energy storage system cooling loop integrated into the truck were as shown in Figure 9 on the next page:

- A 38-plate chiller (refrigerant-to-coolant heat exchanger) with customized vehicle interfaces
- Low-temperature radiator
- Coolant and refrigerant lines
- System components (coolant pump, A/C compressor, valves, etc.): off-the-shelf components selected to meet performance and vehicle packaging requirements

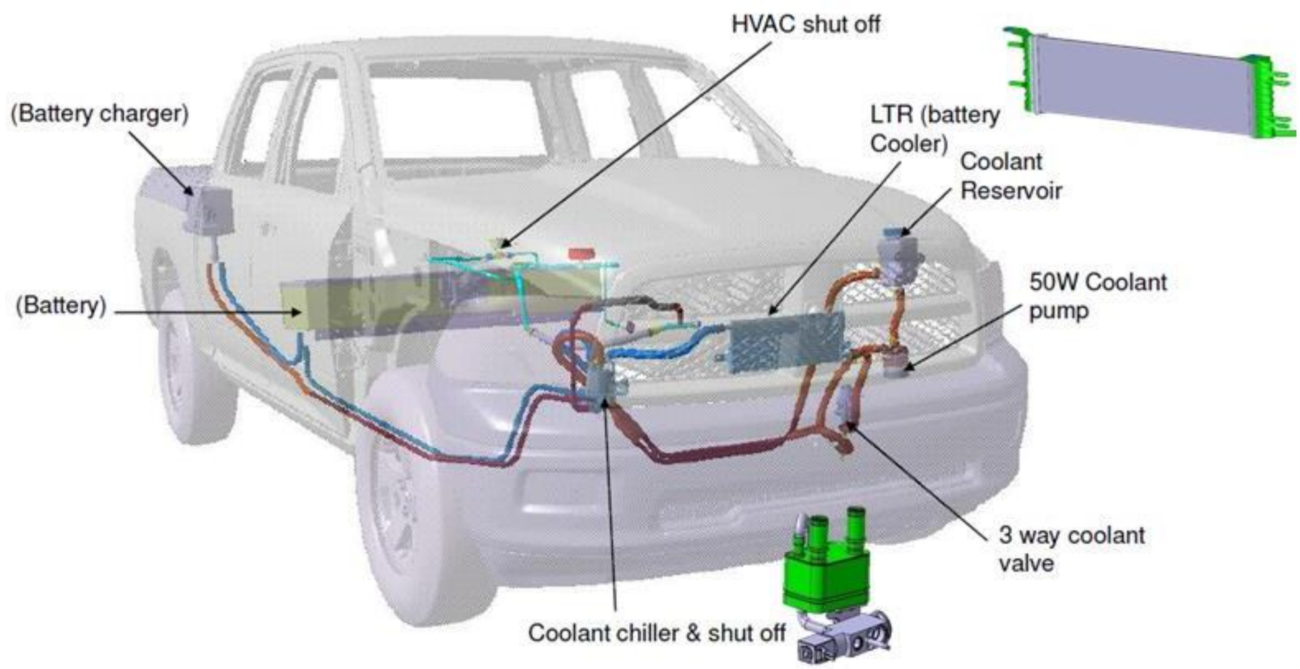


Figure 9: High-voltage energy storage system thermal system integration

2.5 Charging Systems

Description

A major goal of the PHEV vehicle is to use electric grid power to charge the high-voltage energy storage system while the vehicle is stationary. This electric power is then used as primary motive power at very low speeds and loads and supplemental power at higher speeds and loads. Electricity used to charge PHEVs from the grid can be generated through renewable and “clean” sources, such as hydro, wind, solar and ocean energy, thereby reducing U.S. oil consumption. This function is accomplished by the use of a 6.6 kW On Board Charger (OBC) (vehicle connection) and an Electric Vehicle Supply Equipment (EVSE) module (permanently connected to the utility grid). All charging systems comply with the requirements of SAE J1772™. The truck charge port, portable EVSE and stationary EVSE are illustrated in Figure 10 on the next page.

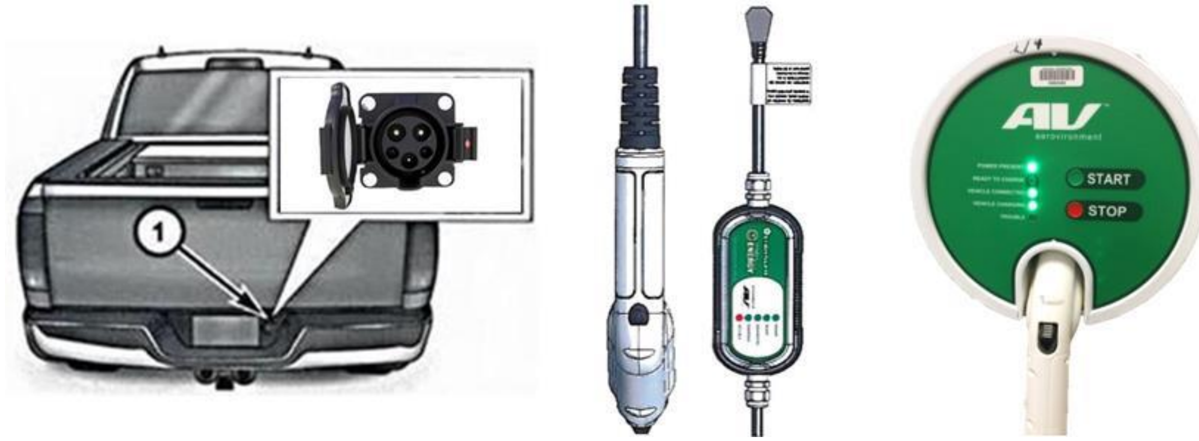


Figure 10: On-board charging port, portable EVSE and stationary EVSE

Goals and Targets

- Verify plug-in charging mode performance based on charger and high-voltage energy storage system model
- Develop bi-directional (communication and power) charger interface
- Create flexibility of plug-in charging times at grid connection
- Smooth daily variations in the grid load

Electric-Utility-to-Vehicle Interface

The OBC enables charging the vehicle from the electric utility grid using a portable Level 1, 120V EVSE (supplied with each vehicle) or a stationary Level 2, 240V EVSE. Table 9 below shows the specifications of the OBC and the EVSE used in this project.

On Board Charger Specifications	
Input (kW)	3.3/6.6 kW (auto-sensing, depending on input voltage)
Plug-In Voltage	120/240 VAC
Max Output	450 VDC
Nominal Output	350 VDC
Minimum Voltage	250 VDC
Expected Frequency	50 to 60 Hz
Cooling Temperature	70°C
Ambient Temp Range	-40 to 70°C
Liquid Cooling	Liquid
CAN Communication	Yes

EVSE Specifications	
Charging Methods	Level 1: 1.4 kW, 110/120 VAC, 12-amp AC Level 1: 1.9 kW, 110/120 VAC, 16-amp AC Level 2: 6.6 kW, 208 to 240 VAC, 32-amp AC
Frequency	50 to 60 Hz
Analogue Communication	SAE J1772™
Operating Temperature	-30 to 50°C
Humidity	Up to 95%
Dimensions	AC Level 1: 4x8x2 in. AC Level 2: 15x15x6 in.
Weight	AC Level 1: 10 lbs. AC Level 2: 15 lbs.
Enclosure	NEMA 2, Cable management
Safety	GFCI for CCID Service Ground Monitor CCID Self-test Automatic re-closure Safety UL/CE
Regulatory Compliance	AC Level 1 & 2 SAE J1772™ Compliant

Table 9: On board charger and EVSE specifications

In addition to the Level 1 EVSE supplied with each vehicle, stationary EVSEs were permanently installed at each partner location, as noted below in Table 10 below.

Partner	Level 2 EVSE
SMUD	7
DTE Energy	7
Duke Energy	2
Tri-State	3
National Grid	3
CenterPoint Energy	2
Argonne National Labs	1
FCA US LLC	10
Totals	**35**

Table 10: Partner stationary EVSE installations

Design, Implementation and Integration

The charging function was implemented using an aluminum tool box located in the pickup bed as shown in Figure 11 below.

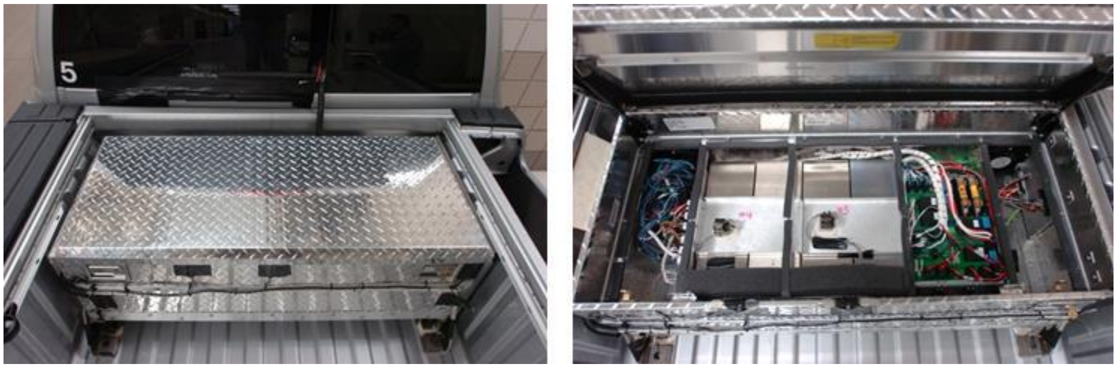


Figure 11: Vehicle charge-box integration

This configuration was chosen to allow for greater flexibility for inverter and charger module development for bi-directional Vehicle-to-Grid (V2G) interaction.

Development and Testing

The development of charging systems was conducted in progressive levels throughout the program. During Phase I, two levels of charging modes were successfully accomplished. Simple manual charging was used to develop basic charging controls, software and hardware. Reverse Power Flow was subsequently developed. The processes for all charging features including manual, scheduled, smart and DC charging as well as reverse power flow, are each described below.

2.5.1 Manual Charging

During Phase I, charging was achieved by simply plugging the vehicle into the EVSE as shown in Figure 12 below.

Figure 12: Manual charging connection diagram

The following is the manual charging procedure:

- Put the vehicle in park
- Turn the ignition switch off and remove the key
- Uncoil the full length of the EVSE cord
- Locate the vehicle charge port on the rear bumper
- Open the protective cover
- Push the charge handle into the charge port until it is mated and the lock engaged
- Once the charge handle mates, the tail lights will flash five times to indicate that proper connection has been made
- The EVSE will also illuminate the vehicle connected indicator light
- Within 5 seconds, the EVSE vehicle charging light will illuminate

2.5.2 Scheduled Charging

The first level of advanced charging developed in Phase I was Scheduled Charging. This function allows a delayed start of the charge cycle. The process is shown schematically below in Figure 13 below.

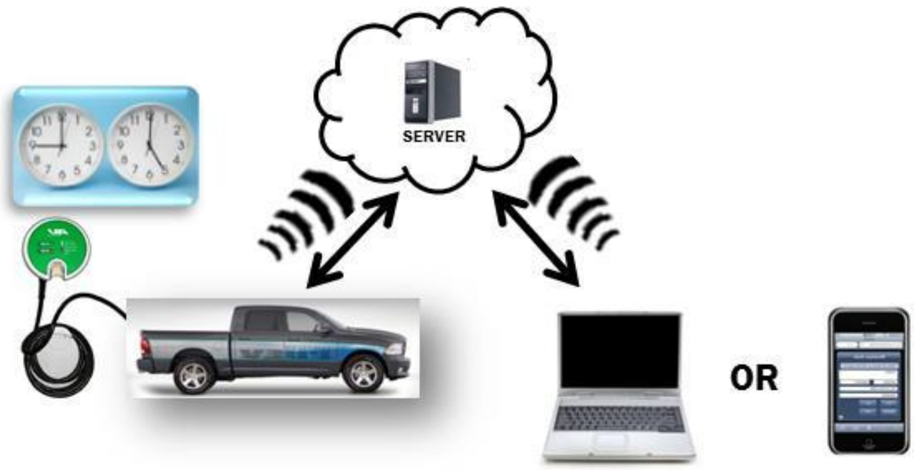


Figure 13: Scheduled Charging communication diagram

The procedure for the manual charging sequence is followed first. The consumer then schedules the following specific parameters (Figure 14 below) for the charge cycle:

- Convenient cycle end date and time; e.g. start of morning work commute at 7:00 AM
- Desired end of cycle State of Charge (SOC); e.g. 100%

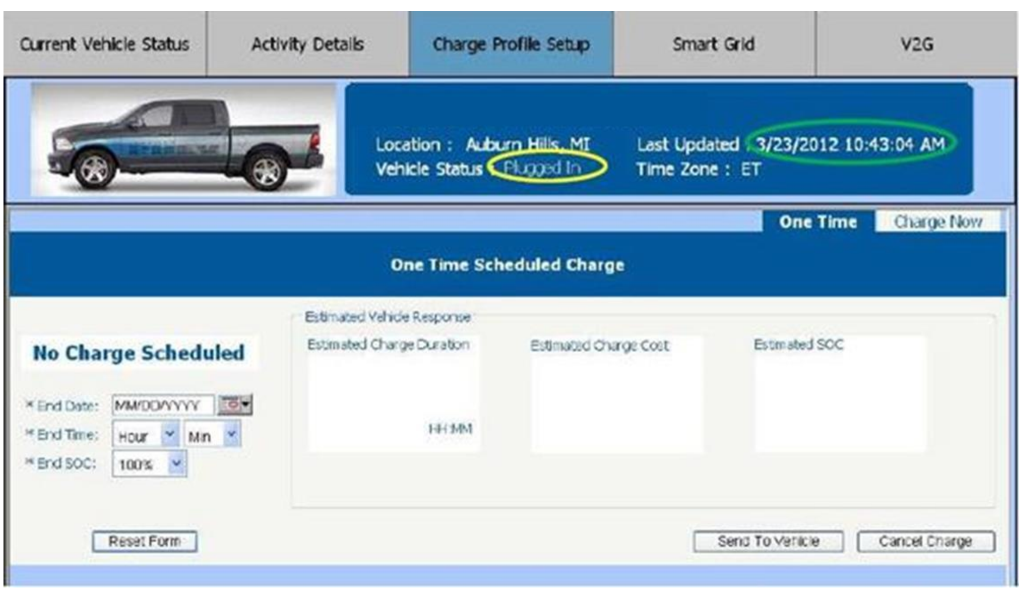


Figure 14: Scheduled Charging parameter inputs

The vehicle and the utility then return estimates for charge cycle duration, cost and final SOC based upon these parameters (Figure 15 below). Charging commences 1-2 hours after initiation, assuring the desired SOC at the end time.

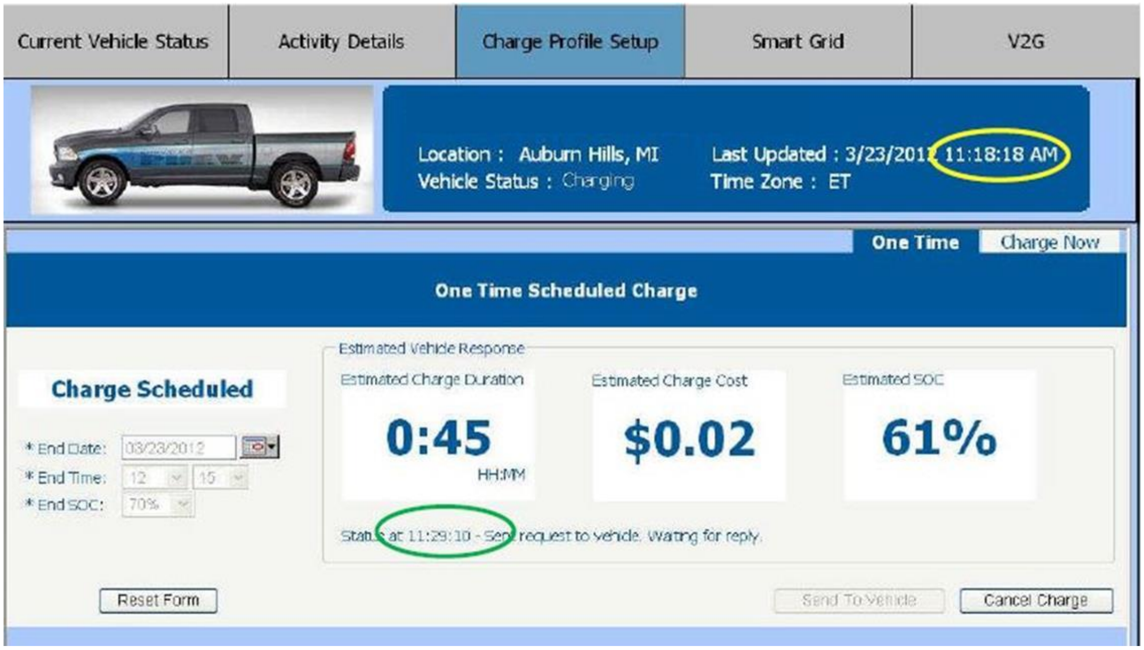


Figure 15: Scheduled Charging parameter outputs

2.5.3 Smart Charging

After success with Scheduled Charging during Phase I, the second level of advanced charging developed in Phase II of the deployment was Smart Charging. It allows the consumer to define the parameters for the charge cycle and see the resulting economic implications based on current information from the utility. The vehicle and utility consider the combination of the time period, base kWh rates and any Demand Response Load Control (DRLC) curtailments or delays to determine the economic results of the charge cycle. In general, the charging will take place during the overnight hours, when cost/kWh and demand are significantly lower. Using the Smart Charging function alleviates the need for the consumer to be aware of the details of these parameters. The communication flow is shown in Figure 16 on the next page.

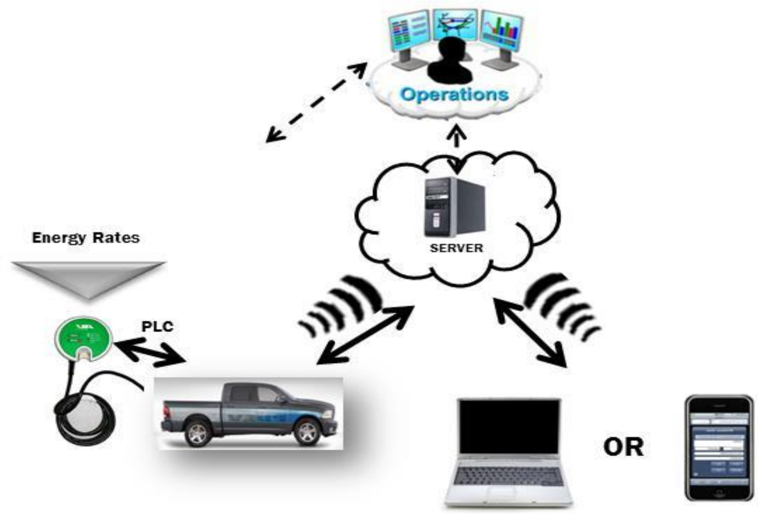


Figure 16: Smart Charging communication diagram

Referring to the graphical representation of smart charging mechanism in Figure 17 on the next page, the Plug-in Electric Vehicle (PEV) Time Charge Is Needed (TCIN) is the variable that is to be met overall by management of the parameters input:

- The fastest charge cycle begins immediately after initiation using maximum power and the shortest interval to fastest TCIN, ignoring all economic costs. The charge period power level, energy and fastest TCIN are transmitted to the utility
- The cheapest cycle delays the charge initiation until price/kWh drops to a minimum using maximum power, ignoring any demand charges due to power level used. The cheapest TCIN is sent to the utility, along with power level and energy
- The optimized cycle delays the charge initiation until price/kWh drops and reduces the power level used by the charge cycle to stay below the DRLC level. This DRLC signal from the utility may also keep the customer below any load demand charges at the site. The optimized TCIN is transmitted to the utility, along with the power level and energy required

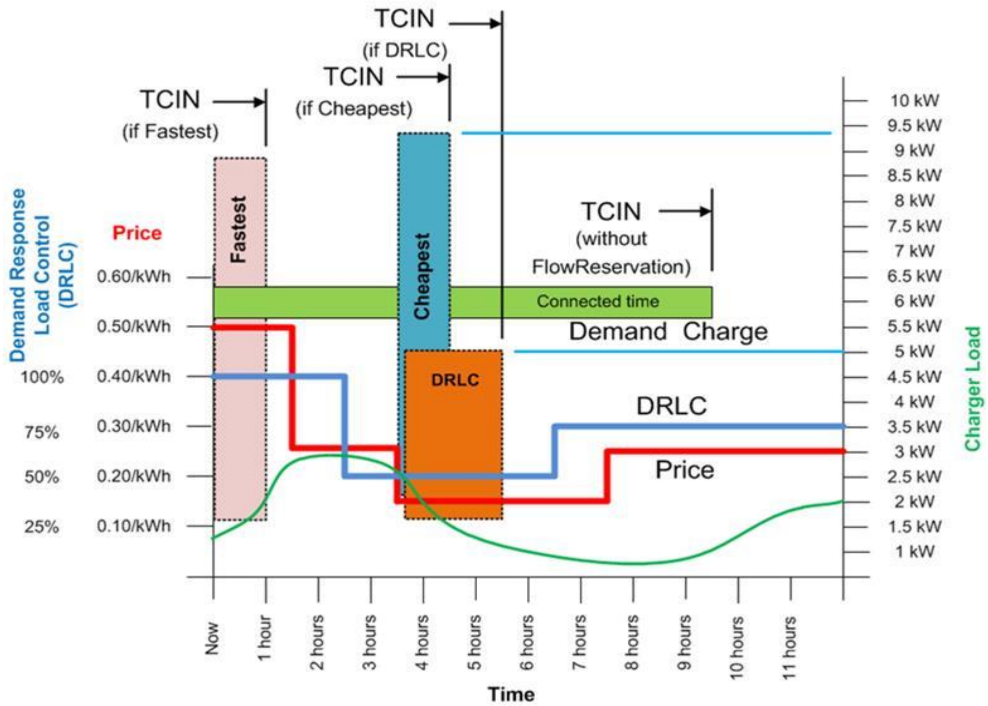


Figure 17: Smart Charging graphical representation

The procedure for the manual charging sequence is followed first. The consumer then schedules the following specific parameters for the charge cycle as shown in Figure 18 on the next page:

- Convenient cycle start date and time; e.g. end of evening commute at 5:00 PM
- Convenient cycle end date and time; e.g. start of the morning commute at 7:00 AM
- Desired end of cycle State of Charge (SOC); e.g. 100%

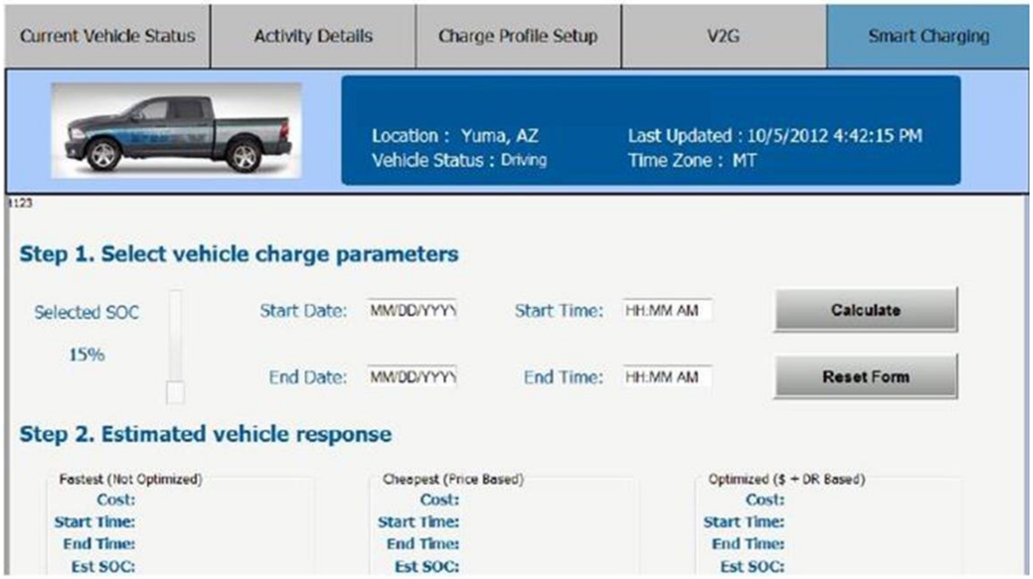


Figure 18: Smart Charging parameter inputs

Information regarding vehicle high-voltage energy storage system conditions (SOC and power level available) and information obtained from the utility (kWh cost and demand response costs) determine the charge time and cost associated with the charge cycle for input parameters.

The consumer then selects the desired fastest, cheapest or optimized charge cycle shown in Figure 19 below.

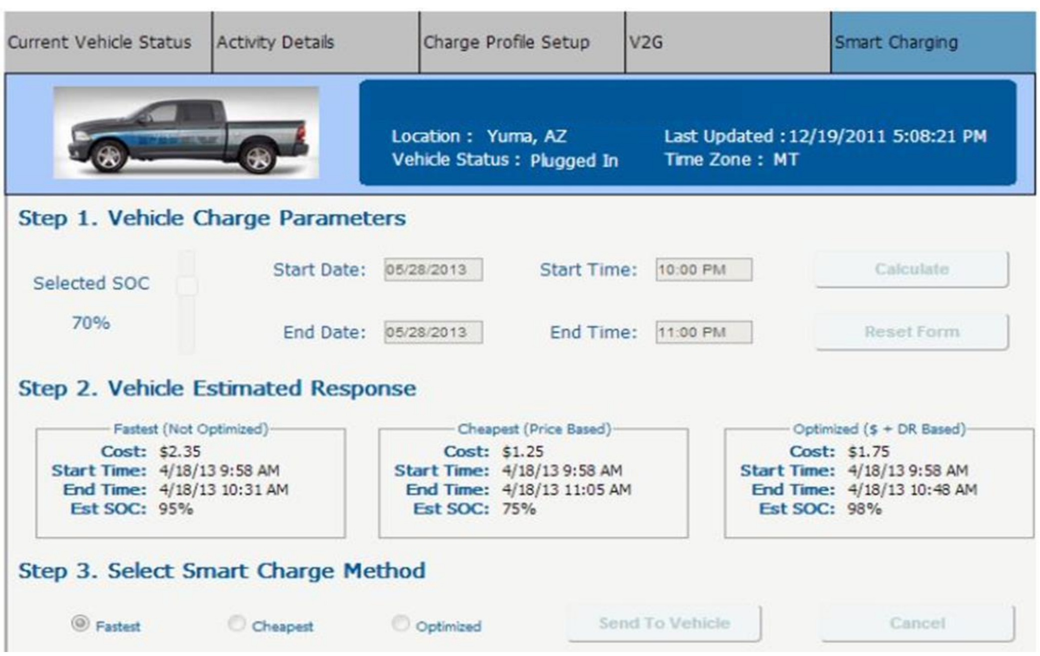


Figure 19: Smart Charging parameter outputs

2.5.4 Reverse Power Flow

The third level of advanced charging developed in Phase II of the deployment was Reverse Power Flow (RPF) using Vehicle to Grid (V2G). This allows the vehicle to return energy to the utility grid, rather than accepting energy from the utility grid during charging.

In this mode, energy may be returned to the grid as requested by the utility at peak periods to mitigate high system power demands. The consumer can potentially buy energy at low-peak periods, low-cost periods and sell power back to the grid during high-price high-peak periods. This function must be used with Level 2, 240 VAC EVSEs to interface with standard grid power parameters.

See communication flow in Figure 20 below.

