FINAL TECHNICAL REPORT

DOE Award Number: DE-EE0004529
(Part of Plug In Hybrid Electric Vehicle Technology Acceleration And Deployment Activity DE-DoE-PS26-08NT00360-01)

Award Recipient: FCA US LLC f/k/a/ Chrysler Group LLC
800 Chrysler Drive
Auburn Hills, MI 48326

Project Title: Advancing Plug-In Hybrid Technology and Flex Fuel Application on a Chrysler Minivan

FCA US LLC Primary Contacts:

Principle Investigator: Abdullah Bazzi

E-Mail: Abdullah.Bazzi@fcagroup.com; old email: aab5@chrysler.com
Phone: (248) 944-3093
Mobile: (248) 705-5752

Manager of Government Collaborative Programs: Steven Barnhart

E-Mail: Steven.Barnhart@fcagroup.com; old email: sab15@chrysler.com
Phone: (248) 576-7361

DOE Program Manager: John Jason Conley

E-Mail: John.Conley@netl.doe.gov
Phone: (304) 285-2023

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Executive Summary

Introduction

FCA US LLC viewed this DOE funding as a historic opportunity to begin the process of achieving required economies of scale on technologies for electric vehicles. The 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 to 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 battery recycling. To support the development of a strong, commercially viable supplier base, FCA US LLC also used this opportunity to evaluate various designated component and sub-system suppliers. The original project proposal was submitted in December 2009 and selected in January 2010. The project ended in December 2014.

Financial Overview

The project budget was $24.6 Million. The contributions of FCA US LLC, the DOE and two sub-recipients are shown in Table 1 below. It is also important to note that Electrovaya and MAHLE Behr USA were component suppliers as well as project sub-recipients.

Participant	DOE Contribution ($ millions)	Participant Contribution ($ millions)	Total Budget ($ millions)
FCA US LLC	8.0	12.6	20.6
Electrovaya	1.7	1.7	3.4
MAHLE Behr USA	0.3	0.3	0.6
Grand Totals	10	14.7	24.6

Table 1: Project Contributions by Participant

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. Results from the study are designed to enable FCA US LLC to gain a better understanding of customer usage, operational needs and, ultimately, consumer acceptance. This could enable FCA US LLC to refine PHEV implementation for all relevant platforms and move toward volume production. The funding opportunity DoE-PS26-08NT00360-01 specified the required conditions for the PHEV vehicle development and demonstration as:

- Including the analysis, design, fabrication and integration of plug-in hybrid electric propulsion systems (including battery, battery charger, power electronics and electric drive) in-vehicle platforms using standard practice for production-intent vehicles
- The deployment of PHEVs in geographically diverse locations throughout the U.S. to allow DOE and industry partners to realistically and clearly identify PHEV performance, operation, and fuel economy in a real-time user environment
- Use of advanced batteries (i.e. lithium-ion) and/or alternative fuels

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.

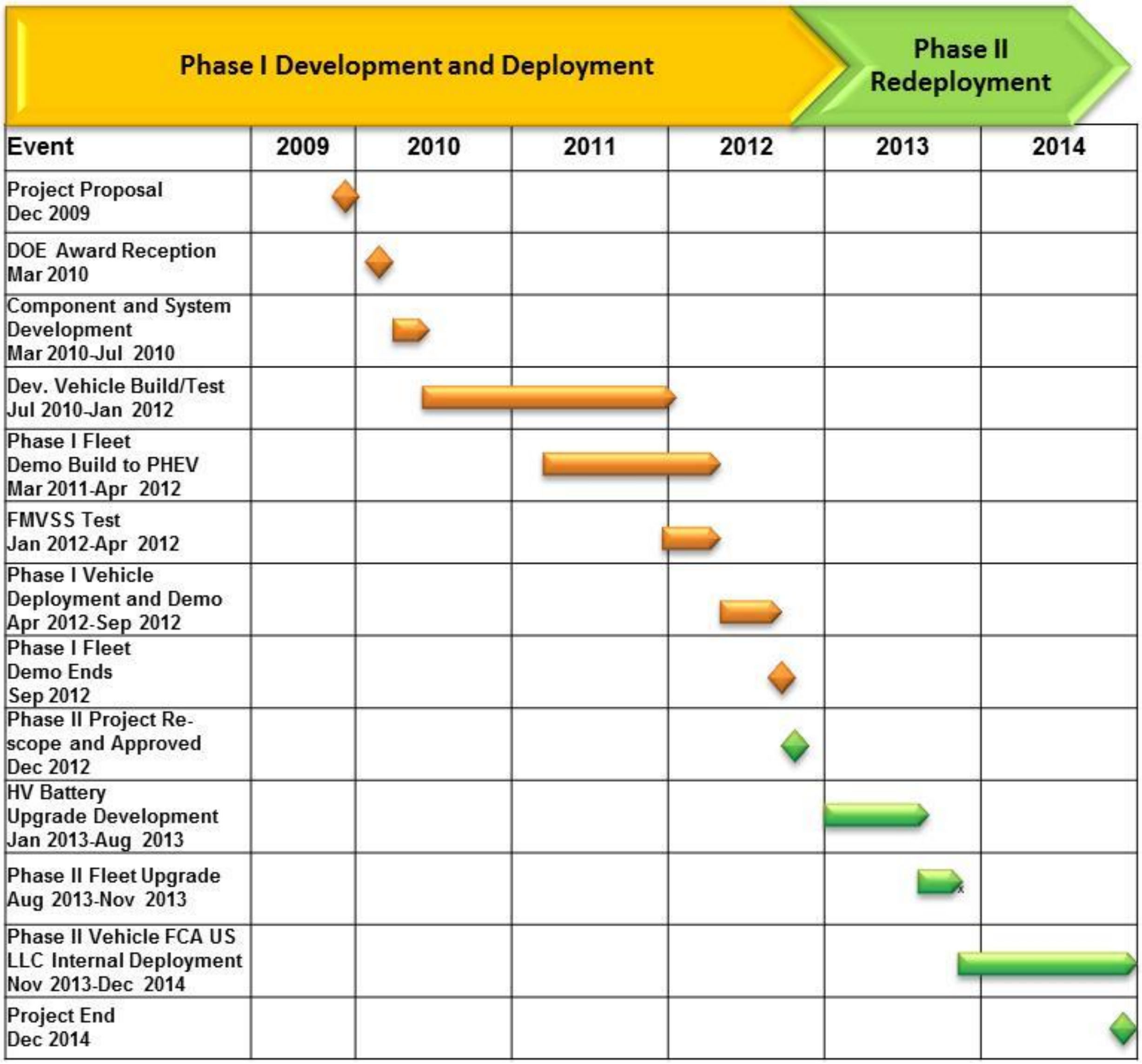

Figure 1: Overall project timeline

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. Determine functional objectives, including petroleum reduction, related to PHEV and E85 flex fuel usage and performance

During the component and system development phase, FCA US LLC successfully built one PHEV prototype concept vehicle for early development and 16 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 fleet of demonstration vehicles.

Phase I

In Project Phase I, 25 demonstration PHEV minivans were built based on 2011 Chrysler Town & Country production model vehicles that were modified and retrofitted with PHEV systems. The vehicles included data collection and remote diagnostics instrumentation for 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 six different external partners, six U.S. locations and the FCA US LLC Technical Center.

In Phase I, the HV battery technology was closely shared between this minivan project and the Ram 1500 PHEV project (DOE Award Number DE-EE0002720). In the Phase I deployment of the Ram PHEV trucks, several field issues were observed in the HV battery that impeded research work progress. 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

These phenomena were not observed in the minivan Phase I deployment fleet. The Ram PHEV truck fleet was deployed earlier, resulting in more vehicle mileage and HV battery use, thus the early detection in the Ram fleet.

Phase II

FCA US LLC upgraded the high-voltage (HV) battery system in the Ram 1500 PHEV to address these issues. This minivan project and the Ram project were closely coordinated, with common technical vehicle facets. Therefore, the same HV battery upgrade was also made in the minivans in this project. These new HV batteries were installed on four Chrysler Town & Country minivans in Phase II. The four minivans were deployed at the FCA US LLC engineering center for continued PHEV development in concert with the Ram 1500 PHEV redeployment activities. For the Phase II minivan development, the focus was on:

- Continued calibration/controls development and optimized fully integrated systems
- Engine start/stop refinement
- Drivability/emissions and Atkinson cycle
- In addition to the four vehicles noted above, two PHEV prototype concept vehicles were built for continued early development of PHEV systems for future FCA US LLC minivan PHEV platforms. These two production-intent vehicles were utilized for development before the first production prototype vehicles became available

Throughout the project, two DOE project award sub-recipients performed a series of research work for the development and implementation of the PHEV technology. Each conducted in-house development and research work; both were also component suppliers. A summary of their projects activities is shown in Table 2 on the next page:

Project Sub-recipients	Project Activity Summary
Electrovaya	Design and manufacture the battery packs for the demonstration PHEVs
MAHLE Behr USA	Engineering R&D for the thermal systems in the demonstration PHEVs

Table 2: Project sub-recipients summary

The approach of the project enabled FCA US LLC to apply lessons learned to improve its fleet vehicle performance in a timely manner, while providing the opportunity to utilize the latest technology and facilitate the achievement of best fleet demonstration results.

Project Lessons Learned

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

- Thermal systems
- Charging systems
- High-voltage energy storage systems
- Vehicle drivability/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 have made them qualified to develop and demonstrate PHEV technology in this project.

PHEV Technology Commercialization and Benefits to the Public

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. The goal is 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 economic benefits derived from the PHEV vehicle, FCA US LLC created FTE (Full Time Equivalent) U.S.-based high technology green jobs including, FCA US LLC engineers, program management and technical support resources. The year-over-year numbers are shown in Table 3 below.

	2009 / 2010 Pre-Award 13 Months	2010 3 Months	2011 12 Months	2012 12 Months	2013 12 Months	2014 12 Months	2015 3 Months
FCA US LLC	12	19	22	14	3	3	1

Table 3: Year-over-year FTE hours

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

NOMENCLATURE

AC	Alternating Current	**GHG**	Greenhouse Gas
A/C	Air Conditioning	**HCP**	Hybrid Control Processor
ANL	Argonne National Laboratory	**HEV**	Hybrid Electric Vehicle
BEV	Battery Electric Vehicle (All Electric)	**HMI**	Human Machine Interface
BMS	Battery Management System	**HV**	High-Voltage
CAN	Controller Area Network	**HVAC**	Heating, Ventilating and Air conditioning
CIL	Controller In-the-Loop	**HVBS**	High-Voltage Battery System
CD	Charge Depleting	**ICE**	Internal Combustion Engine
CPCP	Chrysler Product Creation Process	**INL**	Idaho National Laboratory
CS	Charge Sustaining	**MPG**	Miles per Gallon
DC	Direct Current	**MPGe**	Miles per Gallon Equivalent
DFMEA	Design Failure Mode and Effects Analysis	**MY**	Model Year
DOE	Department of Energy	**NiMH**	Nickel-metal Hydride
DRLC	Demand Response Load Control	**NREL**	National Renewable Energy Laboratory
DRM	Data Recording Module	**NVH**	Noise Vibration and Harshness
DVP&R	Design Verification Plan & Report	**OBC**	On Board Charger
E85	Ethanol (85% Ethyl Alcohol)	**OBCM**	On Board Charging Module
EAER	Equivalent All Electric Range	**OEM**	Original Equipment Manufacturer
ECM	Engine Control Module	**PCM**	Powertrain Control Module
EIA	Energy Information Administration	**PEV**	Plug-in Electric Vehicle
EoL	End of Life	**PHEV**	Plug-in Hybrid Electric Vehicle
EPA	Environmental Protect Agency	**PSAT**	Powertrain System Analysis Toolkit
EPRI	Electric Power Research Institute	**PZEV**	Partial Zero Emissions Vehicle
EV	Electric Vehicle	**SOC**	State of Charge
EVSE	Electric Vehicle Supply Equipment	**SUV**	Sport Utility Vehicle
FCA	Fiat Chrysler Automobiles	**SULEV**	Super Ultra Low Emissions Vehicle
FE	Fuel Economy	**TCO**	Total Cost of Ownership
FMVSS	Federal Motor Vehicle Safety Standards	**TPIM**	Traction Power Inverter Module
FTE	Full Time Equivalent		

1. Introduction and Background

FCA US LLC viewed this DOE funding as a historic opportunity to begin the process of achieving required economies of scale on technologies for electric vehicles. The 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 to 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 battery recycling. To support the development of a strong, commercially viable supplier base, FCA US LLC also used this opportunity to evaluate various designated component and sub-system suppliers. The original project proposal was submitted in December 2009 and selected in January 2010. The project ended in December 2014.

Financial Overview

The project budget was $24.6 Million. The contributions of FCA US LLC, the DOE and eight sub-recipients are shown in Table 4 below. It is also important to note that Electrovaya and MAHLE Behr USA were component suppliers, as well as project sub-recipients.

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Table 4: Project contributions by participant

1.1 Project Objectives

The project's objective 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. Results from the study are designed to enable FCA US LLC to gain a better understanding of customer usage and operational needs, and ultimately, consumer acceptance. This could enable FCA US LLC to refine PHEV implementation for all relevant platforms and move toward volume production. The funding opportunity DOE-PS26-08NT00360-01 specified the required conditions for the PHEV vehicle development and demonstration as:

- Including the analysis, design, fabrication and integration of plug-in hybrid electric propulsion systems (including battery, battery charger, power electronics, and electric drive) in-vehicle platforms using standard practice for production-intent vehicles
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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, ultimately 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
  - Producing controllable traction forces from minimum to maximum under different battery temperatures, ambient temperatures, altitudes and vehicle speeds(2)
  - Displacing fuel efficiently in all driving scenarios for all customers
  - Achieving efficient charge-sustaining operations
- Verify plug-in charging mode performance based on charger and battery model
- 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, battery temperatures, ambient temperatures, altitudes, variations in charging events, and fuel and electricity costs

Development vehicle verification objectives

- Confirm vehicle functional objectives, including petroleum reduction, related to PHEV and E85 flex fuel usage and performance
- Prove emission targets can be achieved
- Demonstrate drivability and validate high-voltage battery pack safety

Fleet demonstration objectives

- Profile vehicle usage
- Profile customer expectation
- Prove product viability in “real-world” conditions
- Confirm that conditions for viable mass productions can be met and quantify the benefits to customers and the nation

Project close-out deliverables

- Final scientific/technical report
- Final invoice; final SF-270 voucher
- SF-425 Federal financial report
- Patent certification
- Property certification

1.2 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. 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. Determine functional objectives, including petroleum reduction, related to PHEV and E85 flex fuel usage and performance

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 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 16 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, 25 demonstration PHEV minivans were built based on 2011 Chrysler Town & Country production model vehicles that were modified and retrofitted with PHEV systems. The Chrysler Town & Country minivan was chosen as the demonstration vehicle platform because of its versatility and capability to offer a wide range of vehicle driving conditions and high vehicle performance.

The demonstration vehicles included data collection and remote diagnostics instrumentation for the deployment to the fleet demonstration partners. They 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 six different external partners, six U.S. locations and the FCA US LLC Technical Center.

Phase I demonstration partners are listed in Table 5 on the next page.