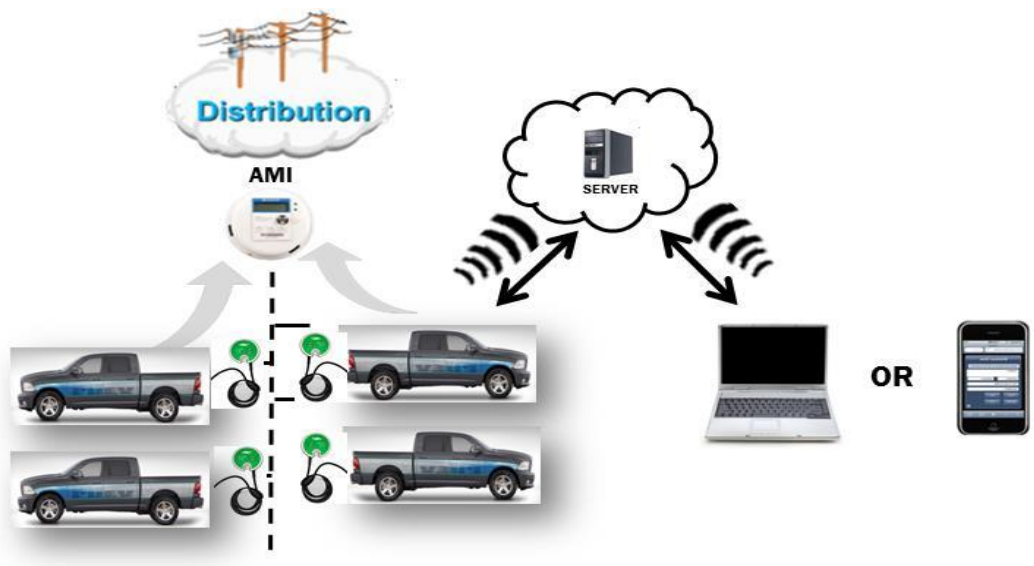


Figure 20: Reverse Power Flow communication diagram

The graphical representation of the approach is shown in Figure 21 on the next page. The Plug-in Electric Vehicles (PEV) many have had enough energy to start the discharge cycle. However, if the electricity price is low when the vehicle is plugged in and then the price goes up. The PHEV could charge for a while (at low price), deliver power to the grid (at high price), and then recharge when the price decreases again. This allows the customer to keep the home loads below the 3.5 kW demand charge limit in this example illustrated in Figure 23.

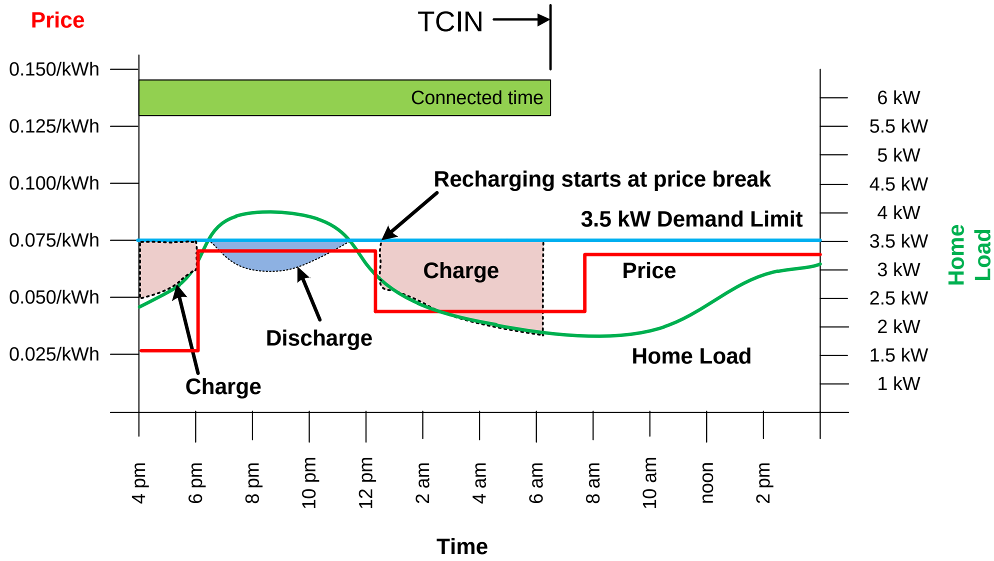


Figure 21: Reverse Power Flow graphical representation

After following the manual charging sequence, the consumer schedules the following specific parameters for the charge cycle as shown in Figure 22 on the next page:

- Select the desired amount of power to be transferred from the high-voltage energy storage system to the grid (37, 50, 75 or 100% of the on-board inverter rating of 6.6kW).
- Select the duration of the power transfer in hours and minutes
- Click the “Send to Vehicle” button
- Open the right side of the Ram Box to access the power panel and ensure the indicator light is green. Press the on/off button to initiate the RPF session

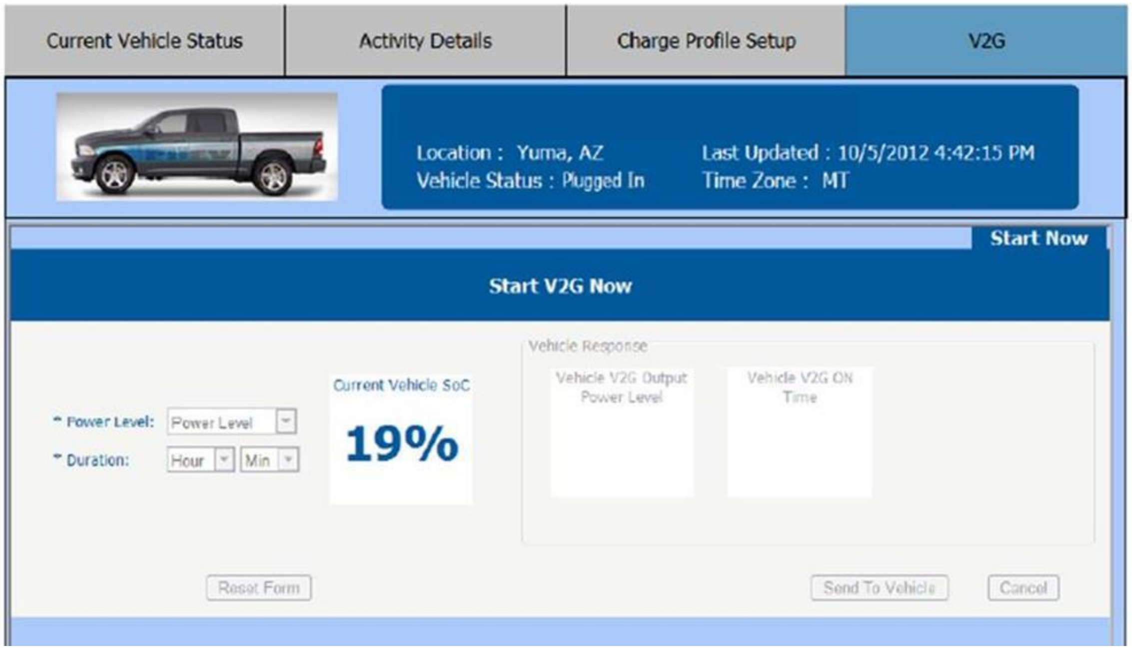


Figure 22: Reverse Power Flow parameter outputs

The power transfer will then begin. The transfer is terminated when either the high-voltage energy storage system is depleted to the power level specified (e.g. 19% shown in Figure 24) or when the time duration specified has been reached.

Key Results and Comparison to Goals/Targets

Goal/Target	Key Result
Verify plug-in charging mode performance based on charger and high-voltage energy storage system model.	Successful real-world manual charging at FCA US LLC and partner locations.
Develop bi-directional (communication and power) charger interface.	Development of Smart Charging and Reverse Power Flow systems.
Create flexibility of plug-in charging times at grid connection.	Development of scheduled charging and Smart Charging.
Smooth daily variations in the grid load.	Development of Smart Charging and Reverse Power Flow systems.

2.5.5 DC Charging

The previous charging activities were centered on AC-based charging; i.e. the power in the vehicle charge port was AC power at Level 1, 120 VAC or Level 2, 240 VAC. This approach to vehicle charging requires an On Board Charging Module (OBCM) charger to accept 120/240 VAC power and convert it to 400 VDC for the high-voltage energy storage system. Given the weight and size restrictions of vehicle design, the OBCM is limited in capacity. A more efficient method of vehicle charging is to move the OBCM off the vehicle to the stationary EVSE. The higher power transfer is then possible. This reduces the charge time from 3-4 hours to less than 30 minutes, since the off-board charger power is generally 50 to 60 kW. The FCA US LLC vehicle charge port is the industry standard combination connector and is both AC and DC EVSE compatible, as shown in Figure 23 below.

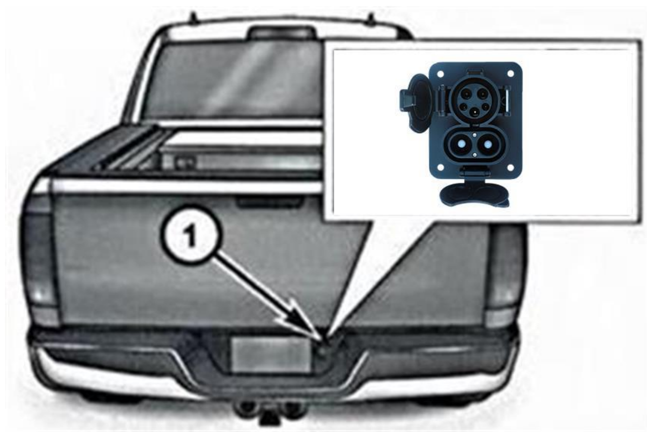


Figure 23: Vehicle bi-functional AC & DC charge port

FCA US LLC and Argonne National Laboratory (ANL) jointly developed the hardware and software for the addition of DC charging capability.

ANL hosted a DC Charging Interoperability Event on November 11-14, 2014. FCA US LLC participated in this event with five DC fast-charging EVSE suppliers and four other OEMs. The DOE Ram 1500 PHEV deployed to ANL successfully completed sustained and repeatable charging sessions with Bosch and BTC Power EVSEs at the event. Four brands of the DC EVSEs used at that event are shown in Figure 24 on the next page.

Chargion BTC Power, CA USA	EFACEC Efacec, GA USA (Portugal)	Veefil Tritium, Australia	Bosch Germany

Figure 24: Example DC EVSEs presented at the ANL event

2.6 Auxiliary Power Panel

Description

For Phase I, the Ram PHEV was equipped with a 6.6 kW AC on-board auxiliary power outlet (shown in Figure 25 below). The power panel was located in the bedside storage compartment. This resulted from an FCA US LLC corporate market research survey that indicated 59% of potential buyers preferred the power panel mounted in the truck bed. It supported two 120 V/20 A duplex and/or one 240 V/30 A plug rated at 60 Hz.

Figure 25: Auxiliary power panel vehicle integration

Goals and Targets

- Offer 6.6 kilowatts of continuous on-board auxiliary AC power
- Available in two modes of operation
  - Silent Mode: Stationary power with the vehicle engine off
  - Continuous Mode: Stationary power with the vehicle engine on

Design features

- Weather-resistant receptacles
- Temperature-compensated circuit breakers
- High-temperature internal wiring

Operation

- Place shift lever into park
- Turn the ignition key to the off position
- Close all vehicle doors
- Wait 30 seconds and activate remote start of the internal combustion engine by a double pressing of the remote start button on the key fob
- Open the passenger-side Ram box, press and release the power panel on/off button to power up the power panel receptacles
- The power panel ready light will glow green indicating that AC power is available
- When work is completed, press and release the power panel on/off button to power down the panel. The internal combustion engine will then shut down automatically, if running

Modes of Operation

- **Silent Mode:** After the initial internal engine remote start, the engine will automatically shut down and electrical power will be drawn from the high-voltage energy storage system, providing the high-voltage energy storage system state of charge is above 20%. If the high-voltage energy storage system state of charge is below 20%, the system will use the continuous mode describe below.
- **Continuous Mode:** When the high-voltage energy storage system state of charge is below 20%, the Partial Zero Emissions Hemi® internal combustion engine starts automatically providing continuous power after depletion of the high-voltage energy

storage system charge. This mode is comparable to conventional aftermarket generator operation. The system will continue to operate in this manner until the vehicle gasoline level falls to one-eighth of the fuel tank capacity.

Key Results and Comparison to Goals/Targets

Goal/Target	Key Result
Offer 4.8 kilowatts of continuous on-board auxiliary AC power.	The final power capability was increased to 6.6 kW for enhanced real world performance.
Available in two modes of operation.	Two modes of operation (silent and continuous) were supplied. The "Power-on-the-Fly" mode was omitted for safety reasons (the power panel was integrated into the Ram toolbox on the truck bedside, per market survey results cited earlier).

Auxiliary Power Panel Usage by Fleet Partners

An auxiliary power panel was a favorite feature during both phases of deployment. The power panel was often utilized as a portable generator by the utilities during severe winter weather. During power outages, the trucks supplied power to critical functions within the utility network to assist in power restoration. In one case, a partner utilized the power generation capability to assist in the building activities at a cabin in a remote area of Kentucky.

See Figure 26 below for two examples power panel utilization by fleet partners at worksites.

Figure 26: Power panel usage by fleet partners

2.7 Power Electronics

To charge the on-board battery, we employed a traction power inverter that converts the high-voltage power from the three-phase AC motors to high-voltage DC power. The traction power inverter also performs hybrid supervisory and e-motor controls via three microprocessors. The power rating is 300 A_{rms} at 414V. The demonstration vehicle is equipped with a DC-to-DC converter that assumes the functionality of the alternator, which has been eliminated. The converter transfers electrical DC power bi-directionally between multiple voltage levels on the vehicle (i.e. 390V <=> 12V). The power ratings are 2.2 kW at 390V and 0.6 kW at 12V. In addition, the inverter and converter were integrated into one assembly and share a common cold plate for liquid cooling.

2.8 PHEV System Operations

The demonstrated PHEV operations consist of three operating modes: normal vehicle propulsion, plug-in charging, and AC power generation. Figure 27 illustrates the basic control architecture at the vehicle level.

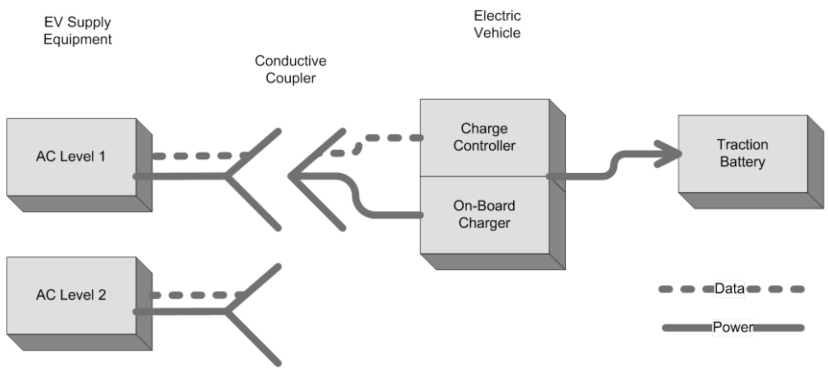


Figure 27: Vehicle level control architecture

Under normal use, it is expected that the driver will recharge the high-voltage energy storage system from the electrical grid at every opportunity. The default charge-depleting range is approximately 35-55 miles, depending on the particular drive cycle.

An FCA US LLC internal study has revealed that city fuel economy of an HEV is more sensitive to aggressive driving than in a conventional vehicle. Therefore, a feature was designed to provide feedback to the driver in real-time of his/her current driving behavior.

It is worth emphasizing that system fuel-saving capability remains largely intact even if the high-voltage energy storage system power is severely limited due to battery conditions. That is because only low discharge power of 5-10 kW is needed. Although basic PHEV functions of e-drive and regenerative braking may be limited by battery power when the high-voltage energy storage system is too cold or too hot, the vehicle is capable of maximizing engine-off near idle and capable of running the engine optimally. Therefore, the vehicles can still deliver significant PHEV benefits to customers, even if the energy storage system is not in ideal conditions.

AC power generation from the vehicle (high-voltage energy storage system and IC engine) is possible only when the driver has turned the key on and has selected the AC power generation option. In AC power generation mode, the AC power is generated with DC to AC converter from the high-voltage energy storage system to the external AC load. This AC power may be provided by discharging the high-voltage energy storage system under appropriate conditions, or by running the engine to charge the high-voltage energy storage system to maintain the State of Charge (SOC) within a certain range.

To clearly present the vehicle's PHEV system operations to the driver, the vehicle HMI – which consists of the dashboard and the center console Uconnect® system – were modified to include such information. Figure 28 on the next page shows the redesigned dashboard inside the Ram 1500 PHEV truck.

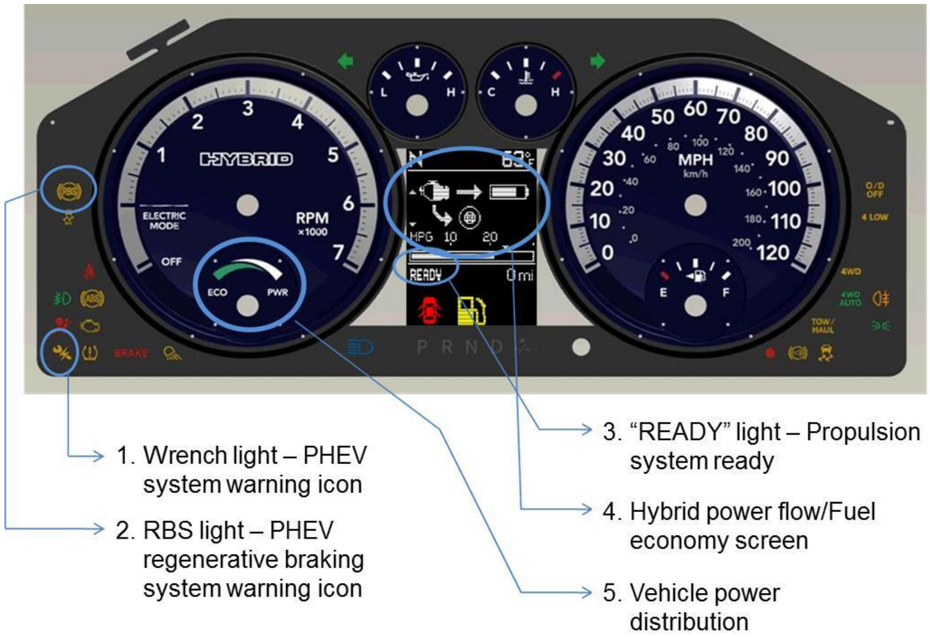


Figure 28: Redesigned dashboard in the Ram 1500 PHEV

The center console Uconnect® system was reprogramed to clearly illustrate different PHEV system operating modes without affecting other infotainment and navigation features provided by the system. This additional feature provides the real-time status of PHEV system operations, which enables drivers to manage their driving behaviors and achieve best fuel economy. Charge Depleting (Figure 29 below) and Regenerative Braking (Figure 30 on the next page) PHEV operation modes are presented here as examples.

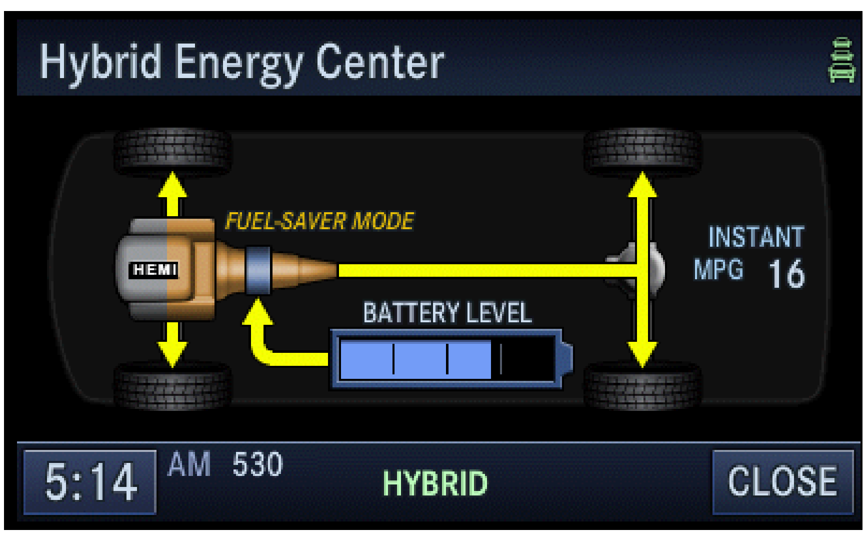


Figure 29: Charge depleting mode presented on the PHEV's HMI

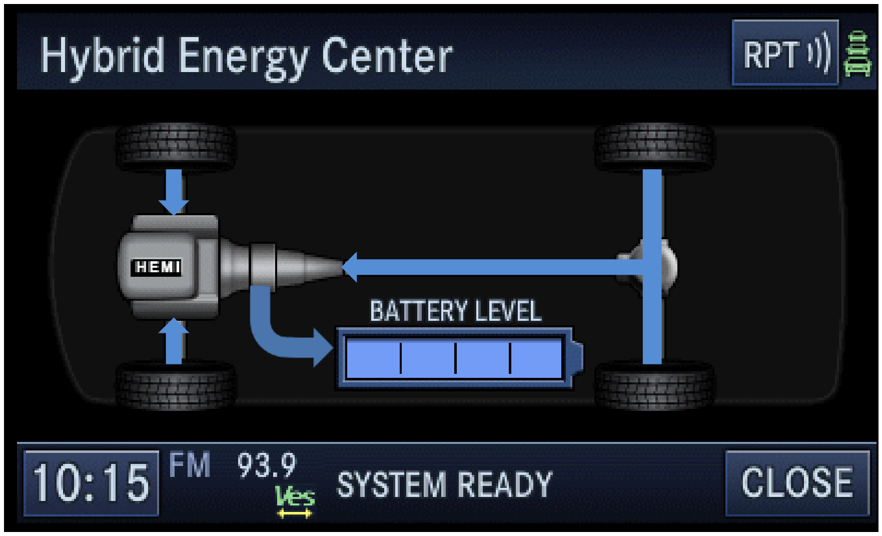


Figure 30: Regenerative braking mode presented on the PHEV's HMI

2.9 Transmissions and Motors

The Two-Mode Hybrid Transmission System (shown in Figure 31 on the next page) was developed by the Global Hybrid Cooperation (a joint effort among DaimlerChrysler, General Motors and BMW). It was a full hybrid system that enabled significant improvement in composite fuel economy while providing uncompromised performance and towing capability. In city driving and stop-and-go traffic, the vehicle could be powered either by the two electric motors or by the gasoline engine, or both simultaneously. The Two-Mode Hybrid could also drive the vehicle using an input power-split range, a compound power-split range or four fixed-ratio transmission gears.

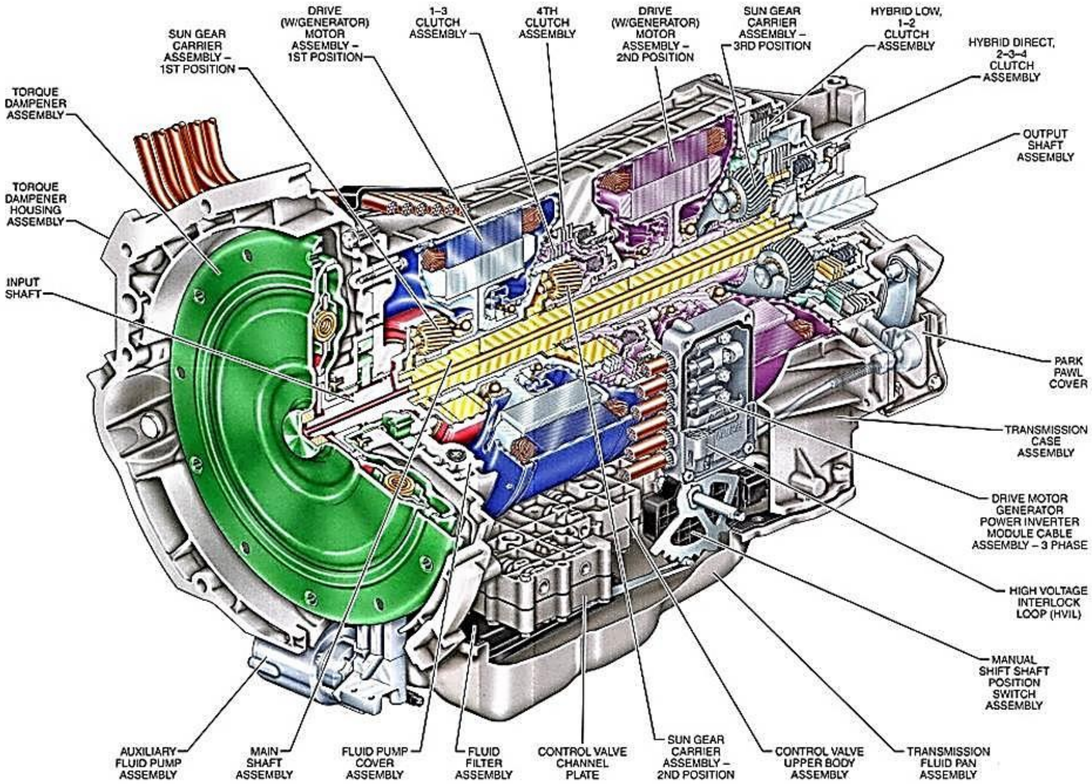


Figure 31: Two-Mode Hybrid transmission system

The Two-Mode Hybrid system was designed to meet mainstream market demands by providing the positive aspects of both hybrid and conventional transmission operation in one package and across a broad range of products. Two permanent magnet electrical motors were integrated into a conventional RWD transmission configuration. Both motors produce 65 kW power and 320 Nm torque.

The Two-Mode Hybrid Transmission – a synergistic combination of the strengths of Electrically Variable Transmissions (EVT) and conventional transmissions – formed a competitive and attractive hybrid system. The input-split EVT range and compound-split EVT range allow for continuously variable engine speed and full hybrid functionality throughout the vehicle speed range. In addition to these two EVT hybrid modes, four fixed gear ratios enable parallel hybrid operation with electric motors used only for boosting and braking.

2.10 Internal Combustion Engine (ICE)

The demonstration PHEV truck featured a 5.7 Liter HEMI® V8 engine that provides improved fuel economy through technologies such as Variable Cam Timing (VCT), increased compression ratio, improved cylinder-head port-flow efficiency and reduced-restriction exhaust and induction systems. Additional fuel economy improvements include a Multi Displacement System (MDS), Exhaust Gas Recirculation (EGR), axle efficiency improvements with a 3.21 axle ratio (versus 3.55), electric cooling fan (instead of the classic engine-mounted mechanical fan) and a simplified accessory drive. Only the water pump is driven by the crankshaft.

2.11 AT-PZEV Emissions Systems

In addition to GHG and fuel consumption reductions, the Ram PHEV delivered Advanced Technology Partial Zero Emissions Vehicle (AT-PZEV) emission levels. Non-methane hydrocarbons, carbon monoxide and oxides of nitrogen are catalyzed by ~99.9% reduction. To achieve AT-PZEV emissions, secondary air is injected directly into the exhaust ports. The exhaust manifold oxidation reaction pre-conditions the engine-out emissions and causes an exothermic activity to rapidly light off the catalyst for improved catalyst conversion efficiency. The AT-PZEV evaporative hardware includes a steel fuel tank, fuel tank isolation valve, fuel tank pressure sensor, canister secondary HC trap, mechanical-seal fuel-fill tube and fuel cap and fuel filler hose with fluorocarbon material.

2.12 Map-Based Fuel Economy

Description

FCA US LLC utilized a Global Positioning System (GPS) navigation map-based fuel economy system, which enables the PHEV to optimize charge depletion based on learned trip route. By continuously monitoring information such as vehicle speed, elevation and location, an optimized high-voltage energy storage system discharge strategy was calculated to take advantage of road conditions and maximize vehicle fuel economy during repeated trips. Figure 32 on the next page explains the energy management strategies behind this technology in two typical road conditions.

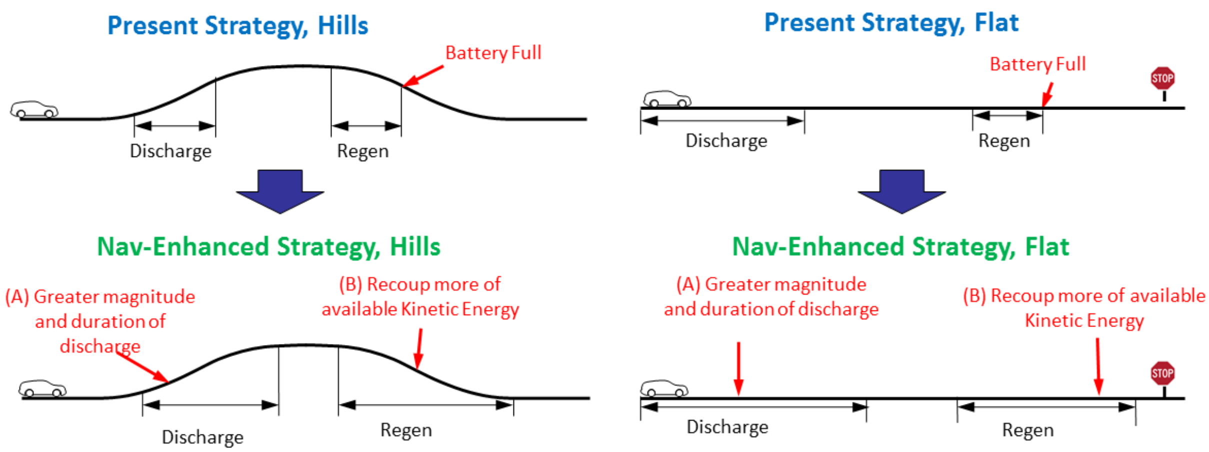


Figure 32: Map-based fuel economy energy-management strategies

Using known topography in three-dimensional axes (X, Y and Z) for a learned trip, GPS navigation map-based fuel economy can:

- Manage SOC to maximize regeneration during the trip and charging opportunities before and after the trip, thus minimizing fuel consumption
- Anticipate downtown/city driving conditions to pre-elevate SOC for longer EV driving duration in city driving cycles
- Rebalance EV-drive power against sustaining SOC by anticipating city driving conditions

This feature can be especially beneficial to customers who have repeated drive patterns, such as commuting between home and work.

Design/Implementation/Integration

This feature was integrated into the vehicle via control module within the vehicle. The functions were:

- Communication with Internet for map information
- Communication with vehicle PHEV systems for EV assist profile

3. PHEV Vehicle Integration and Testing Operations

3.1 Vehicle Development and Validation Timeline

This demonstration program involved testing of key components, subsystems and vehicles during the development phase to ensure a well-integrated vehicle. It also involved testing during the fleet-usage/demonstration phase to ensure proper vehicle-to-grid interface. Figure 33 below illustrates key development and testing milestones performed during the three stages of Phase I.

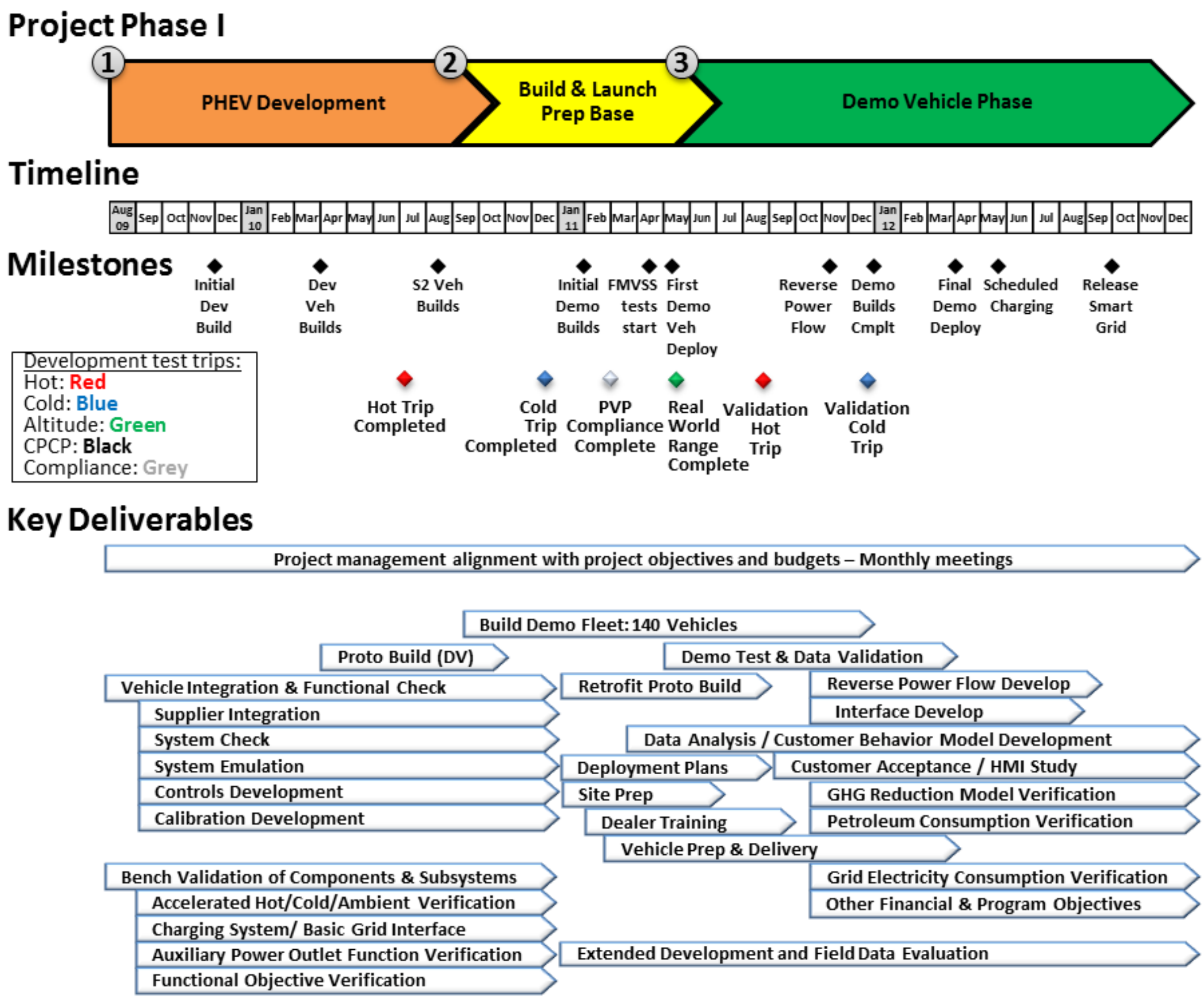


Figure 33: Phase I project timeline and key development milestones

The Phase II demonstration program involved integration of the high-voltage energy storage system upgrade. Key development and testing milestones for Phase II are presented in Figure 34 below.

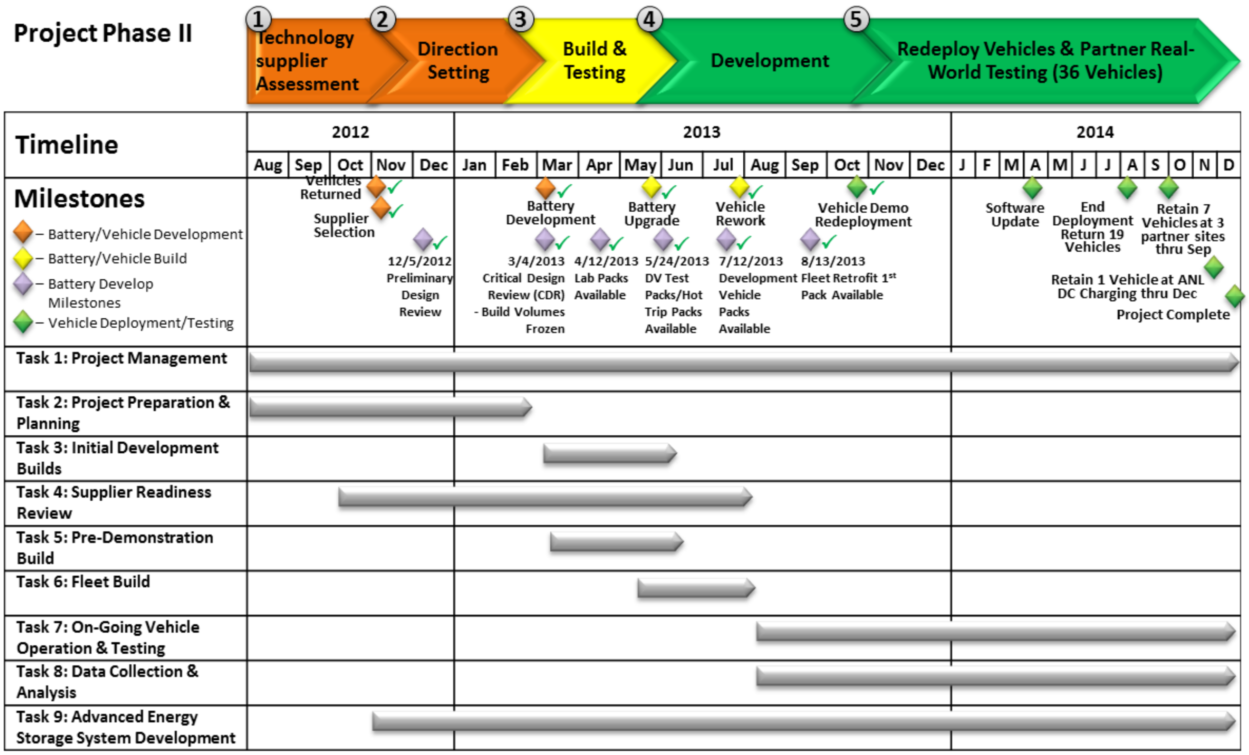


Figure 34: Phase II project timeline and key development milestones

3.2 Vehicle Integration Process

The development of Ram 1500 PHEV followed the Chrysler Product Creation Process (CPCP), which defines the strategy and method used to execute the development of world-class vehicles from concept to market. Fundamental principles include:

- Voice of the Customer – Dictates product decisions
- Timeline Compression – Enables speed to market
- Flexibility – Allows for unique vehicle program characteristics
- Consistency of Execution – Facilitates continuous improvement
- Clear Performance Indicators – Drives accountability
- Interdependencies Identified – Aligns activities across functional areas

As a significant percent of the system architecture is leveraged from existing Chrysler Aspen Hybrid platforms, the value chain for the majority of sub-systems and components is well established. Existing PHEV technology was also tested extensively to enable accelerated integration. A robust process for the selection of reputable and experienced suppliers, coupled with FCA US LLC's tried and tested CPCP process ensured refinement of the new technological elements were achieved with a high level of quality and on schedule.

The detailed and well-tested CPCP process ensured the technology was properly integrated and all vehicle testing (including safety tests) were completed to deliver a high-quality vehicle to the demonstration users. The highlights of the CPCP process are provided in Figure 35 below. Our development partners, such as EPRI, ensured that proper integration of the vehicles into the home and electric grid infrastructure took place at all locations.

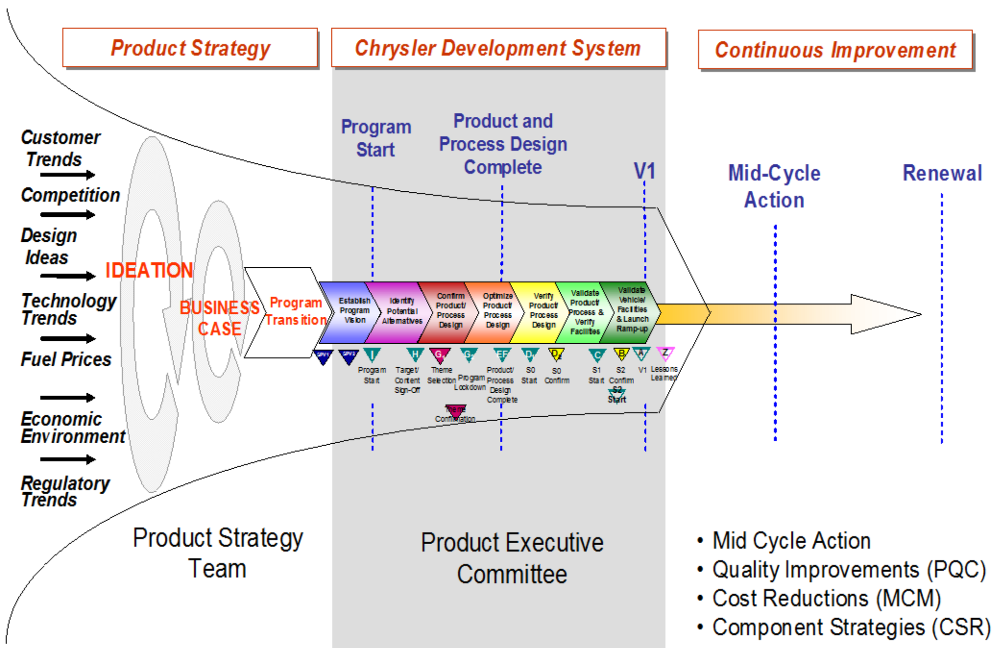


Figure 35: Chrysler Product Creation Process (CPCP) overview

Though iterations of CPCP process, an efficient vehicle integration solution was created for the demonstrated PHEV vehicle. Figure 36 on the next page presents the overall vehicle packaging for key elements:

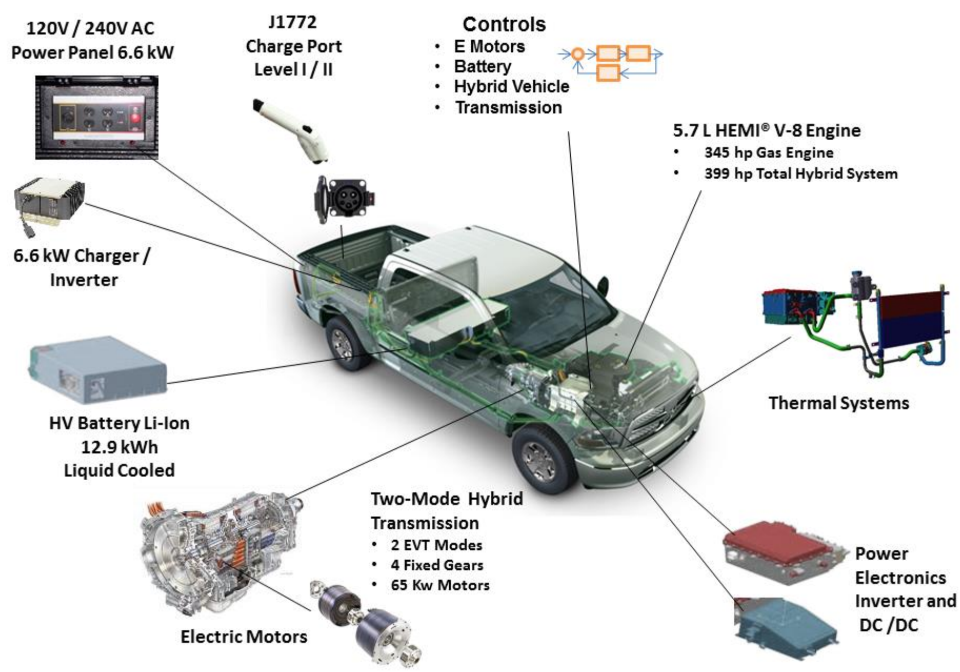


Figure 36: Vehicle integration overview for the Ram 1500 PHEV

Table 11 below provides the technical specifications and key features of the demonstration Ram 1500 PHEV truck.

Technical Specifications			
High-voltage energy storage system	Next-generation lithium-ion high-voltage energy storage system	**Target charge time**	2-4 hrs. @ 220V Up to 15 hrs. @ 110V (Full-hybrid system function without plug-in)
Fuel economy (city)	32 mpg @ charge depleting	**EV range (city)**	20 (Phase I)/12 (Phase II) miles
Range	655 miles	**Transmission**	Advanced two-mode hybrid
Brakes	Regenerative Braking System	**Capacity**	Towing: 6,000 lbs.
Max. power	399 hp		
Key Features			
• Does not compromise any of the standard pickup volume or utility • Maintains trailer towing and grade-ability advantage of standard truck • Classified as Advanced Technology Partial Zero Emission Vehicle (AT-PZEV) 			

Table 11: Technical specifications and key features of demonstration Ram 1500 PHEV truck

3.3 Vehicle Testing Operations

3.3.1 High-Voltage Energy Storage System Testing Operation

During Phase I, 16 high-voltage energy storage system packs were used for testing and 140 packs were used for demonstration PHEVs. Qualification and approval testing for cells, modules, high-voltage energy storage management system, electrical and mechanical components, thermal management, and mechanicals were conducted prior to the release of packs. Specific testing included power tests at various temperatures and states of charge, energy characterization at various discharge rates and temperatures, recharge power and efficiency tests, state-of-charge accuracy tests, lifecycle tests, EPA cycle test, and random vibration and other environmental testing (humidity, dust, shock, etc.). In addition, destructive testing to cell modules with the integrated high-voltage energy storage management system, per the United Nations' IATA requirements was conducted.

3.3.2 Equivalent All Electric Range (EAER) Compliance

Equivalent All Electric Range (EAER) testing is part of the SAE J1711 testing procedure designed to address PHEVs. It quantifies the effects of PHEV operations in terms of fuel economy and emissions reduction. It also evaluates criteria emissions under worst-case operating scenarios and helps determine electric range contribution and ZEV credit qualifications. For instance, a rating of PHEV20 indicates that the PHEV behaves like an EV for the specified 20-mile range before switching to charge-sustaining operation with the internal combustion engine active. However, a vehicle may enter a blended mode for some time before completing charge-sustaining mode. Therefore, in order to determine the EAER for a PHEV, a series of five tests in charge-depleting mode are designed to cover both pure EV and blended mode operations.

In this project, EAER testing was performed based on the procedure specified in Figure 37 on the next page. The target of 20 miles was met in Phase I as the result shows.

Phase I Test Procedures Results

Objective	Target	Status	Procedure	R/G/Y	Phase II Target
RANGE	Equivalent All Electric Range (EAER) of 20 miles	20+ miles EAER achieved	California Exhaust Emission Standards And Test Procedures, as amended December 2, 2009	GREEN	EAER 10 (DOE Approved. Magna/JCI Pack Support 14)

Phase I Real World Results

	INL Data September 2014	Background
Partners FUEL ECONOMY & Mileage Accumulation (Real World)	• Charge Depletion: Accumulated Miles – **230,741** – **City**: **22** mpg; **Hwy**: **26** mpg • Charge Depletion / Charge Sustaining: Accumulated Miles – **88,728 (CD) / 155,504 (CS)** – **City**: **19** mpg; **Hwy**: **21** mpg • Charge Sustaining: Accumulated Miles – **564,843** – **City**: **16** mpg; **Hwy**: **19** mpg	• Data gathered from **111** partner vehicles deployed throughout the United States • Partners Total Mileage : **1,039,138** through Sept 12 • Vehicle fuel economy is based on customer usage and may not be representative of maximum potential fuel economy

Figure 37: Phase I EAER results

Due the upgrade of the energy storage system, EAER testing was performed again for Phase II based on procedures noted in the figures below. The target was reduced from 20 to 10 because of the lower energy capacity the Phase II system vs. the Phase I system (9.7 kWh vs. 12.9 kWh). In Phase II, an EAER result of 12 miles was achieved, exceeding the target of 10 miles. (See Figure 38 below)

Phase II Test Procedure Results

Objective	Target	Status	Procedure	R/G/Y
RANGE	EAER 10	EAER 12 Achieved	California Exhaust Emission Standards And Test Procedures, as amended December 2, 2009	GREEN

Real World Results

DS PHEV Status	INL data December 2013 thru September 2014	Background
Partners FUEL ECONOMY & Mileage Accumulation (Real World)	• Charge Depletion: Accumulated Miles – **56,938** – **City**: **24** mpg; **Hwy**: **27** mpg • Charge Depletion / Charge Sustaining: Accumulated Miles – **22,777 (CD) / 41,802 (CS)** – **City**: **20** mpg; **Hwy**: **22** mpg • Charge Sustaining: Accumulated Miles – **119,453** – **City**: **17** mpg; **Hwy**: **20** mpg	• Data gathered from **22** partner vehicles deployed throughout the United States • Partners Total Mileage : **240,729** (December 2013 through September 2014) • Vehicle fuel economy is based on customer usage and may not be representative of maximum potential fuel economy

Figure 38: Phase II EAER results

3.3.3 Federal Safety Compliance and Emission Standards

To ensure all demonstration vehicles were built to comply with federal safety and emission standards, the vehicles were used for Federal Motor Vehicle Safety Standards (FMVSS) and emission testing during Phase I of the project. During the vehicle initial development period, 12 PHEVs were built and used for the FMVSS testing. All the requirements were achieved.

Internal emission testing was conducted with both new and aged components to meet the AT-PZEV compliance. Table 12 below presents a summary of the targets and the results of such testing.

<table>
<tr><th>Testing</th><th>Targets and Results</th><th>Standard</th></tr>
<tr><td>Emission AT-PZEV compliance</td><td>SULEV TP emissions demonstrated for
Charge depleting (CD) city and hwy cycles
Charge sustaining (CS) city, hwy, US06, and cold CO cycles
Based on testing with prior development test vehicles, SULEV TP emissions requirements can be met for 50F test and SC03 cycle.

Met the PZEV Evap emissions requirements for
Rig test, based on the purge volume measurements during the three-bag city cycle
Based on testing with prior development test vehicles , PZEV Evaporating emission requirements can be met for whole vehicle SHED test, ORVR and running loss

<table>
<tr><th>Test</th><th>Test Mode</th><th>Standard</th><th>Results</th></tr>
<tr><td>FTP City</td><td>CD & CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>US06</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>SC03</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>Highway</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>50 F City</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>20 F Cold</td><td>CS</td><td>SULEV</td><td>Passed ✓</td></tr>
<tr><td>Evaporative</td><td>CS</td><td>PZEV</td><td>Passed ✓</td></tr>
<tr><td>Purge Volume</td><td>CS</td><td>PZEV</td><td>Passed ✓</td></tr>
</table></td><td>California exhaust emission standards and test procedures, as amended December 2, 2009</td></tr>
</table>

Table 12: PHEV AT-PZEV compliance status

4. Demonstration PHEV Fleet Deployment

4.1 Fleet Partner Training and Communication

Fleet deployment had to ensure the safety of the partners and that the fleet-partner activities were always aligned with the project objectives. To attain these goals, the following training activities were conducted with the fleet managers and drivers.

- High-voltage awareness
- General vehicle features
- Specific PHEV features of charging, power panel and map-based fuel economy use
- Expectations for the frequency of use of the PHEV features
- Expectations for driving parameters and frequency
- Required maintenance and data reporting

Monthly conference calls between FCA, the fleet partner managers and the fleet drivers were held to lend support to the fleet-partner activities and to check performance to expectations. These discussions included extensive reviews of lessons learned.

4.2 Demonstration Vehicle Maintenance Operation

FCA US LLC developed a robust service strategy for this demonstration project to handle vehicle maintenance and functional issues. The following are a few highlights of this service strategy:

- **Dealer service support.** Selected dealers in each test area were trained to handle scheduled maintenance of the vehicles and to troubleshoot minor issues. Training and service manuals with Statements of Work (SOWs) were prepared and made available to the service engineers, who were provided hands-on training by the mobile on-site support team.
- **Mobile on-site support team.** Two FCA US LLC engineers were dedicated to the PHEV fleets and traveled to demonstration locations to troubleshoot vehicle issues and train local dealers on repairs.

- **Help desk.** In the event of a vehicle breakdown or diagnostic trouble code, PHEV-trained engineers were available to answer questions and resolve demonstration vehicle issues.
- **Service parts.** Extra parts for key commodities (such as chargers) were made available in advance to expedite the repair process in the dealerships.
- **Team leadership.** The service team leader was located at FCA US LLC headquarters. This person oversaw all service issues and was able to call for support from FCA US LLC expert engineers, well as experts from the supply base and development partners. The team leader held routine meetings with all parties, including fleet partners, to discuss pertinent issues.

4.3 Fleet Partner Demonstration Statistics

4.3.1 Geographical Locations of Demonstration Fleet

The Ram 1500 PHEV pickup truck demonstrated the ability to significantly reduce petroleum consumption and GHG emissions. To ensure a robust assessment, FCA US LLC deployed 140 trucks in diverse geographies and climates and across a range of drive cycles and consumer usage patterns applicable to most NAFTA regions. FCA US LLC successfully executed the program through joint efforts with a number of state, city and local governments, research and development authorities, utility companies, non-profit industry organizations and universities across the country. Development and demonstration partners were chosen for the technical strengths, diverse ambient conditions and customer drive cycles, including urban, city and highway driving conditions. The demonstration program also facilitated the promotion of "green initiatives" in many states across the country.

Figure 39 below illustrates the locations and quantities of all demonstration PHEVs deployed in Phase I. The deployment period for Phase I was from May 2011 to September 2012.

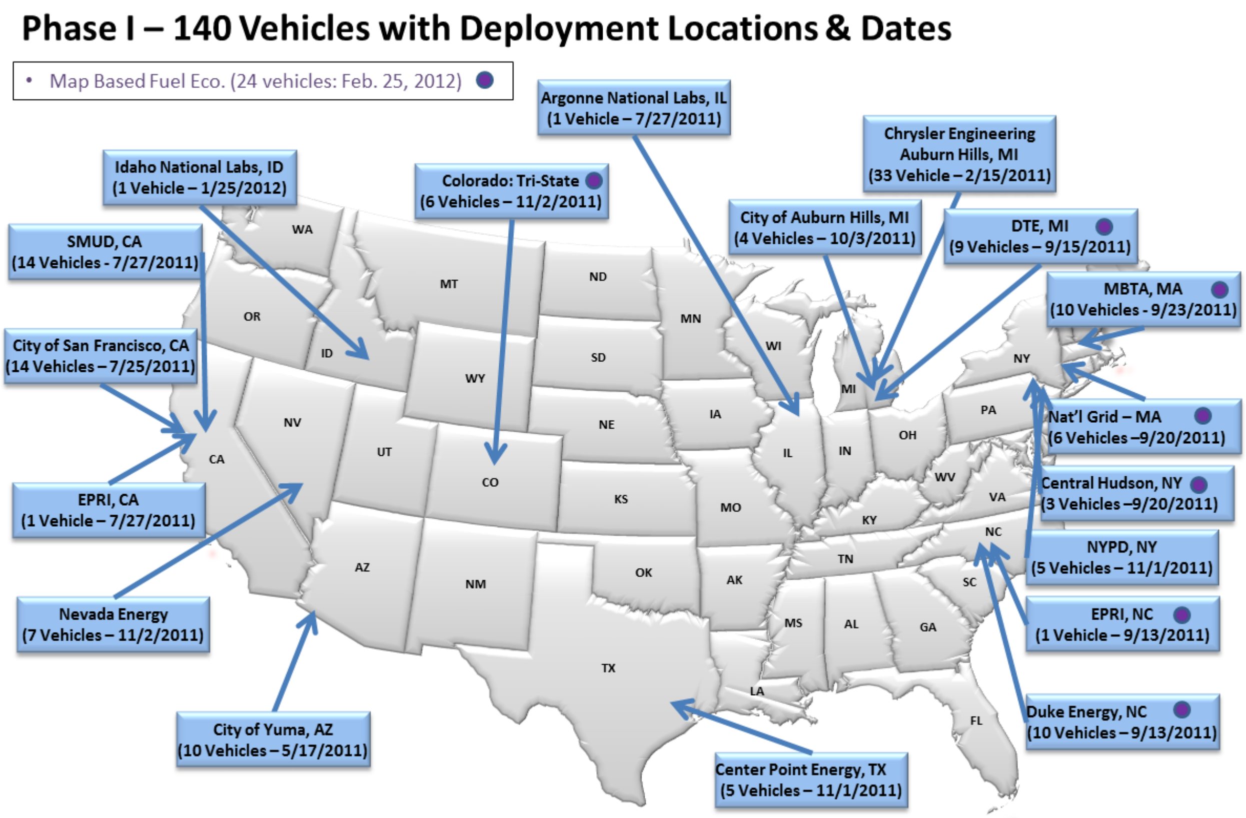


Figure 39: Phase I demonstration PHEV deployment location and quantity details

After Phase I demonstration, 34 trucks were fitted with upgraded energy storage systems. They were then redeployed to the demonstration partners for advanced technology investigation in Phase II. During this time, the PHEVs were subject to routine vehicle use across 16 different external partners, 17 U.S. locations and the FCA US LLC Technical Center. Data collection and analysis processes continued to be performed in Phase II – with the same approach and methods as in Phase I. Figure 40 below illustrates the locations and quantities of all demonstration PHEVs deployed in Phase II. The deployment period for Phase II was from October 2013 to December 2014.