Phase I Partners	Location	Type	# Vehicles
Argonne National Labs	IL	Research	1
City of Auburn Hills	MI	Municipality	4
City of Yuma	AZ	Electric Utility	3
DTE Energy (Detroit Edison)	MI	Electric Utility	4
Duke Energy	NC	Electric Utility	8
SMUD (Sacramento Municipal Utility Dept.)	CA	Municipality	3
FCA US LLC	MI	Development	2

Table 5: Phase I partners by location and research type

Data was collected 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

In Phase I, the HV battery technology was closely shared between this minivan project and the Ram 1500 PHEV project (DOE Award Number DE-EE0002720). In the Phase I deployment of the Ram PHEV trucks, several field issues were observed in the high-voltage storage system that impeded research work progress. These issues include:

- 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

These phenomena were not observed in the minivan Phase I deployment fleet. The Ram 1500 PHEV fleet was deployed earlier, resulting in more vehicle mileage and high-voltage storage system use, thus the early detection in the Ram fleet.

FCA US LLC upgraded the high-voltage storage system in the Ram 1500 PHEV to address these issues. This minivan project and the Ram project were closely coordinated, with common technical vehicle facets. Therefore, the same high-voltage storage system upgrade was made in the minivans in this project. These new systems were installed on four Chrysler Town & Country minivans in Phase II. The four minivans were deployed at the FCA US LLC engineering center for continued PHEV development, in concert with the Ram 1500 PHEV redeployment activities. The deployment period for Phase II was from December 2013 to December 2014.

These four minivans were used for the following major areas of development for PHEV characteristics. The engine was replaced in two vehicles with the series production PHEV design-intent 3.6L Atkinson cycle engine. The major objectives are provided below.

Engine Auto Start/Stop and Drivability

- Auto starts and stops calibration for the Atkinson cycle engine
- Cold auto starts with respect to emissions development
- Basic drive tests to validate emissions work noted below

Emissions

Validate the Atkinson cycle engine to meet SULEV30 emission standards without secondary air intakes.

In addition to the four Chrysler Town & Country minivans buit during Phase II of this project, two PHEV prototype concept vehicles for continued early development of PHEV systems for future FCA US LLC platforms were also built. These two production-intent vehicles were utilized for these objectives:

- Validate specific production advancements
- Enhance the production prototype build

1.2.3 Scope of Sub-recipient Activities

Throughout the project, two DOE project award sub-recipients performed a series of research work for the development and implementation of the PHEV technology. Each conducted in-house development and research work and both were component suppliers. A summary of their projects activities is shown in Table 6 on the next page:

Project Sub-recipients	Project Activity Summary
Electrovaya	Design and manufacture the battery packs for the demonstration PHEVs
MAHLE Behr USA	Engineering R&D for the thermal systems in the demonstration PHEVs

Table 6: Summary of project sub-recipient activities

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

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

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

The Chrysler Town & Country minivan was chosen as the demonstration vehicle platform because of its versatility and capability as a family or commercial vehicle. The choice was also consistent with the market's long-term needs for commercial PHEV technologies on larger vehicles, such as minivans, pickups and SUVs.

Key Innovations:

1. Real-time online optimization of battery electric power and engine mechanical power
2. Interactive Human Machine Interface (HMI) to help drivers maximize fuel economy
3. Battery 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 in ways to Argonne National Laboratory (ANL)'s Powertrain System Analysis Toolkit (PSAT). System control laws and actuator responses are 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 has 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.

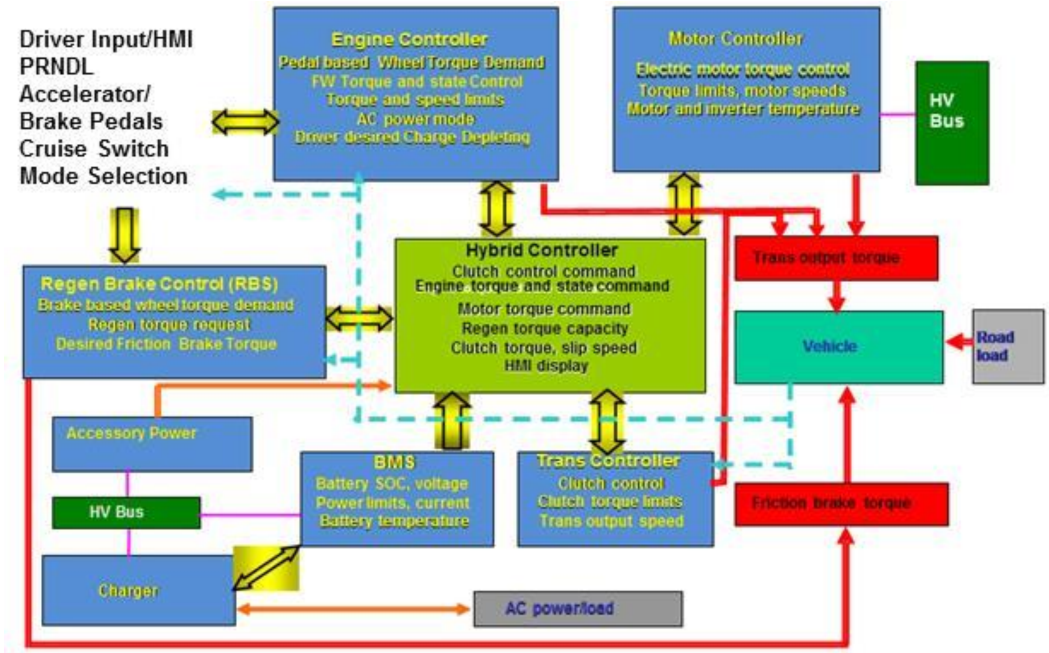


Figure 2: Network topology of the PHEV electrical network

2.2 High-Voltage Energy Storage System

Description

PHEV power and energy requirements for the high-voltage storage system were driven by functional objectives designed to meet customer and regulatory requirements. Energy storage remains a key component to PHEV viability. 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 storage 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 HVBS was required to integrate into the existing Chrysler Town & Country minivan 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°C	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°C	kW	1.4 (110V/15A)
Unassisted Operating & Charging Temperature Range	°C	-30 to 52
Operating Temperatures versus Base 10 sec Peak Discharge/Charge Power		
Above 52°C	kW	0/0
30°C - 52°C (100%)	kW	45/30
0°C (50%)	kW	22.5/15
-30°C (30%)	kW	13.5/9
-20°C (15%)	kW	6.75/4.5
-30°C (10%)	kW	4.5/3
No unassisted operation below -40°C	N/A	N/A
Survival Temp Range	°C	-46 to +66
Capacity of System	kWh	12.1

Table 7: HV battery system requirements for Chrysler Town & Country PHEV

Design, Implementation and Integration

Electrovaya was chosen as the high-voltage storage system supplier for Phase I of the program due to the company's ability to meet the technical requirements and program requirements for the battery 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 storage system was produced at their manufacturing facility in Malta, New York. All systems were assembled tested, and shipped from Malta for all initial production and service pack rework throughout Phase I.

The additional weight of the high-voltage energy storage system required modifications of the minivan Stow 'n Go® storage feature to accommodate the structural and packaging requirements of the HV battery. FCA US LLC then worked with Detroit-area steel stamping companies to create a new tub design to handle the mass. A high-voltage storage system cover was designed to serve as the structural load floor for second-row occupants. The tub was designed for easy installation and service. In addition, the system cover was waterproof. The connections had an inset area within the tub, ensuring they would not be damaged during installation.

The Electrovaya high-voltage 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 battery systems to be packaged within the restrictive volume of the vehicles and meet program energy targets. Figure 3, on the next page, shows the internal configuration of the battery pack comprised of four lithium-ion SuperPolymer battery modules with integrated power control management system, battery management system (BMS), charging system and thermal management system [2].