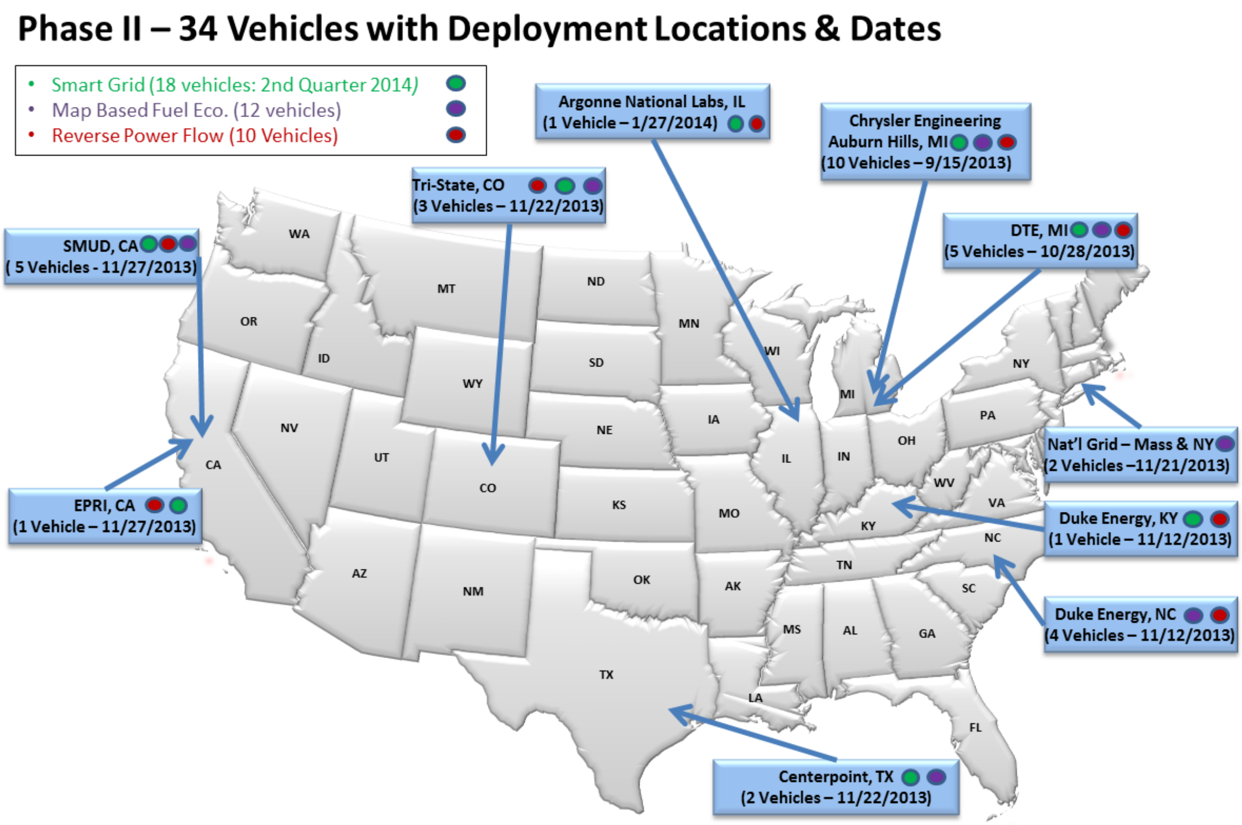


Figure 40: Phase II demonstration PHEV deployment location and quantity details

4.3.2 Vehicle Features Distribution by Location

Details of partner vehicle deployment status regarding vehicle function and features tested in Phase I are shown in Table 13 below.

Phase I Partner	Total Vehicles	Date Deployed	Map-Based Fuel Vehicles
FCA US LLC, MI	33	2/15/2011	2
City of Yuma, AZ	10	5/17/2011	0
City of San Francisco	14	7/25/2011	0
ANL, IL	1	7/27/2011	0
EPRI, CA	1	7/27/2011	0
SMUD, CA	14	7/27/2011	0
Duke Energy, NC	10	9/13/2011	4
EPRI, NC	1	9/13/2011	1
DTE Energy, MI	9	9/15/2011	2
Central Hudson, NY	3	9/20/2011	2
National Grid, MA	6	9/20/2011	2
MBTA, MA	10	9/23/2011	2
City of Auburn Hills, MI	4	10/3/2011	0
CenterPoint Energy, TX	5	11/1/2011	0
NYPD, NY	5	11/1/2011	0
Nevada Energy	7	11/2/2011	0
Tri-State, CO	6	11/2/2011	3
INL, ID	1	1/25/2012	0
Totals	**140**		**18**

Table 13: Phase I partner deployment details and vehicle totals

Details of partner vehicle deployment status regarding vehicle function and feature tested in Phase II are shown in Table 14 below. During the closeout period of the project, all demonstration PHEV trucks were returned to FCA US LLC and the decommissioning process was initiated.

Phase II Partner	# of Vehicles	Date of Deployment	Phase II Features Included			Phase II Equipment		
			Smart Charging	Reverse Power Flow	Map Based Fuel	EVSE MPR	ALG	Gateway
SMUD	5	11/27/2013	Yes		Yes	7	3	0
			Yes		Yes			
			Yes					
			Yes	Yes				
			Yes	Yes				
DTE	5	10/28/2013	Yes		Yes	7	3	0
			Yes	Yes				
			Yes		Yes			
			Yes		Yes			
			Yes	Yes				
Duke Energy	5	11/12/2013	Yes		Yes	2	0	0
			Yes		Yes			
			Yes					
			Yes	Yes				
			Yes	Yes				
Tri-State	3	11/22/2013	Yes	Yes		3	0	2
			Yes		Yes			
			Yes		Yes			
National Grid	2	11/21/2013			Yes	3	0	0
CenterPoint Energy	2	11/22/2013	Yes	Yes		2	1	0
			Yes		Yes			
EPRI	1	11/27/2013	Yes	Yes		1	1	1
ANL	1	1/27/2014	Yes	Yes		1	1	1
FCA US LLC	10	9/15/2013		Yes	Yes	10	7	12
Totals	**34**					**36**	**16**	**16**

Table 14: Phase II partner deployment details and vehicle totals

5. Fleet Demonstration Data Collection and Analysis

5.1 Fleet Data Collection and Evaluation

5.1.1 Categories of Collected Data

FCA US LLC and its partners collected and analyzed two categories of data throughout the PHEV demonstration project: system-monitoring data and driver-profiling data. System monitoring tracked the performance of the system as a whole, exploring the limits of the system and revealing opportunities for further optimization. Key system monitoring data collected were high-voltage energy storage system (voltage, current and temperature), engine operation and power consumption (including SOC, fuel usage and GHG estimation for each trip). Driver profiling was an attempt to understand how a customer uses a particular vehicle and its functions. The data analyzed for driver profiling includes: charging (including power consumption from the grid, and the frequency and duration of charging); mileage per trip and per day; driver aggressiveness (which contributes to power consumption, including vehicle power distribution and pedal distribution); and frequency and duration of auxiliary power panel unit usage.

5.1.2 Technology and Process for Data Collection

FCA US LLC developed a data recording module (DRM) specially designed to collect specific vehicle test data and act as a user interface device for remote diagnostics, Reverse Power Flow, Smart and Scheduled Charging operation. The DRM sampled vehicle CAN bus messages every second whenever the plug-in hybrid system was awake. It was also used to remotely wake-up the plug-in hybrid vehicle system to perform the above features. No operator actions were required to upload the vehicle data. Referring to Figure 41 on the next page:

- The system performed near real-time data uploads limited only by secure cellular service signals. This bypassed the need for Wi-Fi access to secure partner routers for data uploads
- GPS coordinates were included in the data through satellite communication
- It provided engineering wireless vehicle scan-tool diagnostics to triage vehicle issues

- FCA US LLC was able to flash modules remotely, including the ability to read and erase module Diagnostic Trouble Code (DTC)
- The DRM could trigger on specific DTC fault events to capture pre and post vehicle CAN bus data for remote diagnosis and software updates to resolve issues

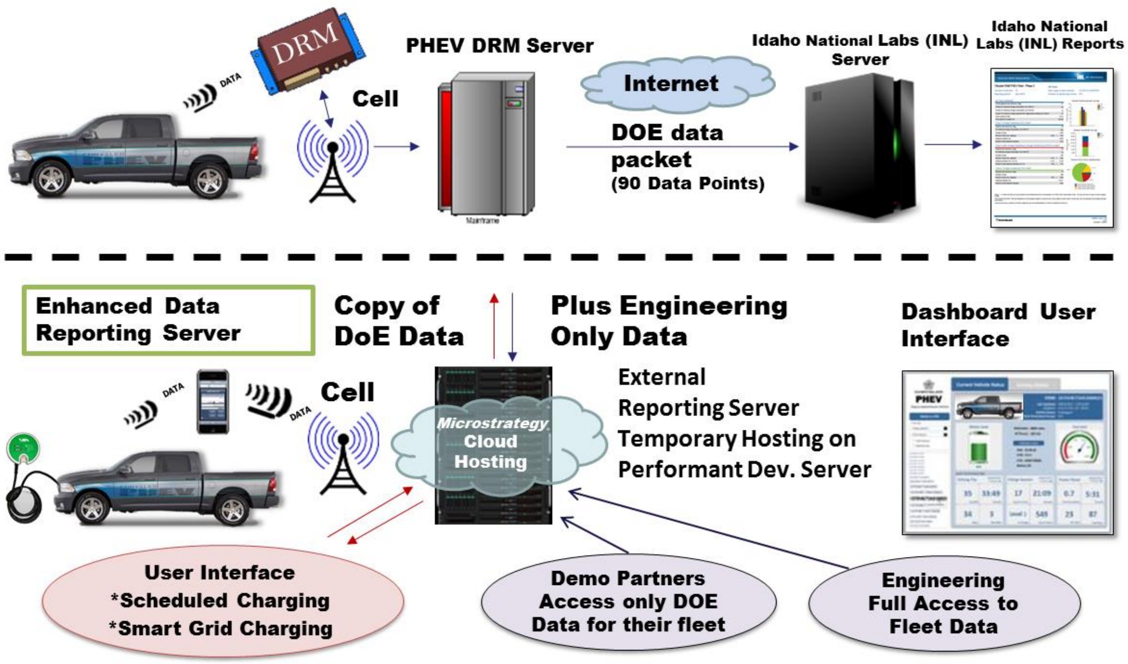


Figure 41: PHEV demonstration data-acquisition process

Acquired Data Path (continued reference to Figure 41):

- Data passed through the cellular system to a dedicated PHEV server database
- Specific DOE data was forwarded to the Idaho National Labs PHEV database for processing and reporting
  1. Idaho National Laboratory, as part of its conduct of the U.S. Department of Energy's Advanced Vehicle Testing Activity, produced monthly reports for the Ram plug-in hybrid electric pickup truck. These monthly reports were publicly available on the AVTA website (http://avt.inl.gov). Three page performance summaries were issued monthly for the entire fleet: for each month and project-to-date. Monthly performance reports were also issued to FCA US LLC.
  2. The contents of the DOE reports categorize the data from the vehicles by trip type, to show results for charge-depleting, mixed charge-depleting and charge-sustaining and charge-sustaining-mode-only trips. Fuel and electricity use was shown for each to isolate the effect of plug-in electrification on fuel consumption, and to show how

much driving was performed in each mode. These results were further refined into city and highway trips to highlight the effects of speed on fuel consumption in each mode. Similarly, the range of fuel economy achieved was shown for different ranges of aggressiveness, which was calculated by the energy expended to accelerate the vehicle per mile. Finally, charging behavior and performance were detailed to show how frequently and when the fleet was charged and how long charge events took with both level-one and level-two AC charging infrastructure.

- A copy of the DOE data and additional detailed engineering data was also sent to the MicroStrategy cloud server from the PHEV server database
- The MicroStrategy data was used in three ways:
    1. The fleet managers at the DOE partner locations could access limited information for their fleet vehicles.
    2. The MicroStrategy cloud took advantage of the DRM two-way communication capability and provided a user interface for vehicle to grid functions. The functions included were Scheduled Charging, Smart Charging and Reverse Power Flow.
    3. FCA US LLC engineering had full access to all data. The cloud provided the list of preprogrammed database reports shown in Table 15 below, along with ad-hoc reporting, enabling the creation of customized reports.

MicroStrategy Cloud PHEV Report Titles	
1. Trip time in high-voltage energy storage system thermal states	11. Engine-coolant temp
2. Drive mode high-voltage energy storage system cell temp	12. Trip distance vs trips
3. Charge mode high-voltage energy storage system cell temp	13. Trip starting and ending high-voltage energy storage system SOC
4. Vehicle speed per trip	14. Charge start and stop high-voltage energy storage system SOC
5. Miles driven per trip	15. Trip time
6. Miles in charge sustain or depletion	16. Trip distance (km)
7. Charge sustain or depletion operation	17. High-voltage energy storage system pack SOC
8. Vehicle speed per trip	18. 12V battery
9. Time in charge sustain or depletion	19. Total energy (discharge)
10. Compressor run time	20. Total energy (charge/regeneration)

Table 15: List of PHEV MicroStrategy reports

5.2 Deployment Data Summary from Idaho National Lab

As previously noted, Idaho National Lab processed the data recorded by the on-board data recording module and provided regular reports. Summaries of the deployment statistics from Phase I for a portion of the deployed vehicles are shown below in Figures 42 through 44. The data period ranges from May 2011 to September 2012.

All Trips Combined			
Overall gasoline fuel economy (mpg)			19
Overall AC electrical energy consumption (AC Wh/mi)[1]			90
Overall DC electrical energy consumption (DC Wh/mi)[2]			61
Overall DC electrical energy captured from regenerative braking (DC Wh/mi)			43
Total number of trips			112,556
Total distance traveled (mi)			1,043,207
Trips in Charge Depleting (CD) mode[3]			
Gasoline fuel economy (mpg)			23
DC electrical energy consumption (DC Wh/mi)[4]			213
Number of trips			42,383
Percent of trips city | highway	94%	|	6%
Distance traveled (mi)			231,186
Percent of total distance traveled			22%
Trips in both Charge Depleting & Charge Sustaining (CD/CS) modes[5]			
Gasoline fuel economy (mpg)			21
DC electrical energy consumption (DC Wh/mi)[6]			68
Number of trips			11,889
Percent of trips city | highway	74%	|	26%
Distance traveled CD | CS (mi)	88,840	|	155,893
Percent of total distance traveled CD | CS	8%	|	15%
Trips in Charge Sustaining (CS) mode[7]			
Gasoline fuel economy (mpg)			17
Number of trips			58,284
Percent of trips city | highway	89%	|	11%
Distance traveled (mi)			568,028
Percent of total distance traveled			54%

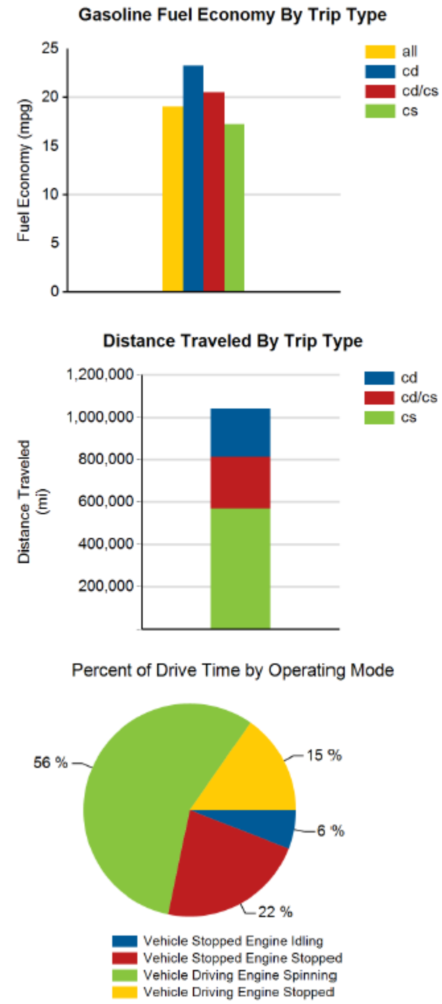
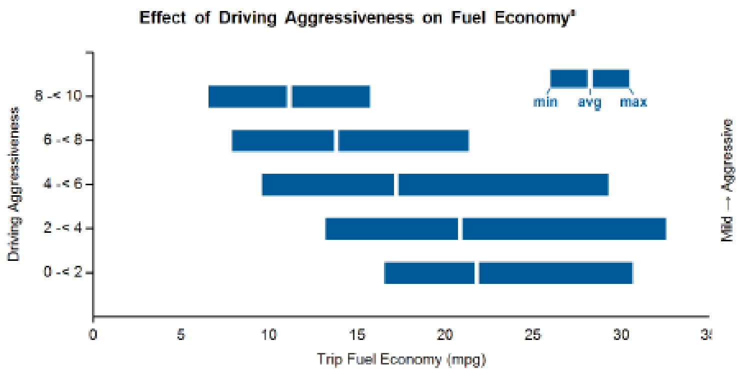


Figure 42: Phase I overall fleet deployment statistics

Trips in Charge Depleting (CD) mode	City	Highway
Gasoline fuel economy (mpg)	22	26
DC electrical energy consumption (DC Wh/mi)	232	161
Percent of miles with internal combustion engine off	16%	3%
Average trip Aggressiveness	6.1	3.7
Average trip distance (mi)	4	25
Trips in Charge Depleting and Charge Sustaining (CD/CS) mode		
Gasoline fuel economy (mpg)	19	21
DC electrical energy consumption (DC Wh/mi)	83	56
Percent of miles with internal combustion engine off	12%	2%
Average trip Aggressiveness	5.4	2.8
Average trip distance (mi)	12	46
Trips in Charge Sustaining (CS) mode		
Gasoline fuel economy (mpg)	16	19
Percent of miles with internal combustion engine off	11%	2%
Average trip Aggressiveness	5.8	2.7
Average trip distance (mi)	6	42



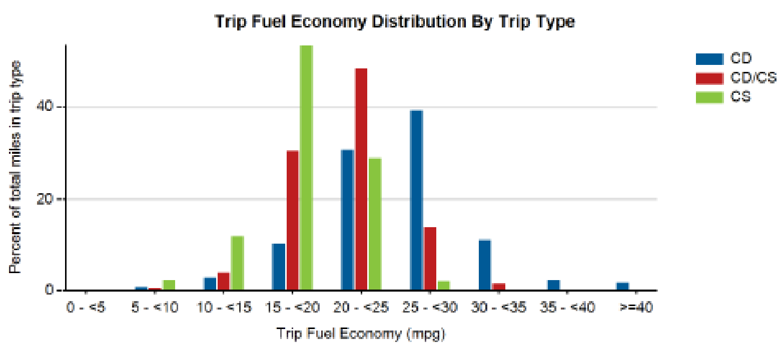


Figure 43: Phase I overall fleet statistics (continued)

Plug-in charging

Average number of charging events per vehicle per month when driven		11
Average number of charging events per vehicle per day when driven		0.8
Average distance driven between charging events (mi)		71
Average number of trips between charging events		7.5
Average time charging per charging event (hr)		2.5
Average energy per charging event (AC kWh)		6
Average charging energy per vehicle per month (AC kWh)		71
Total number of charging events		14,762
Number of charging events at Level 1 | Level 2	3,568	11,111
Total charging energy consumed (AC kWh)		93,644
Charging energy consumed at Level 1 | Level 2 (AC kWh)	22,230	71,404
Percent of total charging energy from Level 1 | Level 2	24%	76%
Average time to charge from 20% to 100% SOC (hrs) Level 1 | Level 2[9]	12.5	3

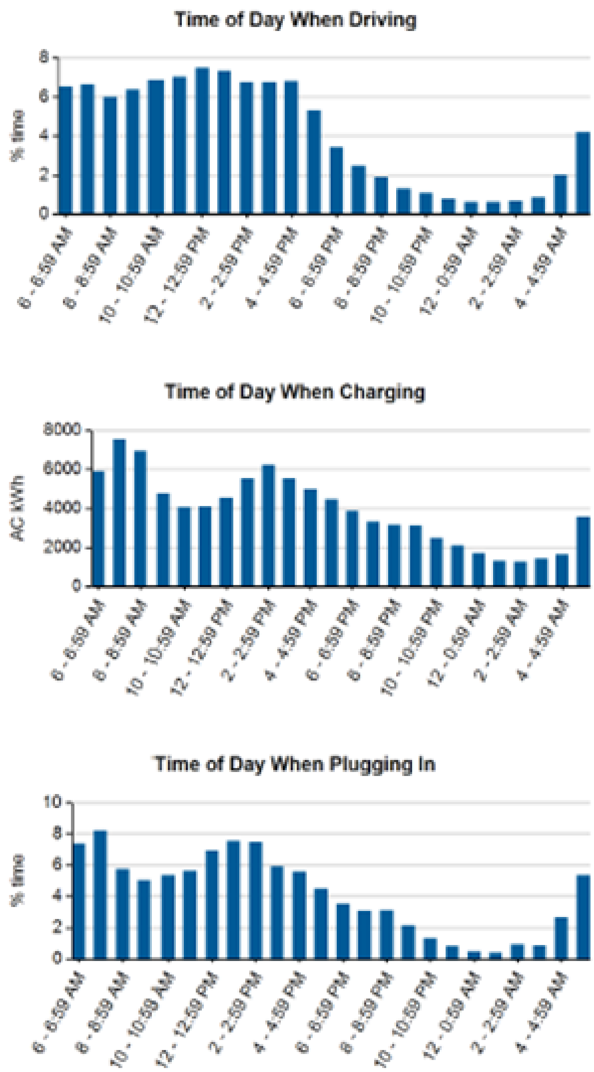


Figure 44: Phase I overall fleet statistics (continued)

The deployment statistics from the Phase II for a portion of the deployed vehicles are shown in Figures 45 through 47. Note that the date ranges from October 2013 to September 2014, rather than the end of project date, December 2014. The vehicles deployed from September to December 2014 were primarily used for vehicle-to-grid and vehicle-to-load communication development – with few or no driving events.

All Trips Combined		
Overall gasoline fuel economy (mpg)		20
Overall AC electrical energy consumption (AC Wh/mi)[1]		87
Overall DC electrical energy consumption (DC Wh/mi)[2]		65
Overall DC electrical energy captured from regenerative braking (DC Wh/mi)		35
Total number of trips		19,715
Total distance traveled (mi)		250,478
Trips in Charge Depleting (CD) mode[3]		
Gasoline fuel economy (mpg)		25
DC electrical energy consumption (DC Wh/mi)[4]		201
Number of trips		7,317
Percent of trips city | highway	86%	13%
Distance traveled (mi)		59,219
Percent of total distance traveled		24%
Trips in both Charge Depleting & Charge Sustaining (CD/CS) modes[5]		
Gasoline fuel economy (mpg)		21
DC electrical energy consumption (DC Wh/mi)[6]		67
Number of trips		2,955
Percent of trips city | highway	68%	31%
Distance traveled CD | CS (mi)	24,129	44,415
Percent of total distance traveled CD | CS	10%	18%
Trips in Charge Sustaining (CS) mode[7]		
Gasoline fuel economy (mpg)		18
Number of trips		9,443
Percent of trips city | highway	82%	17%
Distance traveled (mi)		122,956
Percent of total distance traveled		49%

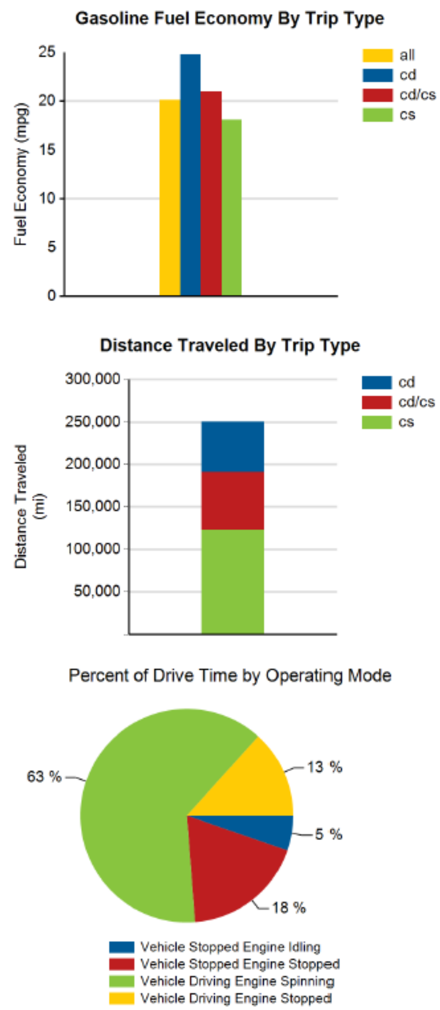
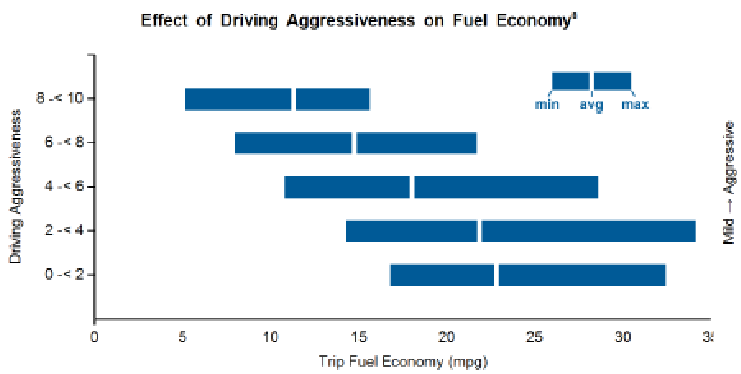


Figure 45: Phase II overall fleet statistics

Trips in Charge Depleting (CD) mode	City	Highway
Gasoline fuel economy (mpg)	24	26
DC electrical energy consumption (DC Wh/mi)	212	175
Percent of miles with internal combustion engine off	12%	3%
Average trip aggressiveness	5.6	3.8
Average trip distance (mi)	7	17
Trips in Charge Depleting and Charge Sustaining (CD/CS) mode		
Gasoline fuel economy (mpg)	20	22
DC electrical energy consumption (DC Wh/mi)	77	57
Percent of miles with internal combustion engine off	9%	2%
Average trip aggressiveness	5	3
Average trip distance (mi)	16	38
Trips in Charge Sustaining (CS) mode		
Gasoline fuel economy (mpg)	17	20
Percent of miles with internal combustion engine off	8%	1%
Average trip aggressiveness	5.5	3.1
Average trip distance (mi)	9	34



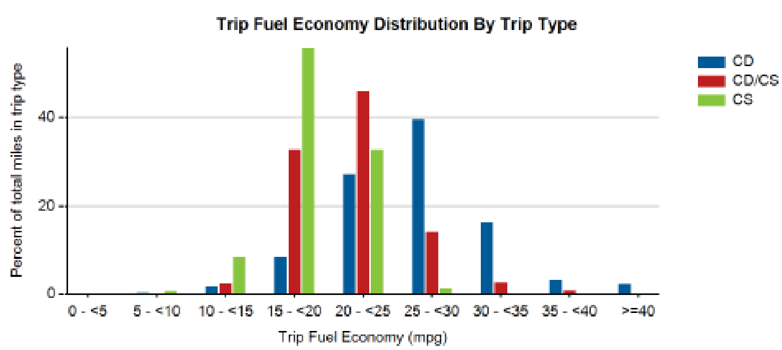


Figure 46: Phase II overall fleet statistics (continued)

Plug-in charging

Average number of charging events per vehicle per month when driven		21.5
Average number of charging events per vehicle per day when driven		1
Average distance driven between charging events (mi)		59
Average number of trips between charging events		4.5
Average time charging per charging event (hr)		1.5
Average energy per charging event (AC kWh)		5
Average charging energy per vehicle per month (AC kWh)		109
Total number of charging events		4,102
Number of charging events at Level 1 | Level 2	713	330
Total charging energy consumed (AC kWh)		20,771
Charging energy consumed at Level 1 | Level 2 (AC kWh)	2,792	17,974
Percent of total charging energy from Level 1 | Level 2	13%	87%
Average time to charge from 20% to 100% SOC (hrs) Level 1 | Level 2[9]	11.5	2

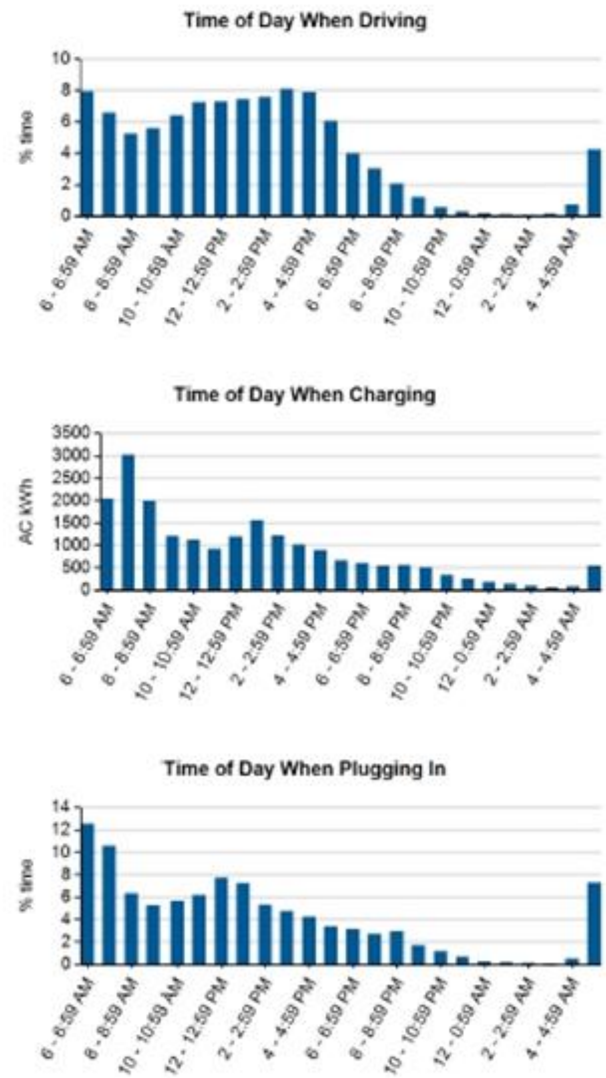


Figure 47: Phase II overall fleet statistics (continued)

5.3 Deployment Detailed Data

The following sections show important data compilations of specific performance parameters, including mileage accumulation, PHEV operations modes and charging activities/frequency. It also shows comparative data for Phase I and Phase II.