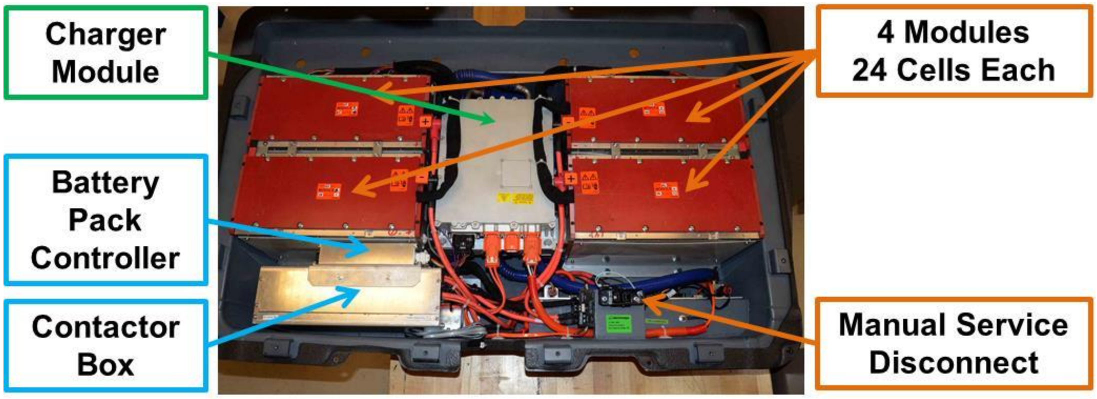


Figure 3: Internal configuration of Electrovaya HV battery Pack [9]

Figure 4 below shows the complete HV battery pack as installed in the minivans:

Figure 4: Electrovaya HV battery pack as installed in Phase I

Instrumental in the minivan high-voltage storage system design was the implementation of a coolant-only thermal management system by Electrovaya. This saved considerable internal package volume and provided a more uniform thermal environment and anticipated benefits. The 24-cell modules had a cold plate on either side with aluminum L-shaped plates placed between each cell, which resulted in a significantly tighter thermal envelope for all cells. This significantly reduced self-discharge and reduced variation of cell imbalance between cells in the pack.

The battery management system optimized the battery system for peak performance at the cell and module level, in addition to protecting the system and providing 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. Battery safety mechanisms included such features as a manual disconnect, thermal management and protection against over-voltage, under-voltage, over-current and over-charge.

2.3 High-Voltage Energy Storage System Upgrade

FCA US LLC chose to utilize the Ram 1500 PHEV project (DOE Award Number DE-EE0002720) high-voltage storage system for the upgrade to four minivan vehicles in this project. This continued a close coordination of common technical facets between the two vehicles. Given successful base vehicles and with a functional battery management system and thermal control systems, the key was to select and implement a new cell design in the same Ram high-voltage storage system housing. Then use this housing in the minivan installation to maintain commonality of hardware and development activities. In this way, the high-voltage storage system upgrade was also incorporated into the minivans in this project.

To evaluate cell supplier alternatives, FCA US LLC focused on domestic suppliers who could be potential 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 HV battery pack supplier because it was capable of providing a battery cell that was compatible from both a physical and performance standpoint with the energy storage system in the Chrysler Town & Country 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 high-voltage storage management system software changes were made to adjust the cell voltage versus SOC and the power versus temperature calibration tables and modify the thermal management system for direct liquid cooling.

The Phase II energy storage system upgrade was implemented in three steps:

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

Design, Implementation and Integration

A key FCA US LLC design objective after the electrochemistry change was:

- Take advantage of the Ram 1500 PHEV learnings by reusing that vehicle's steel battery case and vehicle interfaces

Magna was selected as the 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 Ram 1500 PHEV steel battery case required a modification to the Chrysler Town & Country PHEV, in order to accommodate the new energy storage system packaging.

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's external system; the thermal software was sufficiently adaptable as to avoid a new calibration, as 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 battery 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 battery thermal system, so the liquid thermal system already in the vehicle was not affected.

Magna performed all 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 design and assembly feasibility before moving to manufacture.

Figure 5 below shows the internal configuration of the battery pack.

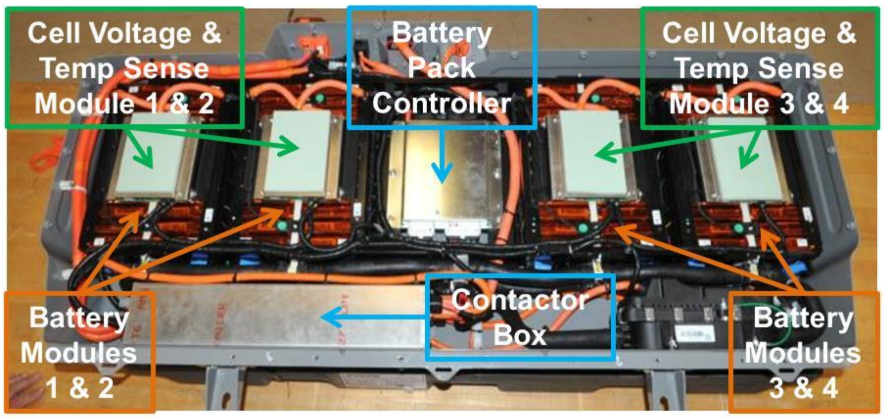


Figure 5: Internal configuration of Magna/JCI HV battery pack

Figure 6 below is the complete Magna/JCI HV battery pack as installed in the PHEV minivans:

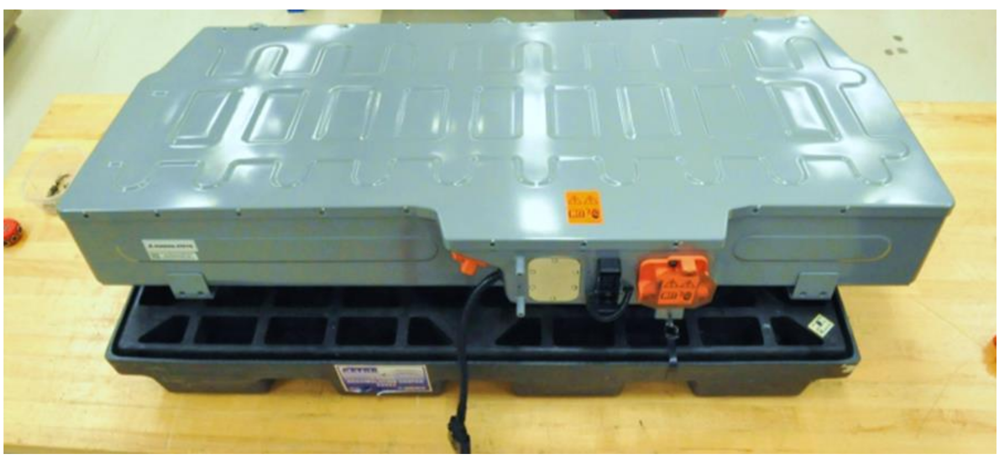


Figure 6: Magna/JCI HV battery as installed in Phase II

A comparison of the specifications of the Phase II Magna/JCI battery pack and the Phase I Electrovaya of the battery pack is shown in Table 8 on the following page.

Properties	Magna/JCI	Electrovaya
Nominal Voltage	355V nominal	355V nominal
Energy	9.7 kWh	12.1 kWh
Power	> 60 kW	> 60 kW
Mass	140 kg	195 kg
Configuration	96 cells in series	96 cells in series
Cell Capacity	27 Ah	33 Ah
Thermal Management	Liquid: 4 zones	Liquid: 4 zones
On-Board Charger Module	Not included	Included

Table 8: Specification comparison Magna to Electrovaya

The package design reused the existing Ram 1500 PHEV high-voltage coolant heater and contactor box components. It created a new assembly for the battery modules, battery controller and Cell Sensor Controller modules. This new package configuration permitted the battery system to be assembled external to the battery case and dropped in as a completed assembly, with only electrical wiring and coolant lines needing to be attached.

Each old battery pack went through a decommissioning process where all parts were either scrapped or reused. The lithium-ion cells were recycled. The following parts were reused:

- Contactor box
- Battery control module
- Individual cell sensor controllers
- High-voltage coolant-heater for the battery thermal loop
- Key interface connectors, such as power battery connector with HV safety interlock
- Manual service disconnect

FCA US LLC had earlier planned to reuse the Electrovaya battery management system and software. The hardware was compatible with the same number of lithium-ion cells and differed only with 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 repackaged the shell for improved manufacturability and ease of service.

High-Voltage Storage System Manufacturing

Magna created an in-house manufacturing plan that incorporated an automotive approach with a documented, illustrated assembly sequence and controlled assembly to ensure good manufacturing practices were followed for all packs. This approach enabled an identical process to service and rebuild packs, should repairs 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 to the internal control boards. These were designed, built to automotive production standards, simplified assembly, ease of service and trouble-shooting.

Magna delivered four complete pack assemblies for re-installation to a reduced Chrysler Town & Country PHEV fleet of four vehicles. Four additional packs were built and held in reserve by Magna for potential field service.

Validation of the Updated Design

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 battery 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 designs 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 and an ABC-150 Battery power cycler to exercise the battery pack and verify the correct software level and function. The purpose was to validate 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.

The completed packs were installed into Chrysler Town & Country PHEV minivans and resulted in very few integration issues.

2.4 Plug-in Hybrid Electric Vehicle Thermal Management

Description

Plug-in electrification of the automobile brought some unique challenges for the vehicle thermal management system, including the addition of new systems, as well as modifications to existing systems. Today's high-voltage power electronics components, including inverters, DC-to-DC converters and battery chargers, use 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.

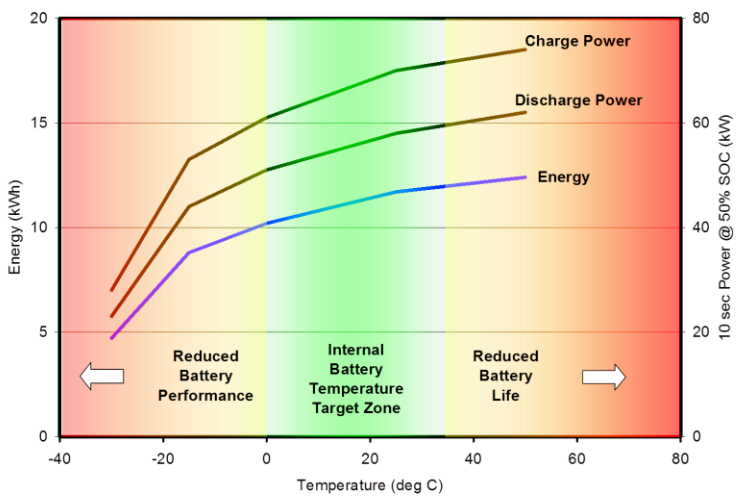


Figure 7: Temperature effects on HV battery cells

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 the thermal management system employed.

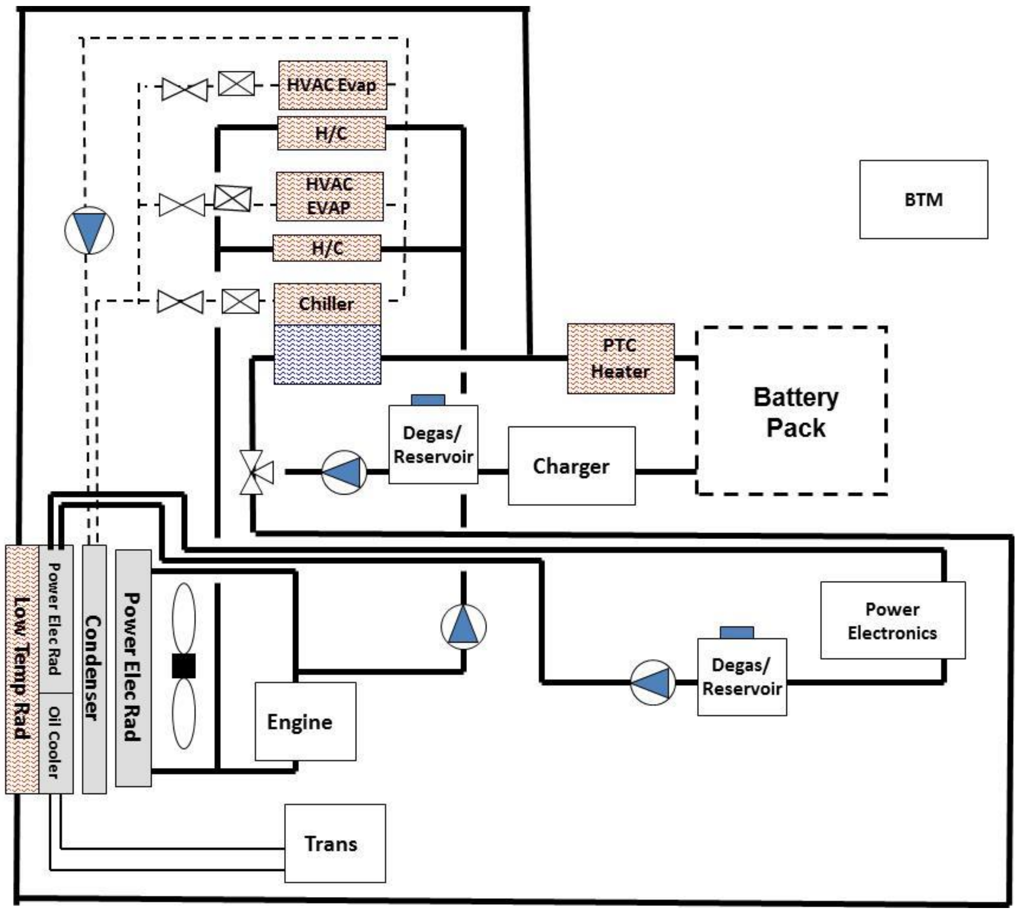


Figure 8: Thermal-management circuits

Goals and Targets

The system was calibrated to meet the following HV battery temperature control specifications:

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

Vehicle Implementation

The main components relevant for the battery-cooling loop were:

- 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 below shows the HV battery thermal system vehicle integration.