Mileage data gathered for each partner in Phase I is shown below in Figure 48 below. The variation in mileage represents the results from diverse geographical locations and types of driving cycles (city and highway).

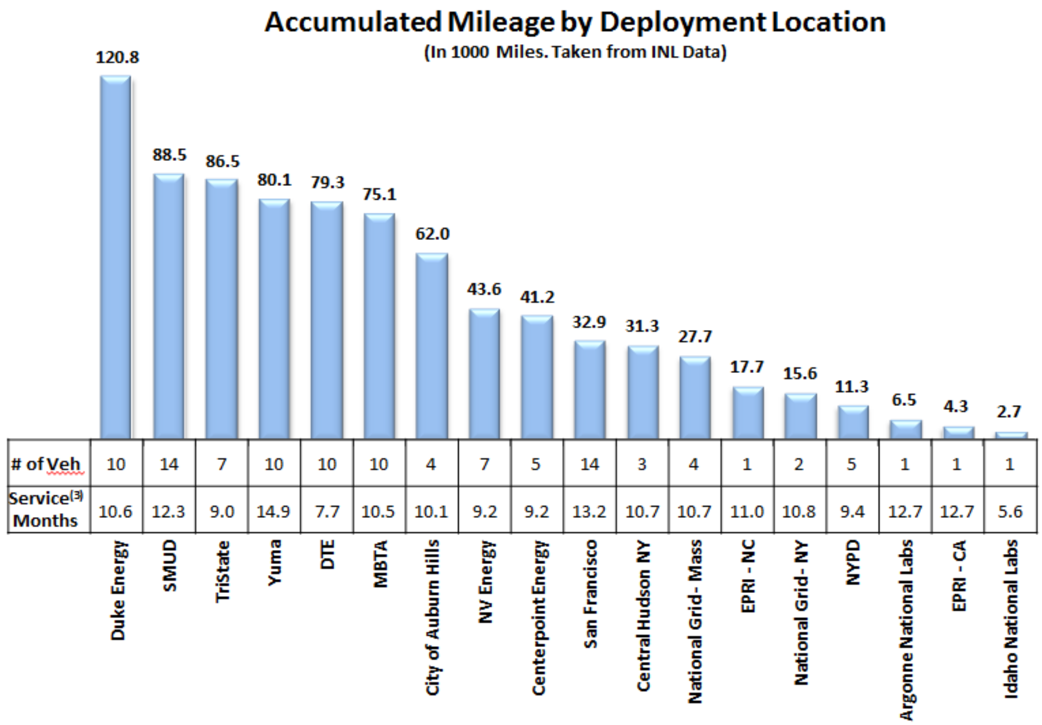


Figure 48: Mileage driven by Fleet Partners

Data was also gathered to determine the charging habits of end users. Three states of high-voltage energy storage system assistance were monitored to analyze PHEV system operation modes. They were: charge depleting (CD), blended charge depleting/charge sustaining (CD/CS) and charge sustaining (CS):

- CD: Trips when the plug-in high-voltage energy storage system charge was depleted throughout entire trip
- CD/CS: Trips when the high-voltage energy storage system was depleted to propel the vehicle for a portion of the trip, but reached a state of charge (SOC) where the vehicle entered CS mode

- CS: Trips when the SOC of the high-voltage energy storage system was not depleted during the trip. Vehicle operation is similar to a HEV in this mode.

Figure 49 below shows the amount of the time spent in each of the state of high-voltage energy storage system discharge and charge at the times of deployment for Phase I.

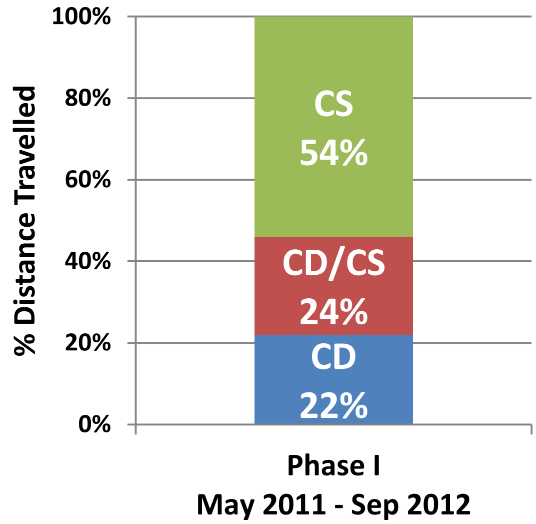


Figure 49: Phase I fleet distance traveled comparison in CD, CD/CS & CS modes

Mileage data was also gathered in Phase II for each partner and compared to Phase I data (shown below in Figure 50 below).

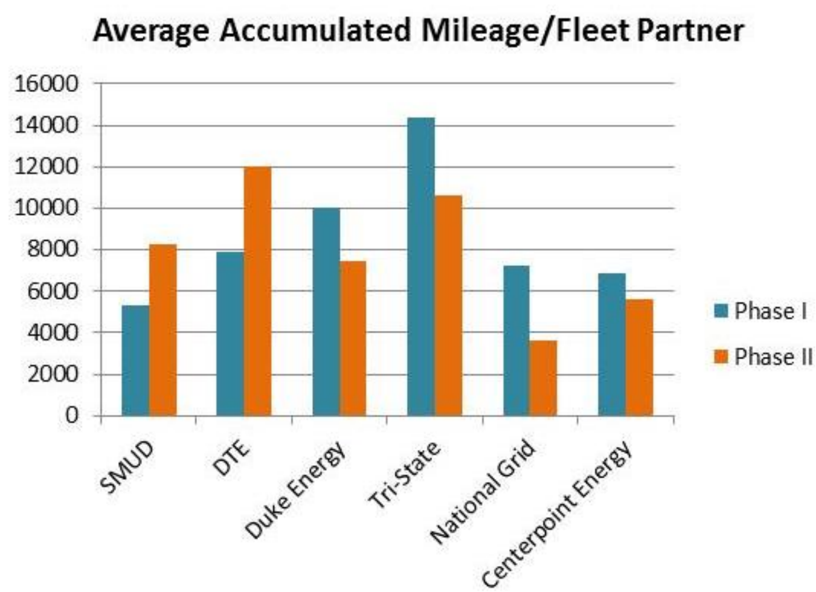


Figure 50: Accumulated mileage by Fleet Partners

In addition, charging activity data was gathered during fleet deployment and utilized for system optimization and determination of the charging habits of end users (Figure 51 below).

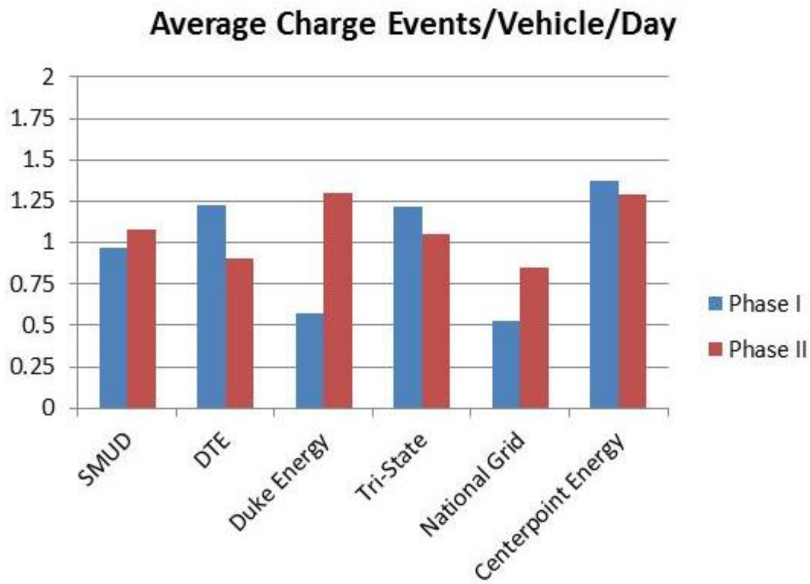


Figure 51: Charging activities statistics by Fleet Partners

The amount of the time spent in each state of high-voltage energy storage system discharge was also monitored in Phase II. Figure 52 below shows the data for both Phase I & II. The chart illustrates that in Phase II, CS mode decreased 5 percentage points, while the CD mode increased 5 percentage points. This is a positive indicator, showing that the demonstration PHEVs are being charged more often and are more effective in displacing petroleum consumption with electricity as "clean" energy.

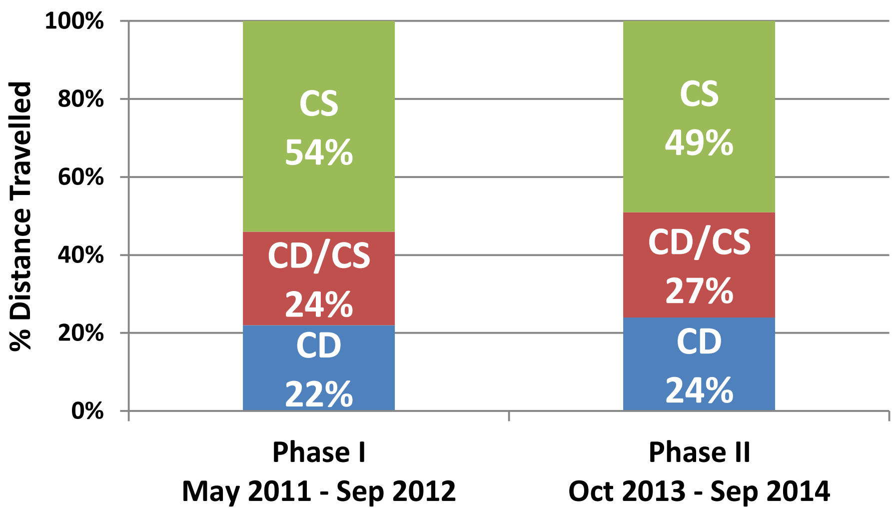


Figure 52: Phase I & Phase II fleet distance traveled comparison in CD, CD/CS & CS modes

5.4 High-Voltage Energy Storage System State of Charge

The State of Charge (SOC) of the high-voltage energy storage system is well known throughout the industry as a dynamic parameter difficult to be determined, as the vehicle is driven under various real-world conditions. In Phase I, the State of Charge was controlled to a 16% minimum value at cell temperatures over 10^{o}C. Figure 53 below illustrates the SOC performance during Phase I.

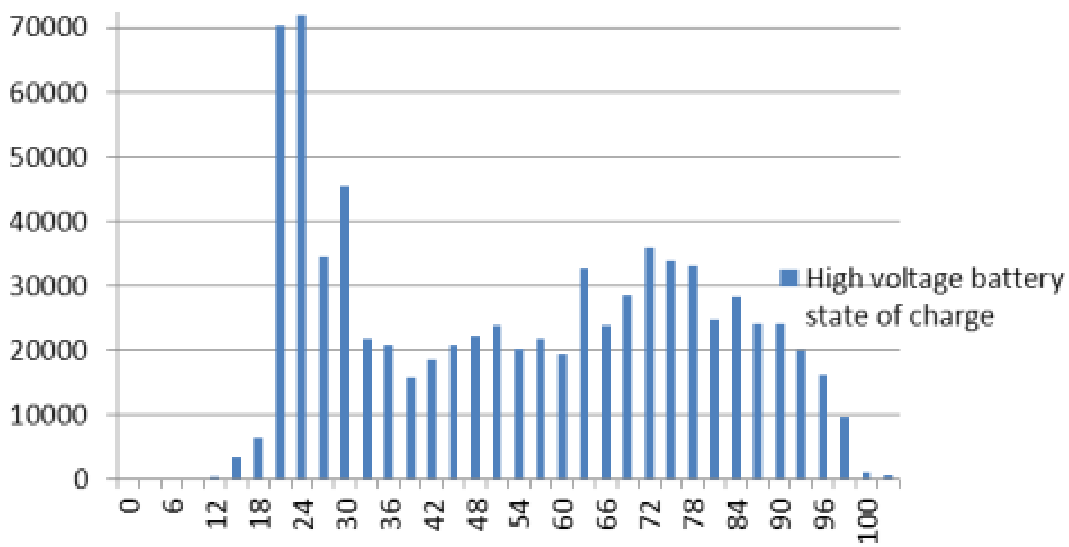


Figure 53: Phase I High-Voltage energy storage system State of Charge

Goal/Target	Key Result
State of Charge was controlled to a 16% minimum value at cell temperatures over 10^{o}C.	Under real-world conditions, the State of Charge minimum was 16% the total system service over all Phase I time and vehicle events.

In Phase II, the high-voltage energy storage system State of Charge was controlled to an 18% minimum value at cell temperatures over 10^{0}C. The adjustment of the minimum SOC level was due to the reduced HV energy storage system design charge capacity for Phase II, compared to Phase I. Figure 54 below illustrates the performance during Phase II.

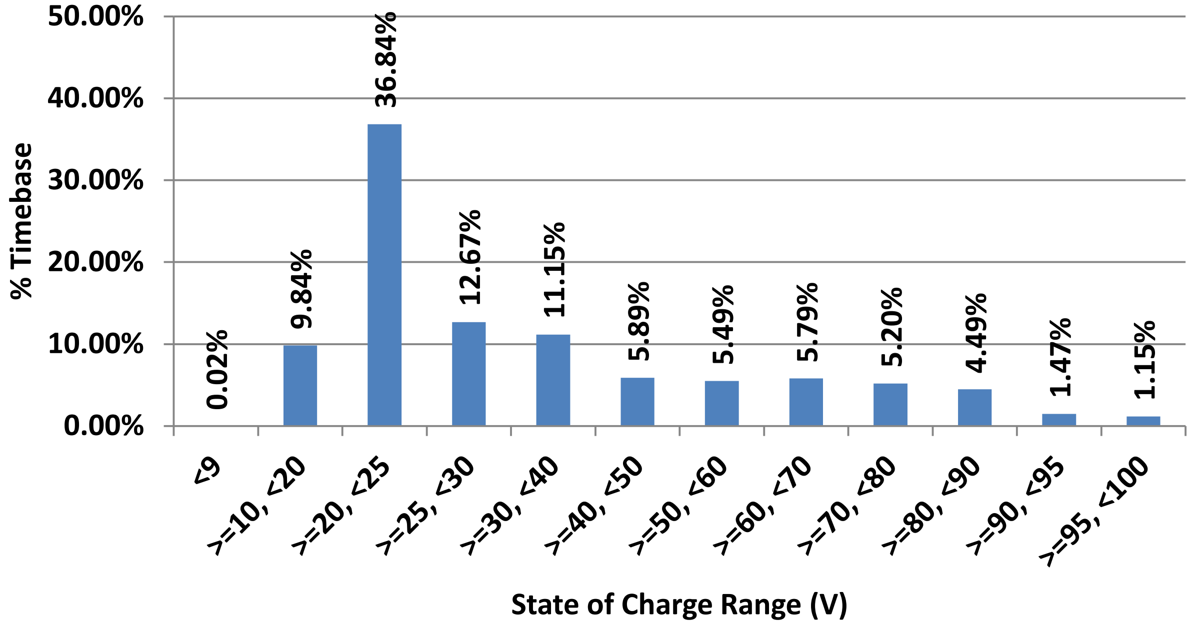


Figure 54: Phase II High-Voltage energy storage system State of Charge

Key Results and Comparison to Goals/Targets

Goal/Target	Key Result
State of Charge was controlled to an 18% minimum value at cell temperatures over 10^{0}C.	Under real-world conditions, the State of Charge minimum was 18% of the total system service over all Phase II time and vehicle events.

5.5 High-Voltage Energy Storage System Cell Voltage Balance

The Phase I objective of the high-voltage energy storage system was effective management of the variation between individual cell voltages to be less than 100 millivolts (mV). The results in Figure 55 below demonstrate that this objective was not met in Phase I. This drove the high-voltage storage system upgrade in Phase II.

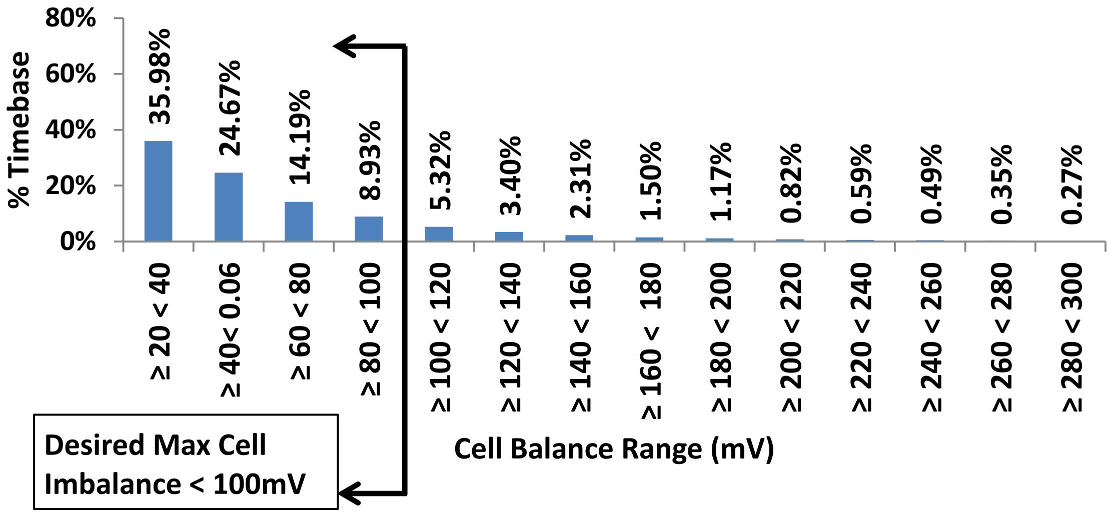


Figure 55: Phase I cell voltage balance statistics

Key Results and Comparison to Goals/Targets

Goal/Target	Key Result
Cell-to-cell voltage variation to be less than 100 millivolts.	Under real-world conditions, the cell-to-cell variation was controlled to less than 100 millivolts in only 84% percent of the total system service over all Phase I time and vehicle events. The target was not met.

The major objective of the high-voltage energy storage system upgrade was effective management of the variation between individual cell voltages to be less than 100 millivolts (mV). The results, shown Figure 56 below, illustrate that this objective was met after the system upgrade.

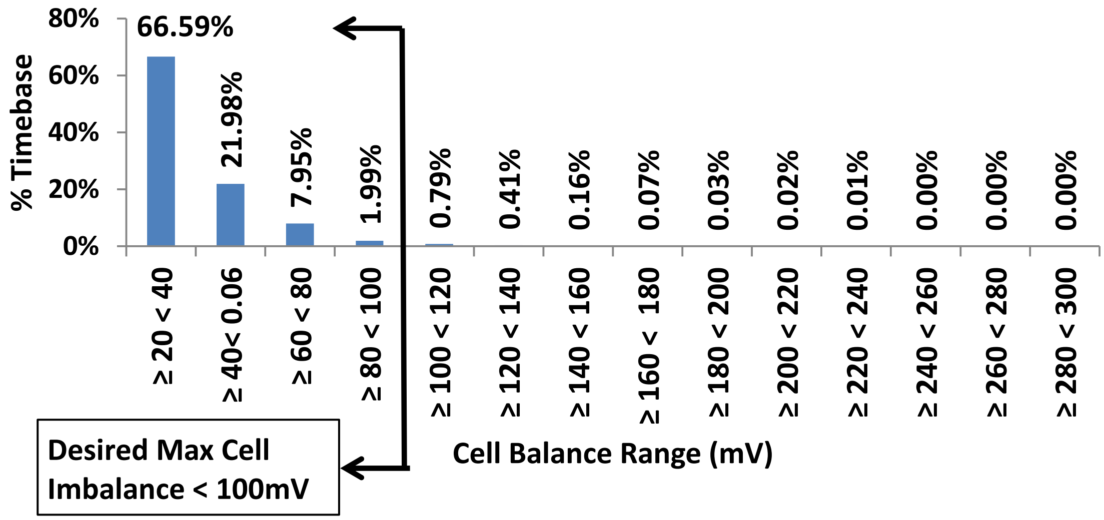


Figure 56: Phase II cell voltage balance statistics

Key Results and Comparison to Goals/Targets

Goal/Target	Key Result
Cell-to-cell voltage variation to be less than 100 millivolts.	Under real-world conditions, the cell-to-cell variation was controlled to less than 100 millivolts 99% percent of the total system service over all Phase II time and vehicle events. The target was met.

5.6 Thermal System Effectiveness in High Ambient Temperature

During the Phase II deployment, high ambient conditions occurred in the Sacramento, CA area. Five days during the period from 6/30/14 through 7/30/14 had a reported maximum meteorological ambient temperature of 38^{0}C (100^{0}F) to 41^{0}C (105^{0}F). Five of the deployed vehicles were operated during these five days of high ambient temperature. The vehicles were driven (trip event), charged (charging event) and the power panel utilized (power panel event). For the three types of events (trip, charging and power panel), percent of time at the maximum cell temperature is noted on the x-axis in Figure 57 on the next page.

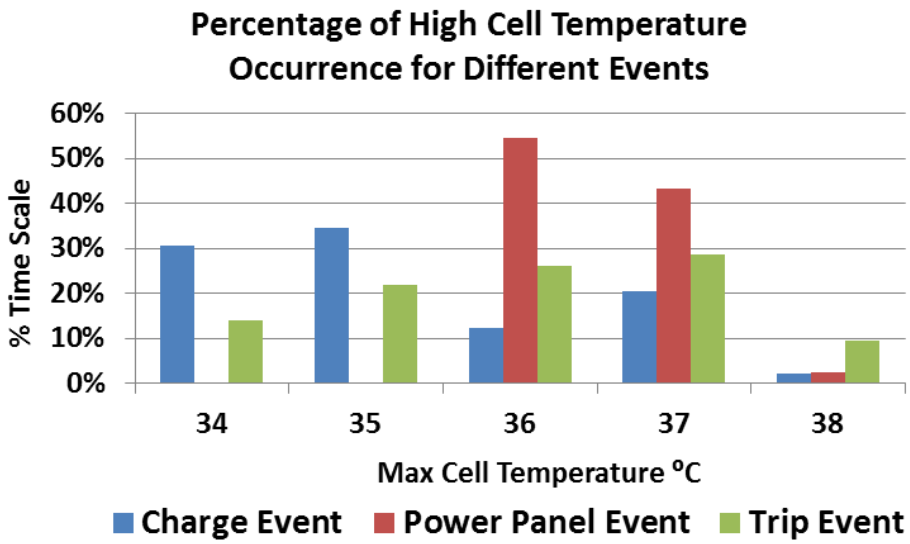


Figure 57: Maximum cell temperature per event type

The percent of time at the maximum cell temperature for all vehicles and events combined is shown in Figure 58 below.

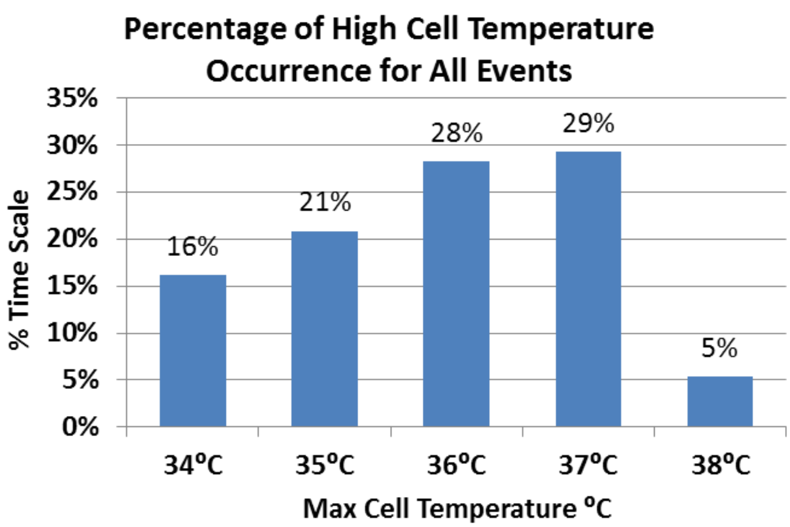


Figure 58: Proportion of time versus maximum cell temperature

Key Results and Comparison to Goals/Targets

Goal/Target	Key Result
Passive cooling (radiator) and active cooling (A/C chiller) were employed to target 37ºC average cell temperature.	Under maximum real-world ambient temperature conditions, the absolute maximum cell temperature reached was 38ºC during all three types of events (charging, power panel and trip). The majority of the time, the cell temp was maintained at 36-37ºC.

5.7 Engine Coolant Temperature and Power Panel

During use of the Power Panel and the high-voltage energy storage system, when state of charge drops to below 20%, the Partial Zero Emissions HEMI® internal combustion engine starts automatically, providing continuous power after depletion of the high-voltage energy storage system charge. During Phase II, a check of the engine-coolant temperature under this condition was performed to ensure that the loading placed on the engine (when acting as a charging power source for the high-voltage energy storage system) does not cause the engine to overheat.

Figure 59 below shows that the predominant temperature of 90ºC to 100ºC for all events matched the temperature range to which the engine is controlled.

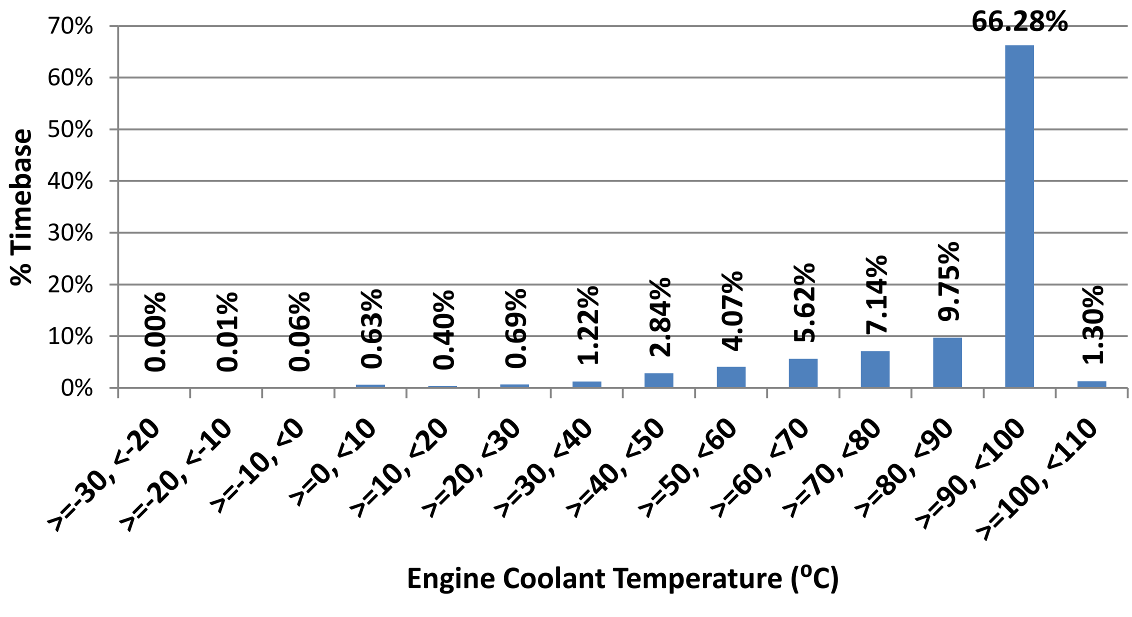


Figure 59: Phase II engine coolant temperature statistics of all events

Figure 60 below shows the engine coolant temperature under only Power Panel events. The percentage of time above the 90ºC to 100ºC range is now significant, but still below the maximum allowable controlled engine temperature of 118ºC. The Power Panel and high-voltage energy storage system under extreme loading conditions did not compromise the performance of the engine-cooling system.