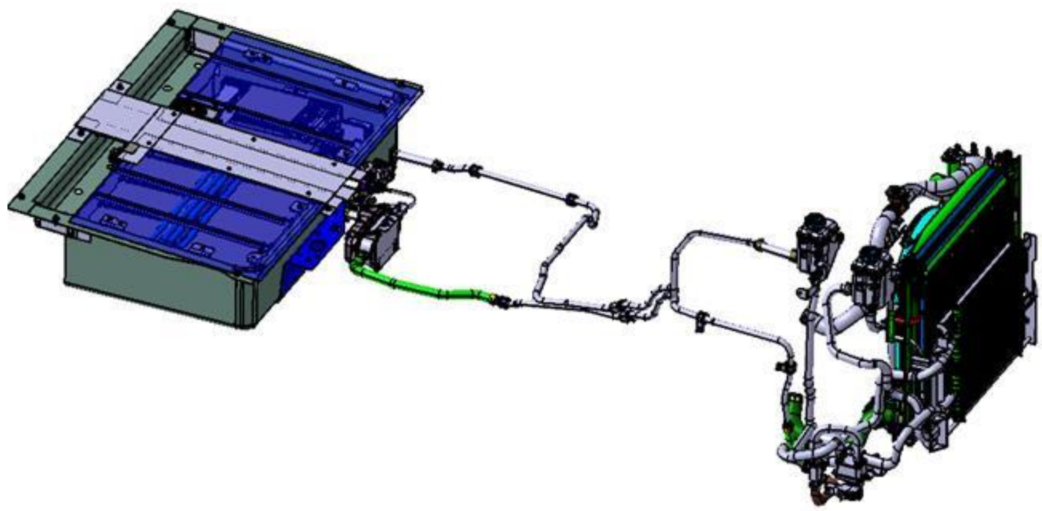


Figure 9: High-voltage storage system thermal system integration

2.5 Charging Systems

Description

A major goal of the PHEV vehicle is to use electric grid power to charge the high-voltage 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 module (EVSE) module (permanently connected to the utility grid). All charging complies with the requirements of SAE J1772™. The minivan 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 battery model
- Create flexibility of plug-in charging times at grid connection

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 on the next page 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	240 VDC
Expected Frequency	50 to 60 Hz
Cooling Temperature	70°C
Ambient Temp Range	-40 to 85°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 part of the deployment of the Ram project vehicles (DOE Award Number DE-EE0002720) that took place prior to the minivan deployment.

Design, Implementation and Integration

The charging function was achieved through the use of the original integrated charger module inside the original high-voltage storage system housing, as shown in Figure 11 below.

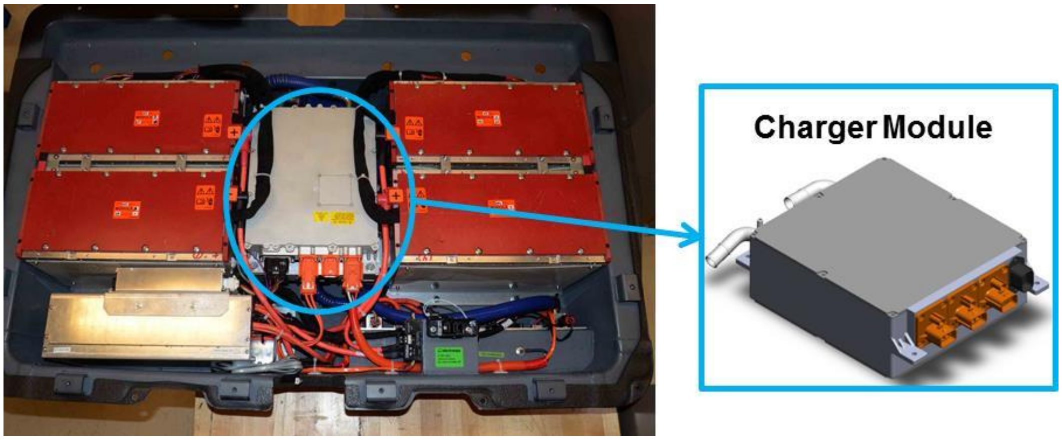


Figure 11: Vehicle charge box integration

Development and Testing

The development of charging systems was conducted in progressive levels throughout the program. During Phase I, simple manual charging was used to develop basic charging controls, software and hardware. Scheduled charging was subsequently developed. The processes for manual and scheduled charging 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 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

Scheduled Charging was developed in Phase II. It allows a delayed start of charge cycle, which is shown schematically in Figure 13 below.

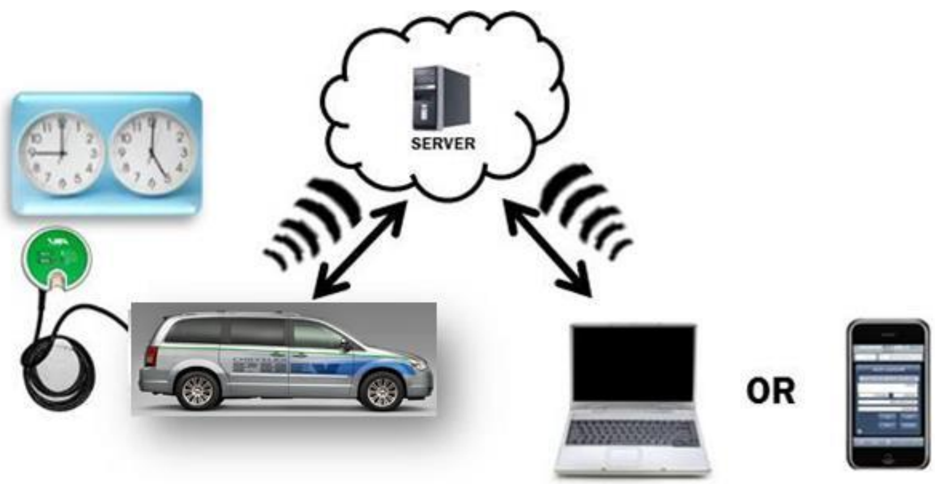


Figure 13: Scheduled Charging communication diagram

The procedure for the manual charging sequence is followed first. The consumer then schedules the following specific parameters (Figure 14 on the next page) 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%

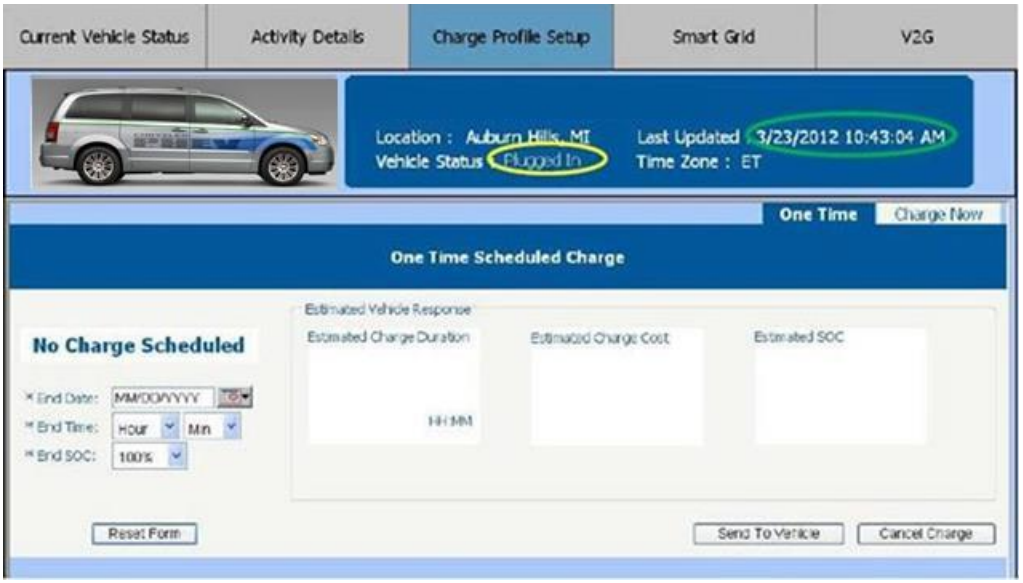


Figure 14: Scheduled Charging parameter inputs

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.

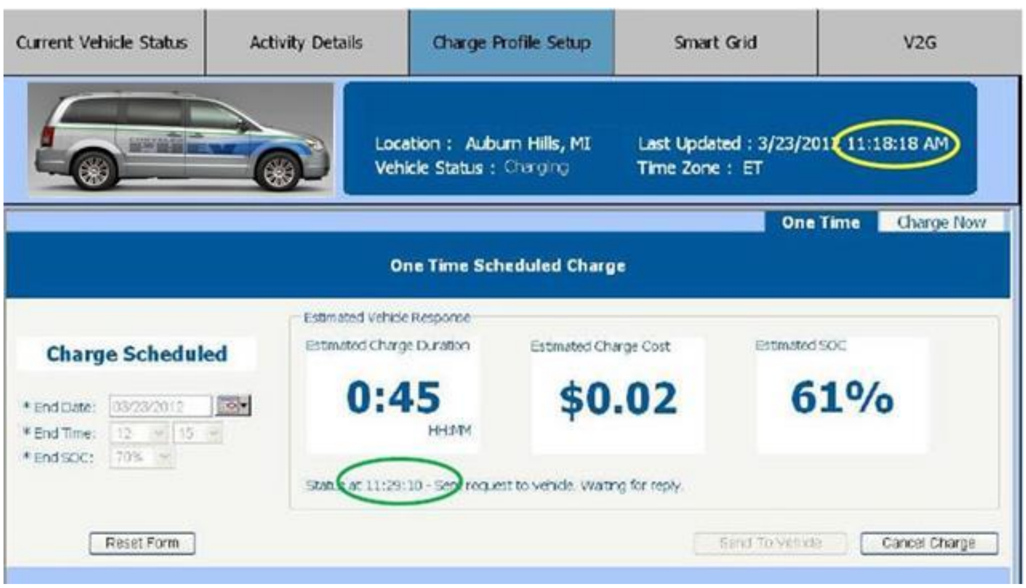


Figure 15: Scheduled Charging parameter outputs

2.6 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.

2.7 PHEV System Operations

The demonstrated PHEV operations consist of three operating modes: normal propulsion, plug-in charging and AC power generation modes. Figure 16 illustrates the basic control architecture at the vehicle level.

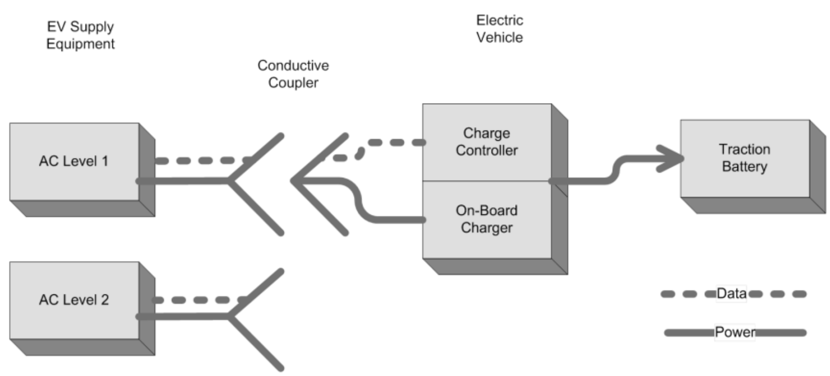


Figure 16: Vehicle level control architecture

Under normal usage, it is expected that the driver will recharge the battery pack from the electrical grid at every opportunity. The default charge-depleting range is about 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 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 is 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.

To clearly present the vehicle's PHEV system operations to the driver, the vehicle HMI on the dashboard system was modified to include such information. Figure 17 below shows the redesigned dashboard inside the PHEV minivan.

Figure 17: Redesigned dashboard in the Chrysler Town & Country PHEV

2.8 Transmissions and Motors

The Two-Mode Hybrid Transmission System (shown in Figure 18 on the next page) is a full hybrid system that enabled significant improvement in composite fuel economy, while providing uncompromised performance. In city driving and stop-and-go traffic, the vehicle could be powered either by the two electric motors, 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.

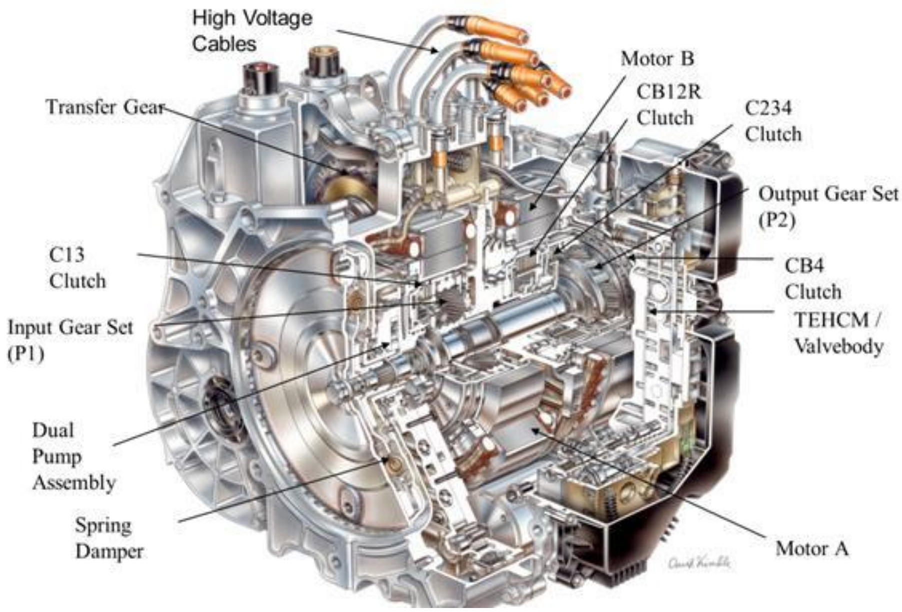


Figure 18: Two-Mode Hybrid transmission system

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 FWD transmission configuration. Motor A produced 52 kW power and 187 Nm torque. Motor B produced 57 kW and 300 Nm torque.

The Two-Mode Hybrid – 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. Additionally, four fixed gear ratios enable parallel hybrid operation with the electric motors used only for boosting and braking.

2.9 Internal Combustion Engine (ICE) and Flex-Fuel Optimization

The demonstration PHEV minivan features the 3.6-liter Pentastar V-6 engine design with double-overhead cams (DOHC), narrow included valve angle, cylinder head and high-flow intake and exhaust ports. This design, combined with dual independent cam phasing, allows optimum volumetric and combustion efficiency over the full speed and load range, resulting in an exceptional, flat torque curve. Ninety percent of the engine's torque is delivered from 1,600 to 6,400 rpm, which will provide customers with outstanding drivability and responsiveness – all without the need for premium fuel.

The FCA vehicle control system detects the ethanol content based on fueling and engine torque estimation. The engine controller optimizes the operation accordingly. Meanwhile, the hybrid controller adjusts the optimization based on the detected content of ethanol to maximize system efficiency and emission controls. To accommodate the use of an alcohol-based fuel, hardware changes to the fuel system were needed. For instance, the fuel injectors were modified to deliver 40% higher flow rates in addition to being ethanol compatible.

3. PHEV Vehicle Integration and Testing Operations

3.1 Vehicle Development and Validation Timeline

This demonstration program involved testing of key components, sub-systems 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 19 below illustrates key development and testing milestones performed during the three stages of Phase I.