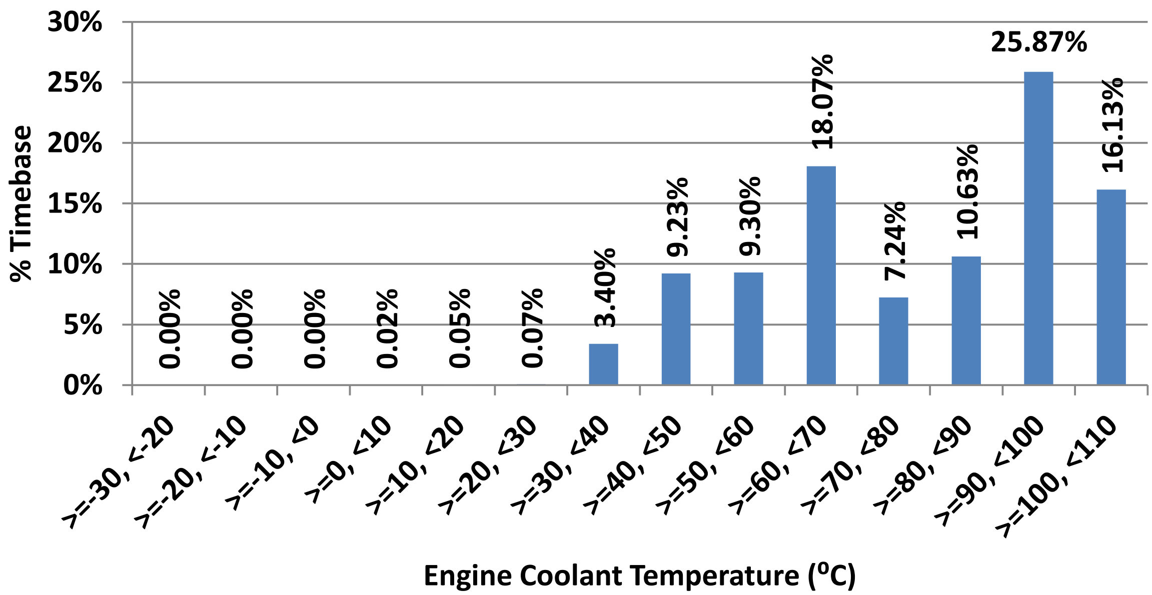


Figure 60: Phase II engine coolant temperature statistics during power panel events

Key Results and Comparison to Goals/Targets

Goal/Target	Key Result
The Partial Zero Emissions HEMI® internal combustion engine-cooling system maintains coolant temperatures within control boundaries of 90-100ºC and maximum temperature of 118ºC.	Under real-world ambient temperature conditions and use of Power Panel, the engine coolant temperatures were within the 90-100ºC operational and maximum 118ºC boundaries.

5.8 Map-Based Fuel Economy Results

During Phase I, the overall MPG of the fleet partners with map-based fuel economy was 24.1, which is 40% increase when compared to vehicles without map-based fuel economy (17.2) as shown in Figure 61 below.

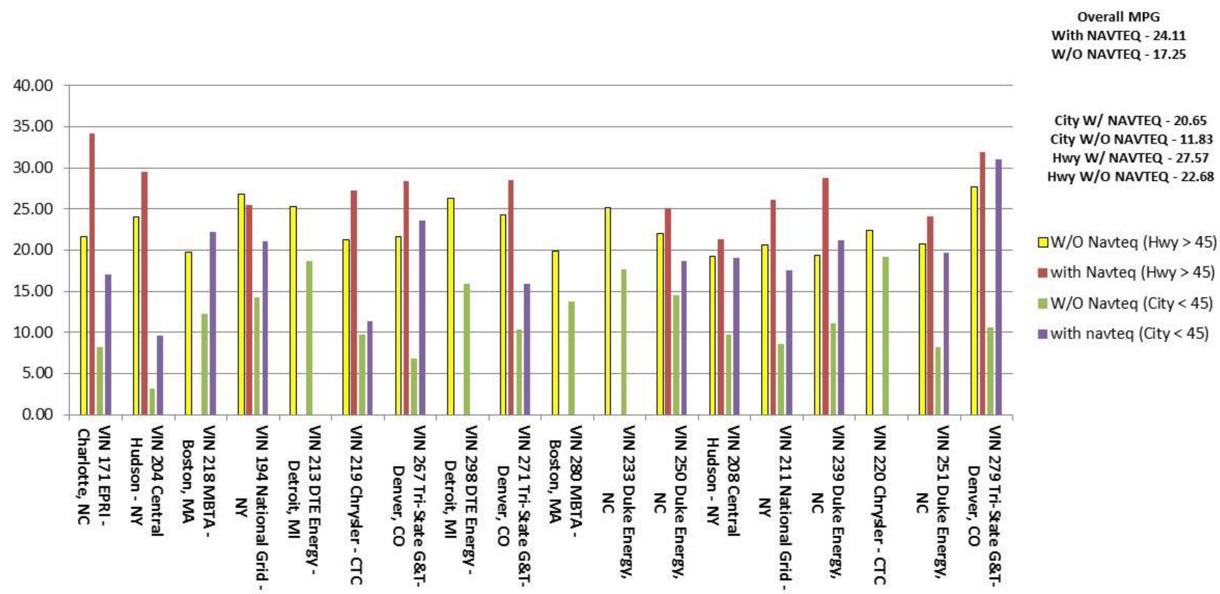


Figure 61: Phase I improvement in MPG with active map-based fuel economy system

At select fleet partners in Phase II, the overall fuel economy of the PHEV trucks with the active map-based fuel economy feature was 24 MPG, which is a 22% improvement over the non-active vehicles. The 24 MPG further reflects a 50% increase compared to the fuel economy of a conventional gasoline engine Ram 1500 of the same model year. Details of the field data and comparisons are shown in Figure 62 below. The difference in the results from Phase I to Phase II is due to the following factors:

- Phase I had a larger fleet size (18 versus 11 vehicles)
- The Phase I high-voltage energy storage system capacity was larger, with a higher CD rate and a longer EV range

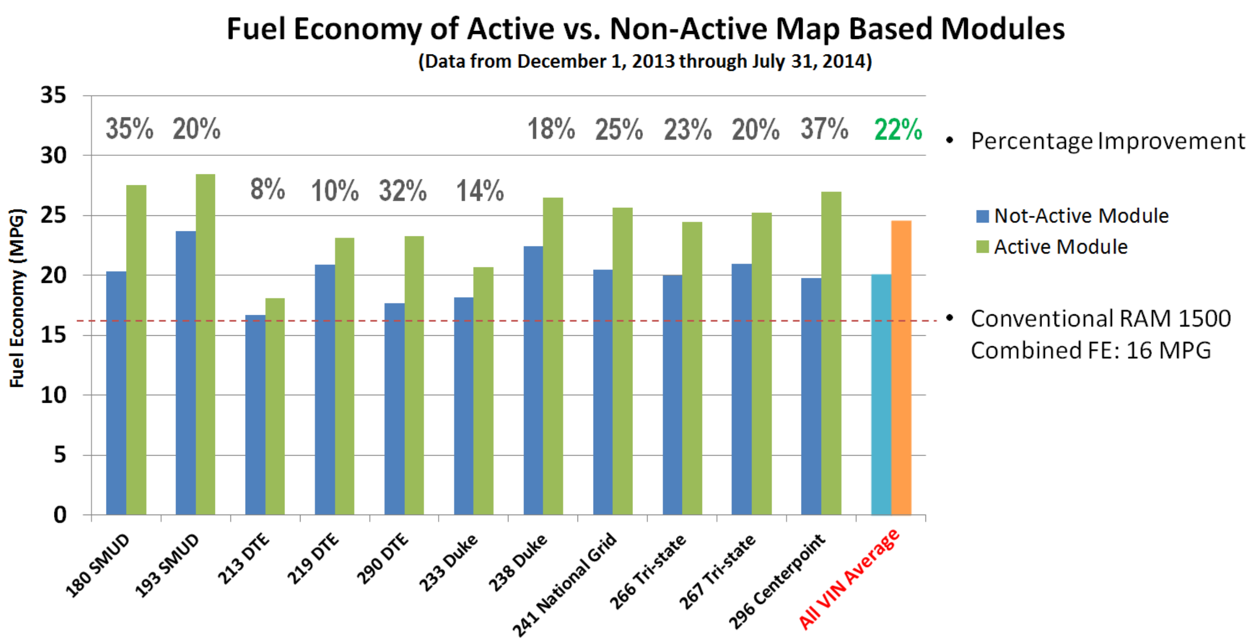


Figure 62: Improvement in MPG with active map-based fuel economy system

6. Project Lessons Learned

6.1 Project Development and Demonstration Lessons Learned

FCA US LLC collected the lessons learned from the project in four major system area activities as shown in diagrammatical form in Figure 63 below. All lessons learned and the associated development activities were carried forward to the development of production PEV platforms. This includes the base controls, tools and people.

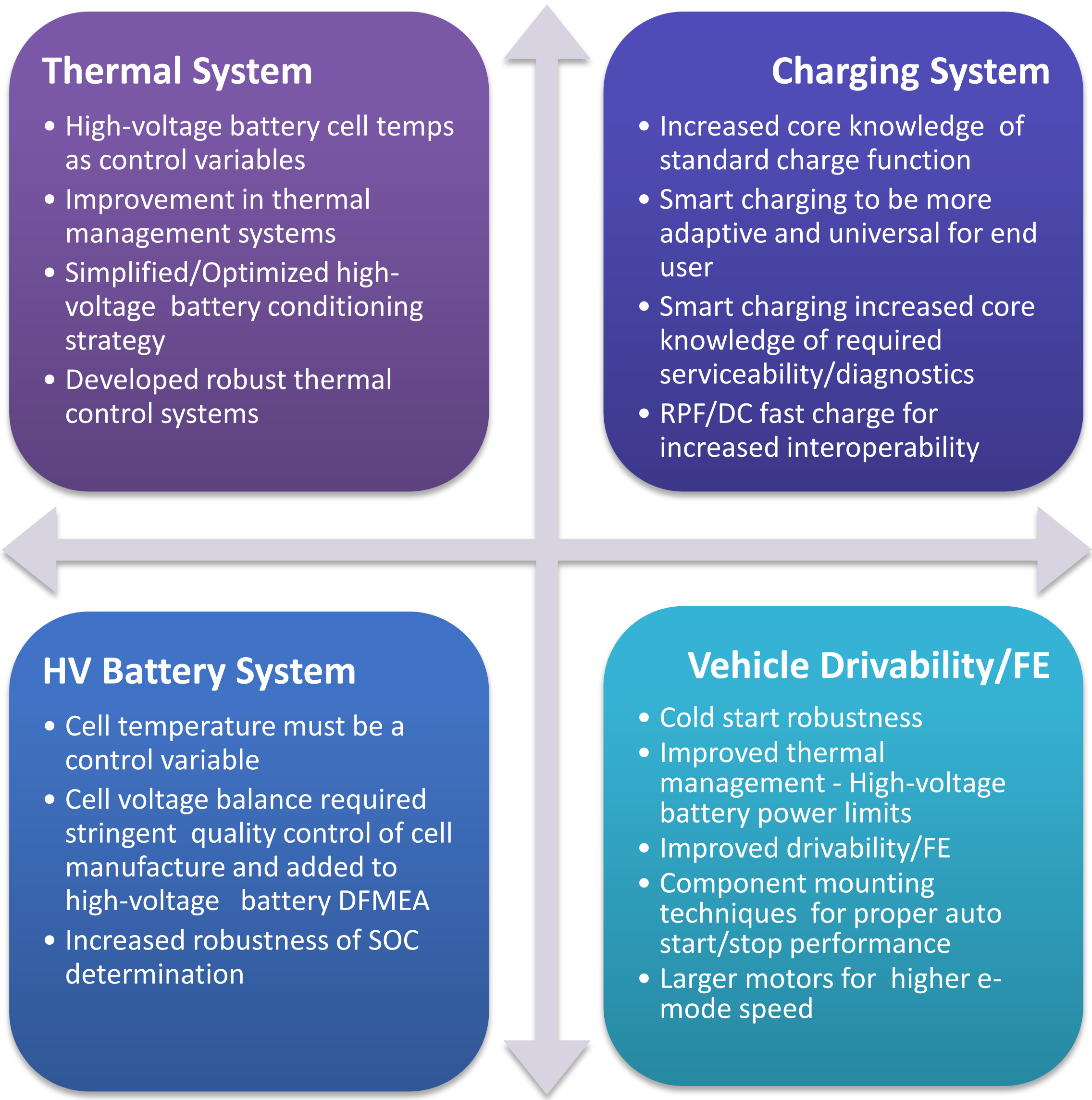


Figure 63: Lessons-learned process from four major systems/ areas

The DRM-collected vehicle data was sent to the MicroStrategy database for analysis of engineering data and corresponding reports were generated. From these reports, FCA US LLC developed solutions or optimization plans that were implemented within customer use profiles.

6.1.1 Thermal System

Cell temperature used as a control variable

- Improved low-temperature coolant loops design and coolant-to-refrigerant chiller integration in the climate control circuit
- Revised heat exchanger sizing process and design validation with real world results

Improvement in thermal-management systems

- Gained a better understanding of individual lithium-ion cell and cell module heat exchange process with the vehicle-level thermal management system
- Understood and optimized the power consumption of the thermal management system

Simplified/optimized high-voltage energy storage system conditioning strategy

- Properly sized the high-voltage energy system heating process for a wide range of operating temperatures

Developed thermal control systems

- Developed multi-mode thermal management systems, including passive cooling, active cooling, thermal equalization and active heating

High-voltage energy storage system thermal state time

- Evaluated and quantified the system as a function of average ambient temperature (including cell temperature)

6.1.2 Charging System: AC Smart Charging/In Vehicle Display (IVD)

Standard charging has increased core competency and design efficiency

- The knowledge gained from the DOE PHEV program is contributing to a better charging system design and integration within core FCA US LLC teams on future programs

- Improved Level 1 & 2 charging modules and hardware and software integration within FCA US LLC

The Smart Charging solution needs to be more adaptive and universal

- Sole reliance on the customer interaction with the web panel was not sufficient. An In Vehicle Display (IVD) was added. A sample display is shown in Figure 64 below. Information also needs to be available on other devices, such as In Home Display (IHD), phone apps, etc.

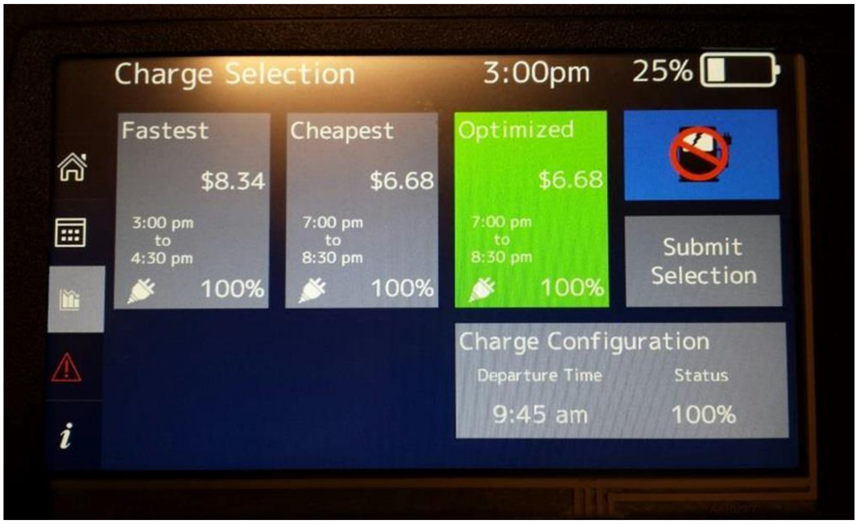


Figure 64: Charging system In-Vehicle Display (IVD) example

The Smart Charging process has improved our approach for customer interfaces

- Default options have been programmed into the vehicle and interaction for exceptions
- We have developed an easy means to opt out of DRLC for Scheduled Charging (e.g. quickly plug-in twice)

Implementing Smart Charging has provided a better understanding of how to design for serviceability and diagnostics

- EPRI's MPR system used WDS (Wireless Distribution System) Wi-Fi between the utility server and EVSE, instead of standard Wi-Fi. This signal required a line of sight between communication modules and caused issues at several sites, since line of sight was not always available

- Early builds of vehicle and communication module MPRs are still periodically failing and locking up. Diagnostics is limited without being on site to validate each step of the process

6.1.3 High-Voltage Energy Storage System

Cell temperature used as a control variable

- In Phase I, cell temperature feature was designed only as a monitor
- Simulations were performed, fleet data was observed and a cell temperature control feature was developed
- In Phase II, this feature was used as a primary source of control to set power limits
- Final control strategy is included in DFMEA for future programs

Cell voltage imbalance reduced

- In Phase I, a large range of ∆V was observed, up to 200 mV. Root cause was determined to be cell electrode and manufacturing quality
- In Phase II, we increased cell quality control (new cell supplier selected)
- Required cell specifications are included in DFMEA for future programs

SOC calculation strategy combining current/OC voltage

- The SOC determination strategy employs current integration for energy removal and reference open circuit voltage to provide a robust and accurate SOC level estimate
- Current integration is calculated using values measured by current sensors
- Real-time open circuit voltage is determined by a circuit model inside high-voltage energy storage system controllers

6.1.4 Vehicle Drivability/Fuel Economy

Improved overall cold start robustness

- Controls and calibration insights allowed a reduction in the HV power requirement for cold start; they also reduced stress on the high-voltage energy storage system

Improved drivability and fuel economy

- Gained insights into the effects of engine torque accuracy on system torque performance
- Added larger motors in the Two-Mode Hybrid system to achieve higher vehicle speeds with the engine off
- This reduced driver-perceived high-voltage energy storage system usage and torque disturbances during transient events, such as vehicle launch at a traffic light
- The fuel economy effect is difficult to isolate but directionally beneficial

Improvement in thermal management systems

- Refined torque path strategy to improve drivability with limited high-voltage energy storage system power limits

Proper mounting design is critical

- Proper mounting designs of engine and transmission are critical to achieve the degree of auto-stop/auto-start feature and NVH refinement required to delight the customer

6.2 Research Results of Sub-Recipients

The project’s success also depended on effective development and research work performed by project sub-recipients. To ensure this success, all project sub-recipients are well-known public or private institutions capable of managing large-scale projects. Furthermore, their extraordinary credentials in terms of research capability, industrial and technological knowledge and academic rigor have made them qualified to develop and demonstrate PHEV technology in this project.

6.2.1 University of Michigan – Dearborn (UM Dearborn)

Major Tasks and Accomplishments

There were 10 major tasks for the UM Dearborn during the project. The details of each task and the related accomplishments are discussed in the Table 16 on the next three pages.

	Tasks	Accomplishments
Task 1	Develop a high-voltage energy storage system state of charge (SOC) calibration algorithm for the lithium-ion high-voltage energy storage system. The calibration will be based on high-voltage energy storage system voltage, temperature, charge and discharge current. A lithium-ion high-voltage energy storage system module will be tested under different operating conditions. A mathematic model will be developed to describe the SOC calibration based on high-voltage energy storage system parameters and operating conditions. Develop a real-time dynamic power capability model based on in-vehicle such observations as current, voltage, SOC and temperature. Develop a method to track the aging of the high-voltage energy storage system by measuring capacity in a certain time interval, and through tracking power in/out of the high-voltage energy storage system.	We have developed a number of algorithms for the calculation and calibration of the high-voltage energy storage system SOC. We have also developed advanced concepts for high-voltage energy storage system cell balancing. A few papers have already been published. We have performed extensive testing on lithium-ion batteries and abundant data have been acquired and supplied for calibration and other uses.
Task 2	E-motor thermal characterization. The focus is to determine performance and power limitations at high temperature operations and how much the motor needs to be de-rated. Mathematic models will be developed to include motor losses and thermal aspects to assist the characterization effort. Dynamometer testing will be performed with the new laboratory equipment acquired and installed by this grant. Develop approaches for calibration improvements of motor control in the following areas: improve motor torque control performance through mathematic model and dynamometer testing, including transient response, stability, and torque error, improvement of motor efficiency by adjusting control.	We have compared different motor topologies for the use in hybrid and plug-in hybrid electric vehicles. A number of papers were published on this topic. We performed thermal analysis of a PM motor based on a Prius PM motor and experiment report from Oakridge National Laboratory.
Task 3	E-motor overall characterization. Develop a loss and efficiency map of the e-motor with relation to power, torque, speed and bus voltage. The work will involve dynamometer measurement and simulations. Finite element analysis (transient electromagnetics) will be used for the simulation models.	Three post-doctorate individuals worked at the FCA US LLC facility on a part-time basis to help with the power electronics/motor control and motor design. One paper was published.

Task 4	Study the aged motors after fleet demonstration is finished to understand the performance degradation, such as property of the magnets, efficiency and torque capability after a certain service period of the motor.	We have performed testing of e-motors in the dynamometer laboratory at UM Dearborn.
Task 5	Power electronics support. Investigate boost converter option for interfacing the high-voltage energy storage system and the DC bus, including simulation, design, and building a scaled-down prototype. The efficiency, cost and high-voltage energy storage system life benefits will be quantified through the study. Study the fail-safe operation of the motor and power electronics system; examples include how to detect if certain magnets are demagnetized; what if motor is out of synchronization; uncontrolled generation; management of power up and power down of system.	We studied the feasibility of various topologies for DC-DC converters. Some experiments were carried out on a scaled-down work bench. We have developed 3 kW resonant chargers and power electronics-based high-voltage energy storage system cell-balancing topologies. A number of papers were published.
Task 6	Controls development. Develop a systems model for the PHEV and study the different control strategies for fuel-efficiency optimization and emission reduction. Advanced control algorithms, such as fuzzy logic-based control, sliding mode control, and drive cycle-based control will be developed and will be implemented in some of the development vehicles in the Phase II. The benefits can be quantified by comparing the results against the fuel economy of vehicles equipped with the base control.	We have investigated the analytical control of power management of PHEV. Two papers were published on this topic. We expect the algorithms can be implemented in a PHEV in the near future. Study of two-speed transmission versus single speed gear box was carried out and indicated the two-speed model will provide 10% more e-drive range.
Task 7	Development of a new minimal-cost search algorithm for real-time cost based optimization to improve convergence speed, errors and robustness. Build a motor generator test bench (set up MG test/development Dynamometer at sub-recipient location). General Description: Two load cells (+/-400Nm @ +/- .4 Nm acc, and +/-100Nm @ +/- 0.1 Nm acc with overload protection), 15K rpm max speed. An M/G similar to the ones used in current HEVs will be tested and used for calibration purpose.	We have investigated the analytical control of power management of PHEV. A number of papers were published on this topic. We expect the algorithms can be implemented in a PHEV in the near future. Study of a two-speed transmission versus a single-speed gear box was carried out and it is shown the two-speed version will provide 10% greater e-drive range.

Task 8	EE system load analysis. Determine the sizing of the 14V DC-DC converter and determine the best architecture for maintaining system functionality during all vehicle conditions (charging, parked, and driving). Characterize the 14V battery under cold temperature for reliable system operation. The effort is based on mathematic, other simulation models and some laboratory testing on the 14V battery.	We studied the 14V battery system demand.
Task 9	Feasibility study of variable-size high-voltage energy storage system. Develop a simulation model and perform feasibility analysis based on simulation models for the sizing of high-voltage energy storage systems to meet individual consumer's needs (range, drive pattern, etc.).	We developed a simulation for the PHEV in simulation model Autonomie to study the fuel optimization of PHEV based on varying high-voltage energy storage system and advanced controls.
Task 10	Drive-cycle fuel-economy evaluations of blended-mode PHEV. Investigate the fuel economy and e-drive range of blended-mode PHEV.	We developed a model for the PHEV in simulation software Autonomie to study the fuel optimization of PHEV based on varying high-voltage energy storage system and advanced controls. Study shows that the overall fuel consumption can be reduced by 5% to 10% based on the advanced algorithms. A number of papers were published in this area.

Table 16: UM Dearborn major tasks and accomplishments

6.2.2 Michigan State University (MSU)

There were three major tasks for Michigan State University during the project. The details of each task and the related accomplishments are discussed in the Table 17 below.

	Tasks	Accomplishment
Task 1	Developed transient torque control strategy for the hybrid powertrain.	For the prediction of the desired torque, an ARX (Auto-Regression model with external input) model-based adaptive recursive prediction algorithm was proposed and its performance was compared with two existing prediction algorithms (step-by-step and fixed-gain prediction). Two weighting factors were introduced for the past and current data respectively to improve the prediction accuracy and avoid prediction calculation over- and under-flow challenges.
Task 2	Validated and improved predictive boundary management control strategy.	A high-voltage energy storage system boundary management control strategy was proposed. It was based on the predicted desired torque with the goal of proactively making the engine power available to reduce the high-voltage energy storage system over-discharging duration, hence improving the useful high-voltage energy storage system life.

Task 3	Validated HIL simulation based on demo fleet calibration data.	For simulation investigation, a series-parallel forward HEV model was constructed in the MATLAB/Simulink environment and five typical driving cycles were used for simulations. The five driving cycles are: o FTP-75 (EPA Federal Test Procedure for city driving cycle) o IM240 (EPA Inspection & Maintenance emissions testing) o US06 (Supplemental Federal Test Procedure in addition to FTP-75) o NYCC (New York City Cycle for low speed stop-and-go traffic conditions) o ARB02 (High-load dynamometer driving cycle designed by CARB) The simulation results showed that the proposed prediction algorithm reduces the prediction error significantly, with a 4% maximum prediction error. The reduced computational load makes it possible for real-time implementation. Due to the online update of regression gain, the proposed prediction algorithm is robust to different driver behaviors. Additionally, the proposed control strategy with desired torque prediction algorithm was compared with baseline control strategy (without prediction) under the above-mentioned five typical driving cycles. A controller-in-the-loop simulation was investigated to check the effectiveness of the proposed control strategy. Both the Simulink and CIL simulation results show that the predictive boundary management control strategy is very effective when the high-voltage energy storage system temperature is low (for instance, under 0 Celsius). Over-discharged high-voltage energy storage system power was reduced more than 65% under aggressive US06 and ARB02 driving cycles, 45% under highway and city FTP and city NYCC driving cycles and 30% under highway IM240 driving cycles, respectively.

Table 17: Michigan State University major tasks and accomplishments

6.2.3 Electric Power Research Institute (EPRI)

Major Tasks and Accomplishments

There were three major tasks for EPRI during the project. The details of each task and the related accomplishments are discussed in Table 18 below.

	Task	Accomplishment
Task 1	Prove product viability in "real world" conditions.	Assisted FCA US LLC in the Phase II demonstration phase, during which the PHEVs were subject to routine vehicle use across 12 different partner locations.
Task 2	Develop bi-directional communication charger interface.	Built the Multi-Protocol Router (MPR), performed bench validation, assisted in the vehicle integration and assisted in the final functional check of vehicle to utility grid communication. EPRI also developed smart utility grid technology used in conjunction with the MPR unit.
Task 3	Confirm that conditions for viable mass production can be met and quantify the benefits to the customers and to the nation.	EPRI fostered the first successful demonstration of the capability of an open standards-based Ram 1500 PHEV vehicle to smart grid interface technology. SAE (Society of Automotive Engineers), IEEE (Institute of Electrical and Electronics Engineers) as well as Smart Energy Alliance developed these standards.

Table 18: EPRI major tasks and accomplishments

6.2.4 Sacramento Municipal Utility Department (SMUD)

Major Tasks and Accomplishments

There were three major tasks for SMUD during the project. The details of each task and the related accomplishments are discussed in Table 19 on the next page.

	Task	Accomplishment
Task 1	Charging Infrastructure Deployment (as per FCA US LLC Subtask 6.2 – Prepare demonstration testing sites for vehicle delivery).	SMUD enlisted the participation of municipal customers to participate in this project. These partners agreed to install charging infrastructure and operate demonstration vehicles in their fleets under regular operating conditions. Partner participation is shown in Table 20 below.
Task 2	Vehicle Demonstration Activities.	See the SMUD fleet data in the "Fleet Demonstration Data Collection and Analysis" section of this report.
Task 3	Smart Grid Integration.	Smart grid integration was hampered by access issues, primarily owed to cyber security regulations imposed on SMUD as an electric utility, to access the Smart Energy Profile 2.0 (SEP2) encryption levels. Due to limited resources, SMUD was unable to deal with these issues directly but was able to accomplish several of the tasks associated with Smart Charging by using a local server instead of the server within the SMUD facility. Scheduled Charging, Demand Response and Reverse Power Flow used the FCA US LLC web- and telemetric-based communications – and later an In-Vehicle Display (IVD) – to successfully demonstrate all of these features. SMUD also hosted the successful OEM Central Server demo mid-October 2014, where the demonstration vehicle validated the direct communication to the grid using SEP2, as opposed to six other OEM's who demonstrated indirect and combinations of standards using an OEM Central Server with OpenADR2 communications.

Table 19: Major SMUD tasks and accomplishments

Project Partner	Ram 1500 PHEV		EVSEs Installed
	Phase I	Phase II	
Sacramento Municipal Utility District	5	1	3*
City of Citrus Heights	1		2
City of Elk Grove	1		3
City of Galt	2	2	3*
City of Rancho Cordova	1	2	3*
City of Sacramento	4		2
Totals	**14**	**5**	**16**

Table 20: SMUD local partner participation

*These sites included hardware for communication and reverse power flow in Phase II.

6.2.5 NextEnergy

Major Tasks and Accomplishments

There were three major tasks for NextEnergy during the project. The details of each task and the related accomplishments are discussed in Table 21 below.

	Task	Accomplishment
Task 1	Assist in the verification of plug-in charging mode performance based on charger and battery model.	Throughout this project, NextEnergy supported FCA US LLC's testing requirements for advanced plug-in hybrid electric vehicle (PHEV) technologies. NextEnergy built new test and validation equipment and integrated same to the existing test facility. Overall, the test results show that all hardware functioned as intended; validation of infrastructure was developed and deployed at NextEnergy. See sample test details following this table below.
Task 2	Aid in proving product viability in "real-world" conditions.	NextEnergy worked with FCA US LLC to support the objectives of the demonstration fleet through data collection, analysis and reporting. See the deployed fleet data in the "Fleet Demonstration Data Collection and Analysis" section of this report.
Task 3	Assist in the testing of bi-directional (communication and power) charger interface.	NextEnergy built new charging capability and utilized its existing charging and discharging infrastructure to prove out the smart grid communication for Utility Demand Response programs and vehicle-to-grid interactions.

Table 21: NextEnergy major tasks and accomplishments

As noted in Table 21, Figures 65 through 67, all on the next page, show the detail data from a sample charging test session at NextEnergy. Figure 65 shows session basic data. Figure 66 shows a constant charging current at 28 amps. This implies charging conditions with a utility grid line voltage of 240 volts and a 6.6 kW power level supplied to the high-voltage energy storage system as shown in Figure 67. All of which is in agreement with the specifications shown in Table 9 in the "Charging System" section of this report.

NextEnergy	
Session Detail Report	
Session #	08022011-1023-CCS-5
Charger #	5
Vehicle ID #	Ram
Start Date/Time	8/2/11 10:23 AM
End Date/Time	8/2/11 11:08 AM
Output Port Total (kW-Hr)	4.53
Renewable Energy Used (kW-Hr)	0.00
Grid Energy Used (kW-Hr)	3.90
Min Current (A)	2.47
Max Current (A)	29.12
Avg Current (A)	28.47

Figure 65: NextEnergy charging session sample report

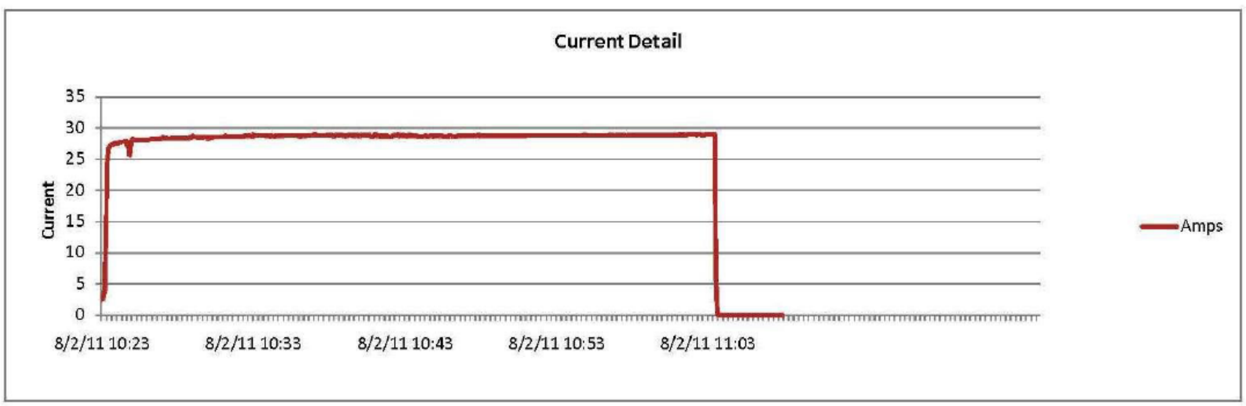


Figure 66: NextEnergy charging session current data

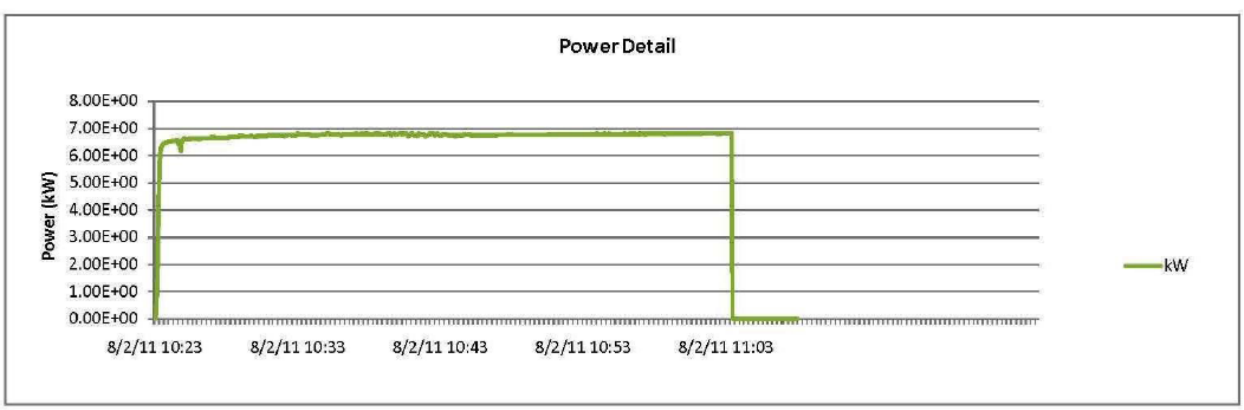


Figure 67: NextEnergy charging session power data

6.2.6 University of California – Davis (UC Davis)

Major Tasks and Accomplishments

There were three major tasks for the Electrovaya Inc. during the project. The details of each task and the related accomplishments are discussed in the Table 21 below.

	Tasks	**Accomplishments**
Task 1	Collect PHEV deployment information from driver and fleet manager interviews and from data recording instrumentation onboard the vehicles.	The demonstration project provided an opportunity to observe the deployment of PHEV technology in fleets and focus on the context in which users responded to the technology. We accomplished this using multiple research instruments, which included surveys, driver logs, site visits, data analysis and in-depth interviews with every vehicle user.
Task 2	Assist the City of San Francisco in finding fleet applications best suited to maximize the benefits of PHEVs.	Our unique approach complements the large scale data gathering and analysis completed by INL; we focus on individual users and explaining broader trends and behaviors. Fleets might provide a good conduit to the consumer market for alternative-fuel pickup trucks and vans. PHEVs have features that appeal to fleets but it takes time, experience and appropriate instructional structure for them to recognize additional values beyond fuel savings.
Task 3	Analyze data and feedback in order to recommend improvements to the vehicle design, applications and market strategies.	FCA US LLC demonstrated PHEV technology in a full-size truck platform and provided a large and distinct market segment (truck users) with access to electric and hybrid vehicle technology. Experiences (good and bad) with a fleet vehicle can shape or influence the opinions of new car-buying consumers around brand, model, technology and fuel type. Pickup trucks, vans and SUVs are the most appropriate vehicle form for many municipal and corporate fleets. However, vehicle functionality is critical. PHEV performance will vary depending on institutional factors, user behavior and operator training. Understanding best practices for PHEV deployment can ensure vehicles meet and surpass performance expectations.

Table 22: University of California - Davis major tasks and accomplishments

6.2.7 Electrovaya Inc.

Major Tasks and Accomplishments

There were seven major tasks for the Electrovaya during the project. The details of each task and the related accomplishments are discussed in the Table 22 below.

	Tasks	Accomplishments
Task 1	Project preparation and planning: Ensure that all pre-build requirements are established and executed. Deliverables: Provide technical information and program support to other participants as directed by FCA US LLC.	A detailed project plan and regular meetings were held to develop and finalize the pre-build requirements.
Task 2	Initial development builds: Procure and manufacture the components required for the 12 development battery packs. Assemble, test and deliver the 12 packs. Provide design verification test data, battery development pack interface specifications to FCA US LLC, deliver 12 functional prototype development battery packs, provide battery pack design refinements and software improvements in support of the PHEV and battery pack development efforts, perform a root-cause analysis and repair and replace supplied development battery packs as requested by FCA US LLC.	Twelve prototypes were built and delivered to FCA US LLC, along with design verification test data and the interface specification. Root-cause analyses were performed and packs were repaired and replaced as needed in support of the PHEV and battery back development efforts.
Task 3	Supplier Readiness Review: Review and ready the supply chain to ensure suppliers are ready to deliver components and kick-off tooling at the supplier. Deliverable: Develop supplier relationships and agreements as needed.	Electrovaya reviewed and updated its supply chain management processes throughout this project. Supplier meetings were conducted and Electrovaya performed site inspections to ensure suppliers could meet delivery and quality targets. A broad range of suppliers were used, due to the complex nature of the battery system. Examples include large chemical companies (battery electrolyte additives), mid-size electronics companies (circuit boards for BMS), or small local machine shops (custom enclosures).

Task 4	Pre-demonstration builds: Ensure that all pre-build requirements for the battery packs are established and executed. Deliverables: Participate in and provide required information and data for system-level DVP&R. Provide Electrovaya demonstration battery pack interface specifications to FCA US LLC and other fleet partners defined to complete their required tasks.	Electrovaya participated in system-level DVP&R, and provided an updated interface specification document and other information to FCA US LLC engineering team and other project participants.
Task 5	Demonstration fleet build and customer readiness: Procure and manufacture the components required for the demonstration battery packs. Assemble, test and deliver the 140 packs. Deliverables: Delivery of 140 demonstration battery packs and subcomponents for use in the RAM 1500 PHEV demonstration fleet.	Battery packs were completed and delivered on time.
Task 6	Ongoing Vehicle Operations: 140 test demonstration fleet operation with partners. Delivery: Provide software improvements in support of project PHEV demonstration fleet and perform a root cause analysis and associated repairs if requested in writing by FCA US LLC.	Software improvements were provided, up to BMS software version 3.0. Root-cause analyses and associated repairs were provided as needed.
Task 7	Data analysis: Analyze data of battery performance in vehicles, provide required support. Deliverables: Review battery data/analysis and provide final report and support FCA US LLC and other participants as necessary.	Data was collected from July 1, 2011 to September 28, 2012 from all demonstration Ram 1500 PHEVs.

Table 23: Electrovaya major tasks and accomplishments

6.2.8 MAHLE Behr USA Inc.

Major Tasks and Accomplishments

There were four major tasks for MAHLE Behr USA Inc. during the project. The details of each task and the related accomplishments are discussed in Table 23 below.

	Tasks	Accomplishments
Task 1	Review interface of the battery thermal management system with the high voltage battery supplier's internal thermal management system and design a capable vehicle level thermal system.	Updated the Ram 1500 PHEV thermal system to integrate the high-voltage energy storage system cooling loop into the refrigerant system (single evaporator) • Established a clear communication flow (internally and with FCA UC LLC) through meetings and documentation to ensure that all partners are closely engaged and working together toward a shared solution • Ensured that Behr had the necessary internal resources and support to meet all requirements • Performed system simulations and size heat exchangers
Task 2	Enhance and refine its system understanding of battery thermal management on a PHEV and of the interaction of the various systems.	Performed thermal system analysis and component sizing through simulation and system calorimeter testing: • Created CAD data and drawings for DV test fleet components • Established quality requirements for DV test fleet • Performed system simulations and size heat exchangers • Contributed to DVP&R and DFMEA with FCA US LLC • Modified CAD data and drawings based on feedback from test fleet

Task 3	Model the thermal systems in BISS (Behr Integrated System Simulation) software in order to predict system performance at various driving cycles.	The thermal management system proved able to handle the additional thermal load generated by the high-voltage energy-storage system and maintained the climatic comfort of the cabin while operating in a stable and controllable manner. Simulation results were confirmed through testing; the simulation software proved a reliable tool for predicting component and system thermal performance. • Completed bench validation of key components and sub-systems and comparison with predicted performances • Perform wind tunnel testing and correlation of wind tunnel data with BISS simulation
Task 4	Manufacture/procure components for high-voltage energy-storage system and power electronics cooling loop	• Ensured supplier readiness for demonstration fleet (batch size and quality requirements) • Determined packaging and shipping methods • Conducted system calorimeter bench testing and compared with predicted performances • Issued all purchase orders to suppliers • Monitored delivery of parts to FCA US LLC

Table 24: MAHLE Behr USA major tasks and accomplishments

7. Comparison of Actual Accomplishments with Project Objectives

7.1 System design objectives

Prove that the system solution is capable of:

- The Ram 1500 PHEV truck produced controllable traction forces from minimum to maximum under different battery temperatures, ambient temperatures and vehicle speeds as shown by the deployment results.
- Displaced fuel efficiently in all driving scenarios for all customers as shown in the "Estimated Impact on Fuel Consumption and GHG Emission" section.

Verify plug-in charging mode performance based on charger and high-voltage energy storage system model

As described in the "Charging Systems" section, the following charging modes were successfully demonstrated in the field:

- Manual Charging
- Scheduled Charging
- Smart Charging
- Reverse Power Flow
- DC Fast Charging

Verify AC power generation mode

As described in the "Auxiliary Power Panel" section, the Power Panel was used successfully and extensively by the partners in the field. It was used to support the power restoration activities of the electric utilities during public power outages. It was also often used for less-critical power generation situations. This 6.6 kW power panel feature was well received by fleet partners.

Optimal cost/benefit tradeoffs

The system solution successfully demonstrated optimal cost/benefit tradeoffs for a wide range of customers and operating conditions.

- Vehicles were used across diverse fleet partner locales ranging from rural to urban
  - Five urban locations on the Northeast coast

    - Four urban locations on the East and West coasts and the Midwest
    - Three rural locations in the Southwest states
- Vehicles were used in a wide range of ambient temperatures – from -10ºC to 41ºC.
- The deployment altitudes ranged from sea level on the East and West coasts to 1600 m above sea level near Boulder, Colorado and near Arco, Idaho
- The successful implementation of Smart Charging and Reverse Power Flow at FCA US LLC and at five fleet partners
- DC charging was successfully implemented at FCA US LLC and Argonne National Labs (both individually and during an industry event at ANL) on three different industry DC charging units

7.2 Development vehicle verification objectives

Confirm vehicle functional objectives

- The fuel economy objective was improvement over the conventional Ram 1500 truck (16 mpg combined city and highway)
    - Phase I real-world fuel economy in CD mode combined city and highway was 24
    - Phase II real-world fuel economy in CD mode combined city and highway was 25
- Compliance to impact requirements was met, as noted in the “Federal Safety Compliance and Emission Standards” section

Demonstrate drivability and safety

- The fleet partners drove the vehicles in excess of 1 million total miles during the deployment for Phases I and II. In addition, the engineering development team exceeded 500,000 miles during the development and testing phase.
- There were minimum drivability issues. Some recalibrations for cold-weather starting performance were required. Feedback regarding one-mode to gas-mode smoothness was also received. None precluded vehicle operation in a normal way
- There were no drivability safety issues

Prove emissions targets can be achieved

- The California Exhaust Emission Standards And Test Procedures, as amended December 2, 2009, were met

7.3 Fleet demonstration objectives

Profile vehicle usage

Each vehicle was tracked on a monthly and aggregate basis using the Idaho National Labs DOE data, as noted in the section 5.2. In this data, the following information was tracked:

- For trip events in charge depleting (CD), charge depleting and charge sustaining (CD/CS) and charge sustaining (CS) modes and all trip aggregates
- DC electrical energy consumption
- Number of trips
- Percent of trips city and highway
- Distance traveled
- Fuel economy in CD, CD/CS and CS modes as a function of
  - Driver aggressiveness
  - Time in e-mode
- Charging activities:
  - Average number of charging events per vehicle per month when driven
  - Average number of charging events per vehicle per day when driven
  - Average distance driven between charging events
  - Average number of trips between charging events
  - Average time charging per charging event
  - Average energy per charging event
  - Average charging energy per vehicle per month
  - Total number of charging events
  - Number of charging events at AC Level 1 and 2
  - Total charging energy consumed
  - Charging energy consumed at AC Level 1 and 2
  - Percent of total charging energy from AC Level 1 and 2
  - Average time to charge from 20% to 100% SOC AC Level 1 and 2

Profile customer expectation

- FCA US LLC demonstrated PHEV technology in a full-size truck platform and provided a large and distinct market segment (truck users) with access to electric and hybrid vehicle technology

- FCA US LLC found the importance of piloting new and different technology among consumers. Fleets can provide a meaningful conduit for new car buying consumers to experience vehicles and technology in certain situations

Prove product viability in real-world conditions

- Vehicles were successfully used for day-to-day work activities at the demonstration partners in Phase I and II for a total of over 750,000 miles

Develop bi-directional (communication and power) charger interface

- Smart Charging communication was successfully developed as noted in section 2.5.3
- Reverse Power Flow power transfer from vehicle to grid was successfully developed ad noted in section 2.5.4

Confirm that conditions for viable mass productions can be met

- The base vehicles, 2011MY RAM 1500 crew cab trucks, were production-based vehicles
- The thermal system employed, though unique, was comprised of mass-production components
- The high-voltage energy storage system was prototype in nature, but production versions for other FCA US LLC production platforms using high-voltage energy storage system systems. Used the lessons learned from the high-voltage energy storage system in this vehicle for successful series-based integrations
- The large toolbox on-board charger was used as a development component, thus its large size. As noted earlier, the larger size fostered this development. Lessons learned here were applied to current and future production platforms

Quantify the benefits to customers and to the nation

- Successfully demonstrated Reverse Power Flow and Smart Charging to mitigate the effect of PHEV vehicle charging on the nationwide electric power grid
- Created core competency "green" technology jobs and have a plan in place to sustain them toward future development of electrification programs
- Completed hiring of critical resources with specialty in electrification technology as part of the DOE funded project

7.4 List of Project Publications and Patents

7.4.1 Project Publications

List of publications during the entire project funding period is shown in the list below:

1. Bingzhan Zhang, Chunting Chris Mi, and Mengyang Zhang, "Charge Depleting Control Strategies and Fuel Optimization of Blended-Mode Plug-in Hybrid Electric Vehicles," IEEE Transaction on Vehicular Technology, Vol. 60, No.4, pp. 1516-1525. May 2011
2. Junjun Deng, Siqi Li, Sideng Hu, Chunting Chris Mi, and Ruiqing Ma, "Design Methodology of LLC Resonant Converters for PHEV Lithium-ion Battery Chargers," IEEE Transactions on Vehicular Technology, vol. 63, no. 6, pp. 1581-1592, May 2014.
3. Junjun Deng, Siqi Li, Sideng Hu, Chunting Chris Mi, and Ruiqing Ma, "Design Methodology of LLC Resonant Converters for PHEV Lithium-ion Battery Chargers," IEEE Transactions on Vehicular Technology, vol. 63, no. 6, pp. 1581-1592, May 2014.
4. Lei Jiang, Chunting Chris Mi, Siqi Li, and Chengliang Yin, "Control Method to Improve the Efficiency of a Soft-Switching Non-Isolated Bidirectional DC-DC Converter," International Journal of Power Electronics, Vol.6, No.1 pp. 66 - 87. March 2014.
5. Mengyang Zhang, Yan Yang, and Chunting Chris Mi, "Analytical Approach for the Power Management of Blended Mode Plug-In Hybrid Electric Vehicles," IEEE Transaction on Vehicular Technology, Vol. 61, No.4, pp. 1554-1566. May 2012.
6. Sideng Hu, Junjun Deng, and Chunting Chris Mi, "Optimal Design of LLC Resonant Converters in PHEV Battery Chargers," IET Electric Systems in Transportation, doi: 10.1049/iet-est.2013.0016, pp. 1-8, 2014.
7. Siqi Li, Chunting Chris Mi, and Mengyang Zhang, "A High Efficiency Low Cost Direct Battery Balancing Circuit Using A Multi-Winding Transformer with Reduced Switch Count," Applied Power Electronics Conference and Exposition (APEC), 2012 Twenty-Seventh Annual IEEE, Orlando, FL, pp. 2128-2133, Feb. 5-9, 2012
8. Zheng Chen, Bing Xia, Chenwen You, and Chunting Chris Mi, "Energy Management of Power-Split Plug-in Hybrid Electric Vehicles Based on Simulated Annealing and Pontryagin's Minimum Principle," Journal of Power Sources, vol. 272, pp. 160-168, September 2014.
9. Zheng Chen, Chunting Chris Mi, Rui Xiong, Jun Xu, and Chenwen You, "Energy Management of a Power-Split Plug-in Hybrid Electric Vehicle Based on Genetic Algorithm

and Quadratic Programming," Journal of Power Sources, vol. 248, (2014) pp. 416-426, 2014.

10. Zheng Chen, Chunting Chris Mi, Jun Xu, Xianzhi Gong, and Chenwen You, "Online Energy Management for a Power-Split Plug-in Hybrid Electric Vehicle Based on Dynamic Programming and Neural Network", IEEE Transactions on Vehicular Technology, vol. 63, no. 6, pp. 1567-1580, May 2014.
11. Zheng Chen, Chunting Chris Mi, Bing Xia, and Chenwen You, "A Novel Energy Management Method for Series Plug-in Hybrid Electric Vehicles," Submitted to Applied Energy, October 7, 2014.
12. Zheng Chen, Bing Xia, and Chunting Chris Mi, "Loss Minimization Based Charging Strategy Research for Lithium-ion Battery", Submitted to IEEE Transactions on Industry Applications, October 22, 2014.
13. Zheng Chen, Wencong Su, and Chunting Chris Mi, "Battery Management Systems - A Critical Review," Submitted to Applied Energy, October 7, 2014.
14. Zhongyue Zou, Jun Xu, Chunting Chris Mi, Binggang Cao, Zheng Chen, "Evaluation of Model Based State of Charge Estimation Methods for Lithium-ion Batteries," Energies 2014, *7*(8), 5065-5082.

7.4.2 Project Patents

A list of patents applied during the entire project funding period is shown below in Table 25 below.

Patent Application USPTO Serial No.	Patent Application Title	File Date at USPTO	DOE Program
12 / 844,872	Remote control system for a hybrid vehicle	28-Jul-2010	IDR – Ram PHEV
61 / 536,173	Electric-drive tractability indicator integrated in hybrid electric vehicle tachometer	19-Sep-2011	IDR – Ram PHEV
13 / 160,561	Adaptive powertrain control For plugin hybrid electric vehicles	15-Jun-2011	IDR – Ram PHEV
13 / 523,943	Hybrid vehicle control	15-Jun-2012	IDR – Ram PHEV
13 / 523,964	Hybrid vehicle control with catalyst warm-up	15-Jun-2012	IDR – Ram PHEV
13 / 778,471	Predictive powertrain control using powertrain history and GPS data	27-Feb-2013	IDR – Ram PHEV
13 / 858,164	Predictive powertrain control using driving history	08-Apr-2013	IDR – Ram PHEV
14 / 251,080	Single phase bi-directional ac-dc converter with reduced passive components size and common mode electro-magnetic interference	11-Apr-2014	IDR – Ram PHEV

Table 25: List of project patents

7.5 Project Tasks Performed

Task 1- Project management: Project management established a clear communication protocol, through meetings and documentation to ensure all partners were closely engaged and working toward a shared solution. There were seven key milestones during the course of the project; they were managed through a robust governance structure. Project management ensured that milestone reports, as well as minutes from working group and advisory board meetings, were communicated in a timely manner to the DOE.

PHEV Development, Build, and Launch

Task 2- Project preparation and planning: Ensured all pre-build requirements were established and executed

> **Subtask 2.1 – Supplier selection and component sourcing:** Ensured suppliers were selected for all components and were capable of meeting functional and timing requirements
>
> **Subtask 2.2 – Perform vehicle packaging:** Ensured all components and sub-systems were packaged to assemble into vehicle frame
>
> **Subtask 2.3 – Procure instrumentation equipment:** Obtained all equipment required for vehicle instrumentation
>
> **Subtask 2.4 – Conduct design and performance standardization:** Finalized the functional specifications of the vehicle including performance specifications
>
> **Subtask 2.5 – Conduct design failure modes and effects analysis (DFMEA):** Performed DFMEA for key vehicle components and sub-systems
>
> **Subtask 2.6 – Perform detailed DVP&R:** Executed component and sub-system testing as called out in the DVP&R
>
> **Subtask 2.7 – Perform system simulation:** Simulated key systems prior to vehicle builds
>
> **Subtask 2.8 – Develop test and build plans:** Determined vehicle-level test plans and build schedules

Subtask 2.9 – Order base vehicles: Ordered carrier vehicles for Ram 1500 trucks as well as high-voltage energy storage system chargers and power panels for bench testing

Task 3- Initial development builds: Procured all components required for the 12 development vehicles and built 12 trucks

Subtask 3.1 – Identifying procurement requirements for prototype vehicle builds: Finalized part and tooling costs and lead times for all components

Subtask 3.3 – Prototype parts tooling and manufacturing: Kicked off tool orders for components and builds

Subtask 3.4 – Prototype parts logistics: Determined dunnage and shipping method for all components

Subtask 3.5 – MRD development build of 12 vehicles: Determined the material required date (MRD) for the parts

Subtask 3.6 – Material staging: Ensure parts are available and placed as required and performed vehicle builds

Subtask 3.7 – Verify basic drivability: Confirmed basic functionality required to drive vehicle

Subtask 3.8 – Conduct Ride and Drive event: Provided opportunities for key stakeholders to evaluate the vehicles and provide feedback

Subtask 3.9 – Conduct cold-weather and other development testing: Ensured that vehicles functioned as intended in cold climatic conditions, including engine, transmission, and battery-pack bench testing

Subtask 3.9 – Conduct impact testing: Ensured that vehicles met FMVSS impact requirements

Task 4- Supplier readiness review: Ensured that suppliers were ready to deliver all components and kicked off tooling

Subtask 4.1 – Ensure supplier readiness for all components: Confirmed all component design and packaging were complete and that each supplier was able to delivery to the quantity of parts required

Subtask 4.2 – Kickoff tooling: Released tool orders for components and manufacturing as required, based on identified lead times

Task 5- Pre-demonstration builds: Ensured all pre-build requirements for the demonstration fleet were established and executed

Subtask 5.1– Verify all functional objectives: Confirmed customer requirements and functional objectives

Subtask 5.2– Conduct all required testing, including hot development tests: Performed component- and system-level testing. Ensured vehicles functioned as intended in hot climatic conditions

Subtask 5.3 – Identify procurement requirements for demonstration vehicle builds: Finalized part and tooling costs and lead times for all components

Subtask 5.4 – Create POs for fleet vehicle builds: Issued part purchase orders to support builds

Subtask 5.5 – Fleet build parts tooling and manufacturing: Issued purchase orders for component tooling and manufacturing equipment

Subtask 5.6 – Fleet build parts logistics: Determined dunnage and shipping method for all components

Subtask 5.7 – MRD demo fleet build including development vehicle upgrades: Established material required date (MRD) for the parts to support build and retrofits

Subtask 5.8 – Material staging for demonstration fleet build: Ensured parts were available and placed as required

Subtask 5.9 – Kickoff demonstration fleet build: Began build process once above tasks were verified

Subtask 5.10 – Install and test map-based fuel economy system: Installed, calibrated, and tested map-based fuel economy system as an advanced driver aid system to help maximize the efficiency of the Ram 1500 PHEV functions

Task 6 – Demonstration fleet build and customer readiness: Built the demonstration fleet of 140 trucks and ensured that all customers were prepared to receive fleet vehicles

Subtask 6.1 – Build demonstration fleet: Built demonstration fleet of 140 trucks and upgraded the development vehicles from Phase I

Subtask 6.2 – Prepare demonstration testing sites for vehicle delivery: Ensured daily charging strategy was established and communicated. Ensured charging infrastructure was in place for all users. Also ensured that roles and responsibilities at partners for usage and data collection and analysis were confirmed

Subtask 6.3 – Kickoff extended durability testing: Performed extended internal durability testing concurrent with demonstration fleet deployment

Subtask 6.4 – Train end users: Trained end users on vehicle operation and safety through onsite training programs and detailed user manuals

Subtask 6.5 – Kickoff dealer training: Select dealers in each test area were trained to handle PHEV-related service of the vehicles and to troubleshoot issues. Training and service manuals with Statements of Work (SOWs) were prepared and made available to the service engineers, who were given hands-on training by the mobile on-site demonstration support team. Many FCA dealers were already trained and certified to service production HEV vehicles

Subtask 6.6 – Deliver demonstration vehicles: Delivered demonstration vehicles to the demonstration partner locations across the U.S.

Vehicle Demonstration

Task 7- Ongoing Vehicle Operations: Ensured the vehicles were utilized and functioned as intended

Subtask 7.1 – Vehicle operations: The vehicles were driven according to mileage requirements confirmed with various partners and across various locations

Subtask 7.2 – Vehicle maintenance: Performed scheduled maintenance on the demonstration vehicles per pre-determined maintenance plan

Subtask 7.3 – Vehicle repairs: Performed necessary vehicle repairs

Task 8 – Data collection and analyses

Subtask 8.1 – Collect data: Collected system monitoring and customer usage data

Subtask 8.2 – Data analyses: The data collected was analyzed to test-out fleet demonstration objectives listed above. Key studies were planned with FCA research partners to gain insights on: consumer usage patterns and behavior; Human Machine Interface evaluation; home-to-vehicle-to-grid interfaces; Smart Grid interfaces. Data was also collected by the utility partners to assist in bi-directional charger development

Subtask 8.4 – Validation/revision of components and subsystems: Data analyses results were used to validate and refine the components and sub-system functional specifications

Subtask 8.5 – Quantify benefits/impact: Verified the estimations of gasoline consumption reduction, GHG emission reductions and job creation/retention across FCA, partners and suppliers

Subtask 8.6 – Collect map based fuel economy data: Monitored customer usage and customer usage data for the subset of fleet vehicles that had map-based fuel economy installed. Evaluated the benefits provided by the map-based fuel economy system. Data was collected for analysis and optimization on an ongoing basis

Task 9 – Advanced Energy Storage System Development

Subtask 9.1 – Advanced battery development and integration: An advanced battery pack was integrated into the vehicle

Subtask 9.2 – Development vehicle build and testing: The advanced battery pack was retrofit into 10 development vehicles for testing

Subtask 9.3 – Demonstration vehicle build and testing: The advanced battery pack was retrofit into in 24 demonstration vehicles from the current fleet.

Subtask 9.4 – On-going demonstration vehicle upgrades: Demonstration vehicles were updated with one set of update software for multiple controllers as required from development and deployed vehicles.

8. PHEV Technology Commercialization and Benefits to the Public

FCA US LLC has a long history of innovation and many first-in-industry achievements – ranging from power steering and driver-side airbags as standard equipment in cars, to the invention of the minivan and the resurrection of the rear-wheel drive vehicle configuration. These, and many other similar industry-leading achievements, showcase FCA US LLC's commitment and ability to commercialize critical automotive technology. A portion of the resources obtained for the DOE project was utilized to help develop the F500 BEV and the upcoming Minivan PHEV.

FCA US LLC also has strong track record in the energy/environmental arena, has been an advocate of alternative fuels and has commercialized associated powertrain technologies.

8.1 Market Opportunities and Technology Commercialization

FCA US LLC's commitment to electrification is manifested in its investments in commercializing vehicles that use advanced powertrains, including the PHEV and Battery Electric Vehicle (BEV). FCA US LLC's technology strategy is built around developing significant capabilities in powertrain platforms and a diverse powertrain portfolio in order to meet customer needs in PHEVs and BEVs and to reduce non-renewable energy consumption and GHG emission. The electrification technology developed and demonstrated in this project has been leveraged for FCA's future programs.

Plug-in Hybrid Electric Vehicles

Prior to the DOE PHEV demonstration project, FCA US LLC had gained experience in building production Hybrid Electric Vehicles (HEV), Dodge Durango and the Chrysler Aspen HEVs. Together with the success of the DOE project, FCA US LLC has obtained the following expertise in building PHEVs:

- Significant technical capabilities in hybrid powertrain controls architecture, high-voltage energy storage system controls and management systems, energy management and hybrid systems controls and optimization
- Furthered our expertise in vehicle integration, including vehicle-level specifications, optimization of sub-systems and components to meet functional requirements and development of integrated control software

- Developed a supply base to develop components and sub-systems to support the PHEV powertrain architecture

A portion of the resources obtained for the DOE project was utilized to help develop the F500 BEV and the upcoming Minivan PHEV. The DOE resources also served as the center of competence for FCA global electrification engineering.

Electric Vehicles

In 2013, FCA released its first BEV – Fiat 500e – whose powertrain was designed by the electrified propulsion system group in FCA US LLC. It was the same group that designed and tested the demonstration PHEV trucks for this DOE project. Since the development of the Fiat 500e and the demonstration PHEV took place during the same timeframe, the engineering team implemented technical expertise gained from developing the PHEV trucks, such as the design of the charging system and the high-voltage energy storage system thermal management system; both will continue to benefit the FCA's future programs on electric vehicles.

8.2 Benefits to US Market Place and Economic Viability

While the demonstration allowed for assessment of technical feasibility of the PHEV technologies and understanding customer behavior and acceptance, another critical element is the benefit that demonstrated PHEV technologies can bring to the customers.

Based on FCA US LLC's previous projections of the cost curves of core PHEV components (high-voltage energy storage systems, thermal systems, electric motors, power electronics, charger and wall units), an assessment of the economic viability was conducted. However, understanding the economics requires understanding the price points/premiums a customer is willing to pay. For the purposes of this analysis, we leverage a total-cost of ownership analysis, assuming a rational customer will be indifferent to a conventional ICE technology or to a PHEV-based vehicle and is willing to pay a premium on the PHEV – up to the total costs saved in fuel consumption.

As shown in Figure 68 below, analysis of the total cost of ownership of a PHEV over a 10-year lifecycle indicates a benefit of $8,800 over conventional ICE vehicles for consumers. (The analysis does not reflect any FCA US LLC's product plan or volume estimation). This cost of ownership benefit is realized through fuel cost saving and is based on an EIA's observed average U.S. regular price of $3.36 per gallon of gasoline [3], and a drive cycle of 15,000 miles annually. Utilizing FCA US LLC's previous understanding of the cost curves for PHEV core components, it is estimated that if PHEVs are priced at a premium of $8,800 over comparable ICE vehicles, the business can break even at an annualized volume of 133,000 vehicles. This analysis is based on high cost components of PHEV technologies only and excludes investment, overhead, marketing and other development and commercialization costs. These costs would influence the associated cost curves, but the trend with volumes is difficult to quantify at this early stage of technology development.

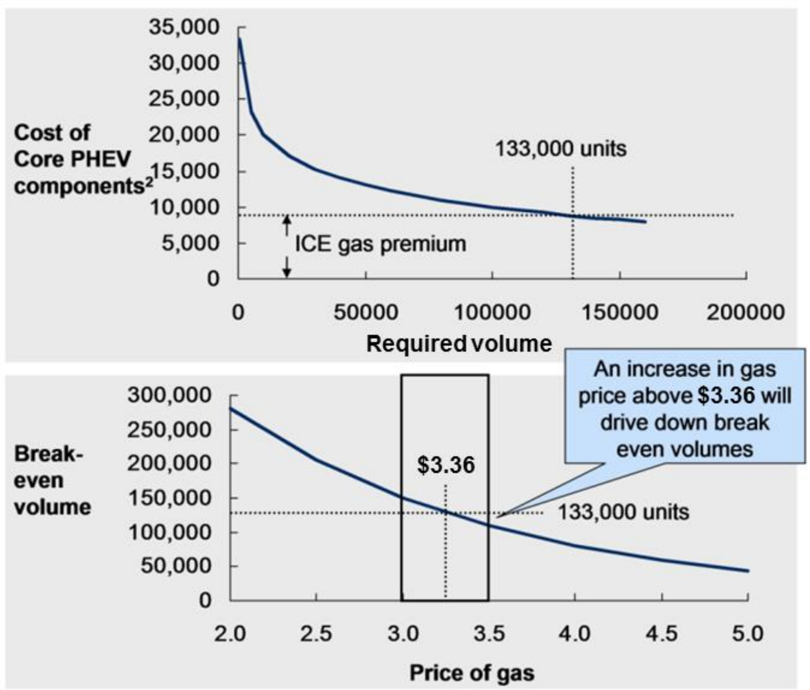


Figure 68: Estimated PHEV total cost of ownership break-even volume[1]

It is important to note that the breakeven volume is sensitive to fuel prices, other ownership costs and government incentives. For example, if the price of gasoline increases to $4.00, the breakeven volume for production would reduce to 80,500 vehicles. In addition, if the

[1] The analysis does not reflect any FCA US LLC's product plan or volume estimation.

government extends tax credits for PHEV buyers (current range of $2,500-$7,500), the breakeven volume would reduce as well.

In addition to the economic benefits derived from the PHEV vehicle, FCA US LLC and the sub-recipient organizations created FTE (full-time-equivalent) U.S.-based high-technology green jobs, including FCA US LLC engineers, program management and technical support resources – as well as sub-recipient resources. The year-over-year FTE hours are shown in Table 26 below.

	2009 Pre-Award 4 Months	2010 Pre-Award 3 Months	2010 9 Months	2011 12 Months	2012 12 Months	2013 12 Months	2014 12 Months	2015 3 Months
FCA US LLC	30	84	91	76	47	26	21	2
Sub-recipients	-	5	3	6	9	8	-	-
Total FTE	30	89	94	81	56	34	21	2

Table 26: Year-over-year FTE hours

In addition to these jobs, there were many more jobs provided by the fleet partner staffs, FCA US LLC dealer service network and component suppliers.

8.3 Commercialization Risk Analysis

As a result of closely monitoring the project objectives and key deliverables, the risks associated with key supplier and partners to support the timing execution were minimized, which enabled the project to meet all objectives and make relevant technologies beneficial the public.

Through commercialization of the PHEV technology, key risks and associated risk-mitigation plans are categorized as market risks, financial risks, regulatory risks and supply risks (shown in Table 27 on the next page). The approach to manage those risks on an ongoing basis follows the FCA US LLC's strategy of tackling commercial risks:

- Commercial risks are business risks that might pose a threat to project completion. Examples include partner non-participation and unforeseen project cost increases.
- To guard against these risks, FCA US has compiled detailed letters of support that clarify the objectives and responsibilities of each project team member.

- Any delay in timing on a partner deliverable will also be detected through the CPCP. Any variation from the plan will be detected by project management and addressed immediately.

Market Risks	Mitigation Plans
Customer acceptance of PHEV technologies remains low.	Market PHEVs as multi use vehicles. Develop multiple product platforms to promote broader customer acceptance. Support fast charging infrastructure and smart grid development. Market heavily to early adopters, green conscious segment and maintain retail consumer push.
Low gas prices minimize PHEV operating cost advantages, affecting sales potential.	Leverage PHEV operating advantages as environmental benefits, quiet and smoother operation for shorter drive cycles, and auxiliary power availability (for trucks and SUV users).
Cyclical economic downturns drive down customer spending and PHEV demand.	Maintain flexibility in production volumes and modular design to reduce vehicle development costs. Focus on costs without compromising on quality.
Lithium prices increase as demand for lithium-ion increases, driving up vehicle cost.	Currently, there is no futures market for lithium. In case of further risk development, help battery suppliers lock down future supply at appropriate costs.
Regulatory Risks	**Mitigation Plans**
Emission regulations or CAFE standards make technology non-compliant.	Track regulatory requirements on an ongoing basis through active dialogue with government. Continuous refinement of technology to maintain/stay ahead of emerging standards.

Table 27: Commercialization risks and mitigation plans

8.4 Estimated Impact on Fuel Consumption and GHG Emission

Through Project Phase I and Phase II demonstration of the Ram 1500 PHEV trucks, great improvement of real-world fuel economy was observed. Tables 28 and 29 below provide the statistics of the average fuel economy under different vehicle operation models in both phases.

Phase I:

Trips in Charge-Depleting (CD) mode	City	Highway
Gasoline fuel economy (mpg)	23	27
DC electrical energy consumption (DC Wh/mi)	216	162
Percent of miles with internal combustion engine off	12%	3%
Average trip Aggressiveness	5.6	3.6
Average trip distance (mi)	5	26
Trips in both Charge-Depleting and Charge-Sustaining (CD/CS) modes		
Gasoline fuel economy (mpg)	20	22
DC electrical energy consumption (DC Wh/mi)	77	59
Percent of miles with internal combustion engine off	8%	2%
Average trip Aggressiveness	4.8	2.7
Average trip distance (mi)	13	49
Trips in Charge-Sustaining (CS) mode		
Gasoline fuel economy (mpg)	17	20
Percent of miles with internal combustion engine off	8%	2%
Average trip Aggressiveness	5.3	2.7
Average trip distance (mi)	6	43

Table 28: Phase I fuel economy statistics

Phase II:

Trips in Charge-Depleting (CD) mode	City	Highway
Gasoline fuel economy (mpg)	24	27
DC electrical energy consumption (DC Wh/mi)	213	175
Percent of miles with internal combustion engine off	12%	3%
Average trip Aggressiveness	5.6	3.8
Average trip distance (mi)	7	17
Trips in both Charge-Depleting and Charge-Sustaining (CD/CS) modes		
Gasoline fuel economy (mpg)	20	22
DC electrical energy consumption (DC Wh/mi)	77	56
Percent of miles with internal combustion engine off	9%	2%
Average trip Aggressiveness	5	3
Average trip distance (mi)	16	38
Trips in Charge-Sustaining (CS) mode		
Gasoline fuel economy (mpg)	17	20
Percent of miles with internal combustion engine off	8%	1%
Average trip Aggressiveness	5.5	3.1
Average trip distance (mi)	9	34

Table 29: Phase II fuel economy statistics

Figure 69 below illustrates the combined average city and highway fuel economy in Phase I and Phase II. The EPA fuel economy ratings for the base gasoline 2011 Ram 1500 truck are also shown in the chart for detailed comparison.

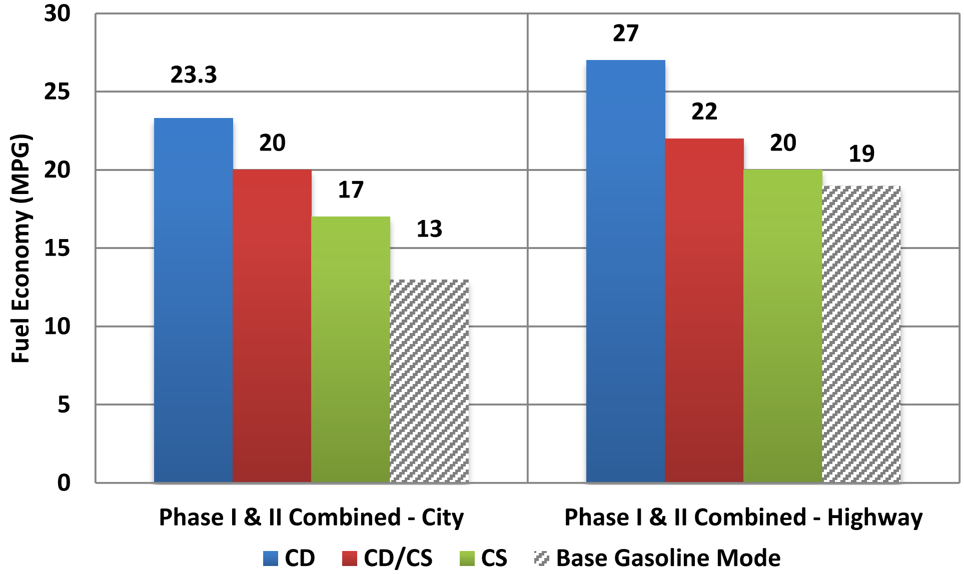


Figure 69: Phase I and II average city and highway fuel economy

In summary, the fuel economy improvements are as follows:

Phase I and II combined average fuel economy – City

- Charge-depleting mode – 79% increase versus base vehicle
- Charge-depleting/charge-sustaining mode – 54% increase versus base vehicle
- Charge-sustaining mode – 31% increase versus base vehicle

Phase I and II combined average fuel economy – Highway

- Charge-depleting mode – 42% increase versus base vehicle
- Charge-depleting/charge-sustaining mode – 16% increase versus base vehicle
- Charge-sustaining mode – 5% increase versus base vehicle

GHG emission reduction can also be calculated according to fuel consumption reduction due to the linear relationship between the two variables. Assuming 15,000 miles drive cycle per year and using EPA value of 8.887 kg CO_2/gal of gasoline, the annual greenhouse gas emissions per vehicle in different driving modes can be calculated and are shown in Figure 70 below.

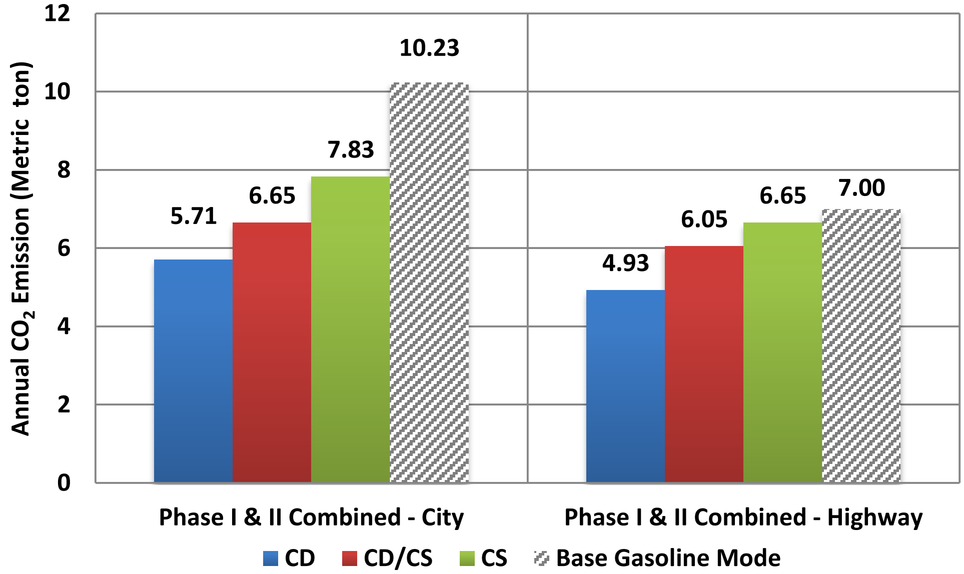


Figure 70: GHG emission per vehicle per year

In summary, the GHG reductions per vehicle are as follows:

Phase I and II combined average GHG emission per vehicle – City

- Charge-depleting mode – 44% decrease versus base vehicle
- Charge-depleting/charge-sustaining mode – 35% decrease versus base vehicle
- Charge-sustaining mode – 23% decrease versus base vehicle

Phase I and II combined average GHG emission per vehicle – Highway

- Charge-depleting mode – 30% decrease versus base vehicle
- Charge-depleting/charge-sustaining mode – 14% decrease versus base vehicle
- Charge-sustaining mode – 5% decrease versus base vehicle

8.5 Benefits of Advanced Power Grid Management

With the introduction of PHEVs as a means to reduce national fuel consumption and GHG into the atmosphere, the PHEV effect on the U.S. electric grid system must be minimized.

Challenges of PHEV Charging and Residential Transformer Loading:

Transformer Loading Challenges

- A single 25 kW residential transformer may serve 3-5 or even up to 10 homes
- In peak periods, residential transformers may already be overloaded at 150% to 200% for an hour or more
- Adding one PHEV at 7.5 kW to a 150% overloaded transformer increases the overload to 180%; two PHEVs increase it to 210%
- Adding one or two PHEVs to the existing local distribution is not seen as an immediate issue. When more than two PHEVs are charged during peak periods, potential overloading issues with residential transformers may occur.

Current Load-Mitigation Solutions

- For Utilities
  - Price-based incentives to reduce peak time usage (critical/peak pricing)
  - Demand Response Load Control (DRLC) that delays the start of, or reduces the use of, high-demand appliances – such as air conditioning or water heaters
  - Demand charges have been added to residential users based on daily or monthly peaks
- For Consumer
  - PHEV- or EVSE-scheduled charging to delay charge event from peak periods
- Future Loading
  - As one or two PHEV are introduced to a residential grid, existing utility controls may be successful
  - Scheduled or smart charging can reduce the PEV impact on peaks, while still meeting customer expectations for charging
  - Price, DRLC, demand charges and scheduled charging are not considered long-term solutions but can complement Smart Charging solutions as incentives

Grid Integration of Plug-in Electric Vehicle (PEV) – Vehicle-to-Grid (V2G) and Reverse Power Flow (Bi Directional)

Given the challenges and mitigating opportunities outlined above, V2G PHEV featuring Smart Charging and Reverse Power Flow allow for coordination of grid management by electric utilities.

Figure 71 on the next page shows the variation between "charge now" or fastest, versus waiting for the cheapest session at 11pm. It also shows if the utility has sent a 50% DRLC signal that would reduce the load on the home from 10 kW to 5.5 kW.

The price shown is a Time of Use (TOU) rate varying from $.04 to $.07 to $.12/kW. Generally, this would remain constant for the year or season, but it may change 6 to 12 times a year to a Critical Peak Period (CPP) rate where the $.12/kW time period would be replaced by $1.00/kW. In that case, the homeowner is expected to reduce the 2.5 to 3.5 kW load and if the PEV is charging at this time, the fastest rate increases from $1.80 to $15.00 or a $13.2 increase. The vehicle, however, is not intended to be used for another 12 hours and there is no need to charge when connected and impose the additional cost plus stress on the grid. In the event of a CPP period, the DRLC command may also be lower than 50%, depending on the duration of the particular stress that caused the TOU period to change to the CPP event.

As shown, the cheapest price, TOU or CPP is only $.60; that saves the customer $1.20 from the TOU rate and $14.40 from the CPP rate. The DRLC rate is the same, but other incentives are offered to the customer to be in a DRLC program since the customer is expected to reduce loads within any DRLC signal period. Cheapest or DRLC still provides the vehicle with a 100% SoC when needed.

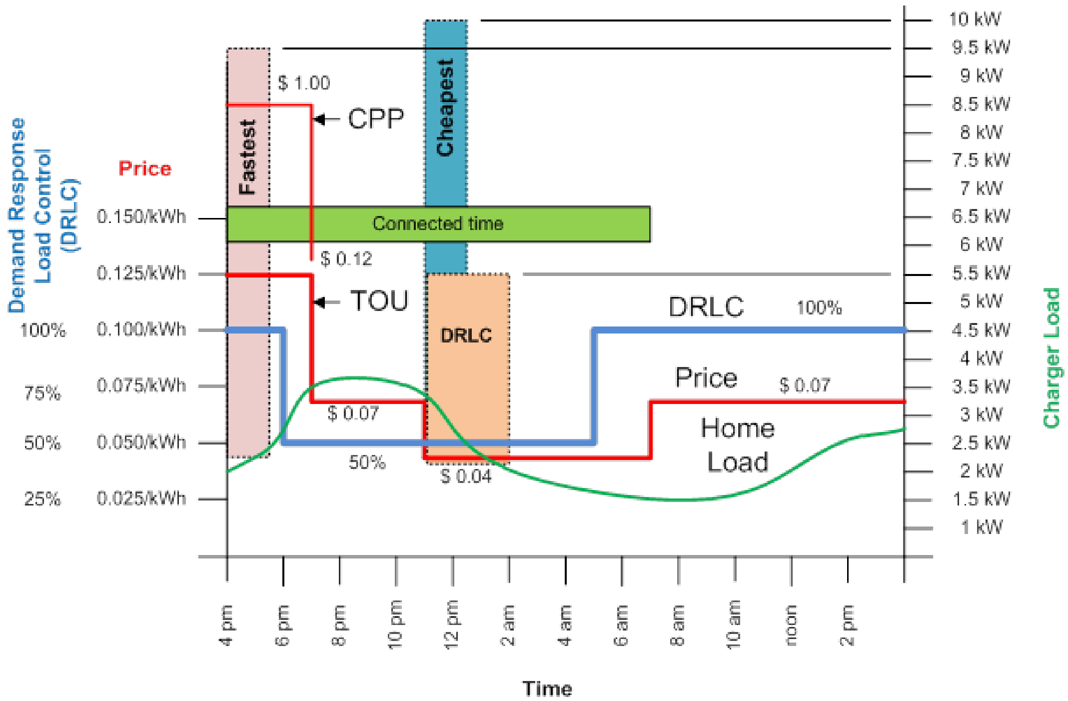


Figure 71: Time of Use (TOUC) rate variations

Reverse Power Flow (RPF) can also be used to reduce peak loads and cost. Generally either a PHEV or BEV being driven 30 miles or less/day, and if a PHEV also has the capability of charging at work, it may still have some battery power available for a Vehicle-to-Grid (V2G) session. A BEV, whether charging at work or not, would have around 60% SoC when arriving home and have more capability to provide V2G power for a longer duration than a PHEV.

In either case, providing V2G power during the home's peak period, then recharging once the price and home load is less, may provide cost savings toward Demand Charges some utilities are now including with TOU and DRLC programs. A Demand Charge may be added for any peak during the month and some are $7.17/kW. This means a home with a normal 3.3 kW peak would pay an additional $23.66 in Demand Charges for the month. If a PEV could reduce this by one or two kW, the savings of $7.17 or $14.34 respectively are realized.

If the PEV is charging during a non-reduced peak, the total load could be as high as 9.5 to 10 kW as shown in Figure 68. This makes the Demand Charge $68.11 to $71.70 for the month.

The home load curve could be completely flattened by using Smart Charging with SEP2 that includes the Flow Reservation signals. This provides the information on Time Charge Is Needed

(TCIN) during the initial connection and can dynamically control the charge rate to match the Home Load curve while charging. This flattens the entire home load to a level selected by the customer and provides the lowest cost for the charging session, by combining V2G and Smart Charging.

In summary, V2G PHEV featuring Smart Charging and Reverse Power Flow can create grid management opportunities to mitigate additional grid loading. The V2G vehicles can:

- Enhance power grid operation by smoothing the rate at which power is consumed – lower peak loads at homes and businesses
- Provide power back to the grid helping to balance load levels
- Stabilize solar sources and other transient fluctuations on the grid

PEV consumer experience is enhanced by V2G

- Allows remote power at non-grid sites
- Functions as home generator but without the added fuel tank and engine (that generally fails to start when needed)

To provide the above benefits:

- Individually owned EVs are expected to participate significantly in grid services during the second half of this decade, with more than 250,000 V2G-enabled PHEV sold worldwide by 2030
- Both Plug in Hybrid EV (PHEV) and Battery Electric (BEV) plug-in electric vehicles need to consider AC and/or DC options for V2G; they must do so at various power levels to match grid and consumer needs

In summary, V2G is a critical subset of the total PEV market, which is expected to evolve steadily in the coming years.

9. Closing Statement

FCA US LLC greatly appreciates the opportunity to have partnered with the U.S. Department of Energy as a major recipient of the ARRA Act funding. Such an opportunity facilitated the development of an emerging technology with groundbreaking features. It also provided FCA US LLC, and the sub-recipient partners the opportunity test PHEVs in real-world environments.

The key benefits realized on this project were the ability to help create and sustain core competency “green” technology jobs and place them toward future development of electrification programs – such as the Fiat 500e Battery Electric Vehicle and the upcoming Chrysler Minivan PHEV. In addition, it provided utility companies a deeper understanding of the effect PHEVs will have on their power grid as a result of charging and reverse power flow operations.

The field partners and academia benefited from the learning associated with customer driving behavior, acceptance of technology and advancing research toward improvements of the design and integration of key components and system operation.

The Ram 1500 PHEV project met the key objectives and metrics outlined in the DOE DE-FOA-0000028 Area of Interest 1.

References List

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