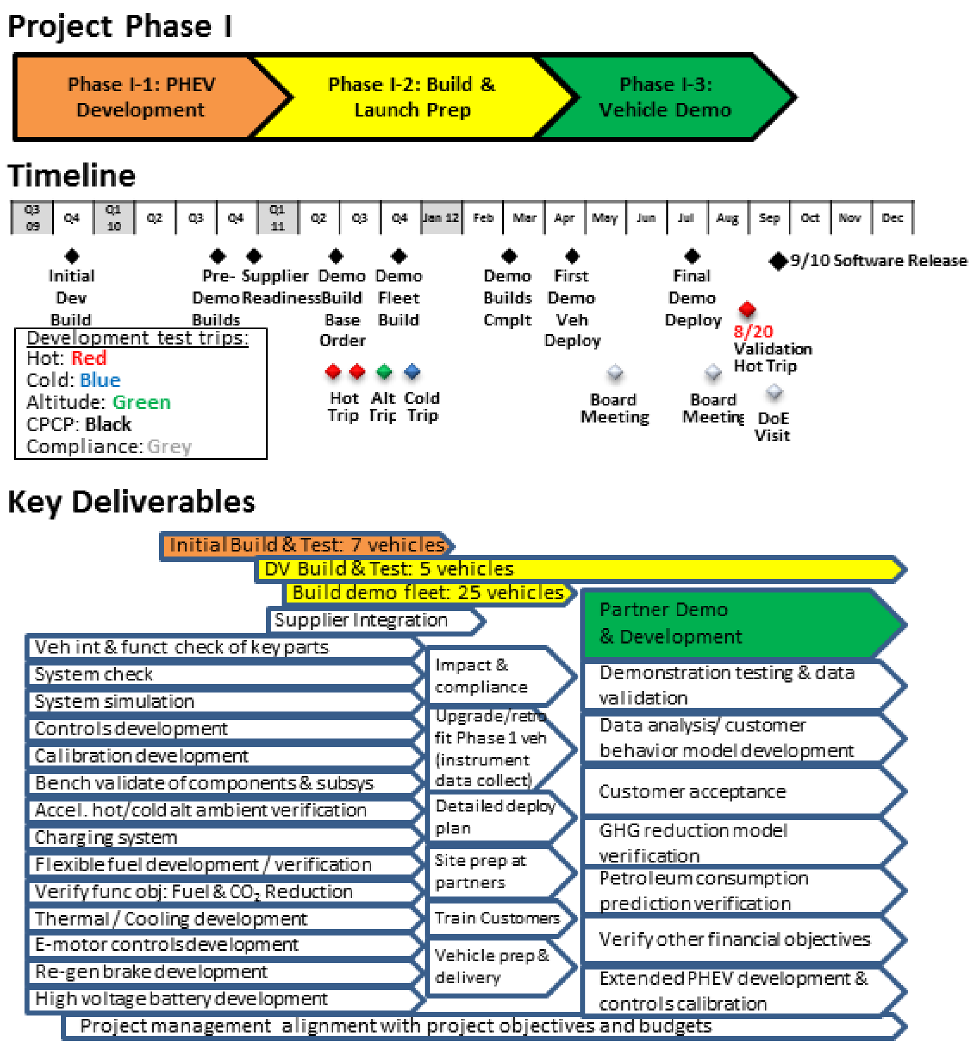


Figure 19: Phase I project timeline and key development milestones

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 20 below.

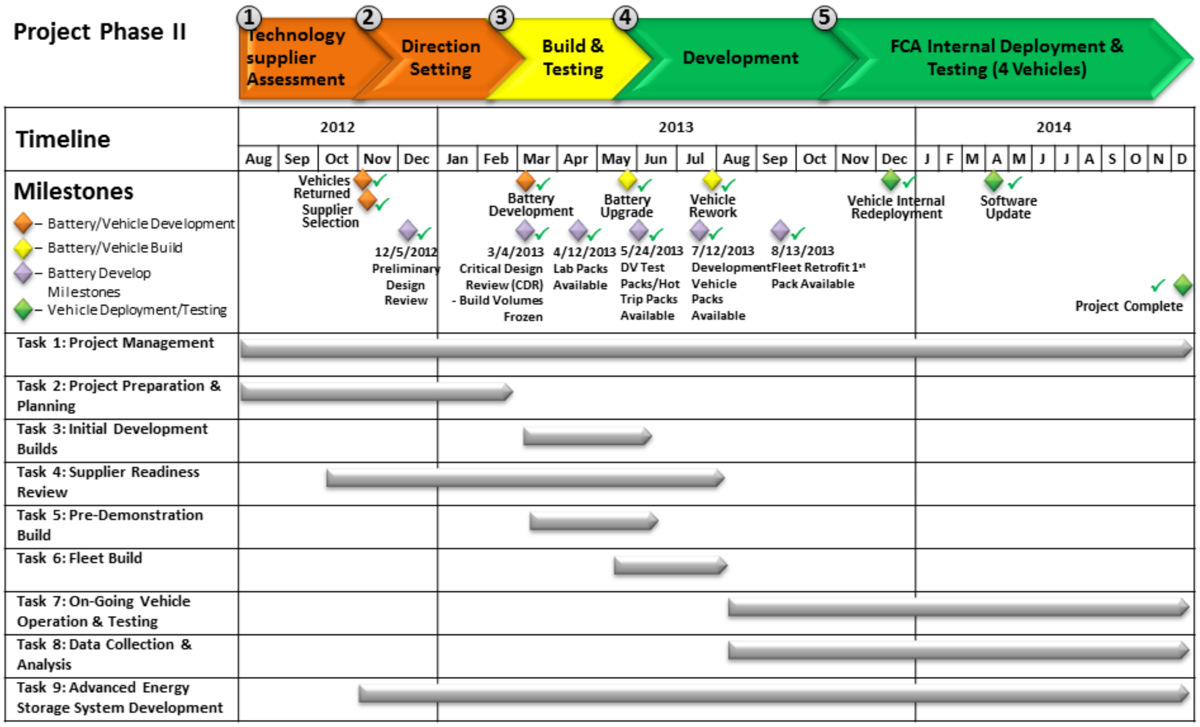


Figure 20: Phase II project timeline and key development milestones

3.2 Vehicle Integration Process

The development of Chrysler Town & Country 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 21 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.

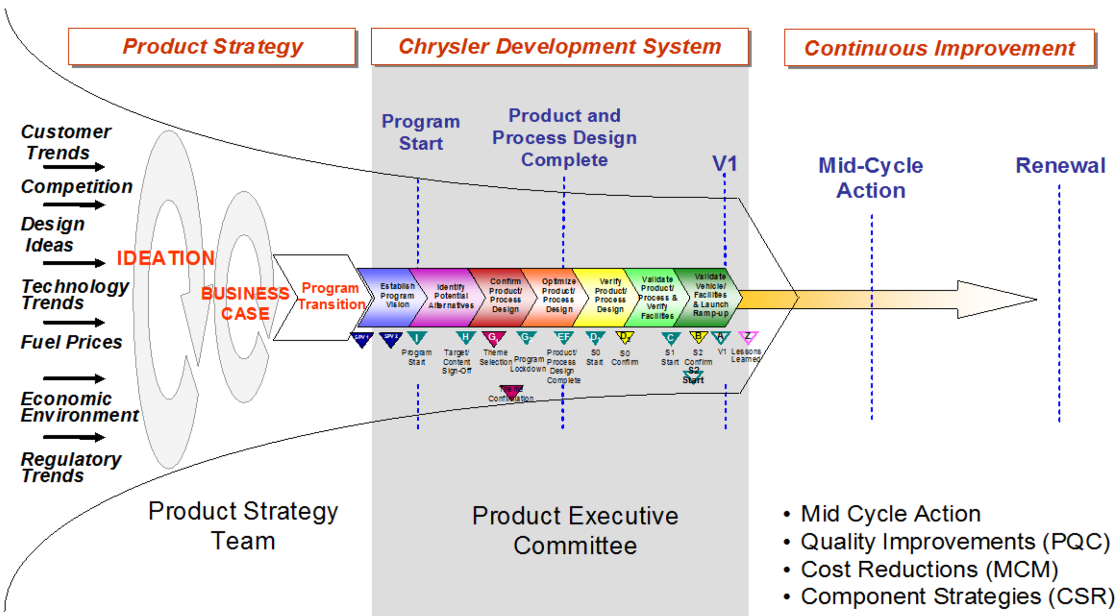


Figure 21: Chrysler Product Creation Process (CPCP) overview

Iterations of the CPCP process created an efficient vehicle integration solution for the demonstrated PHEV vehicle. Figure 22 on the next page presents the overall vehicle packaging for key elements.

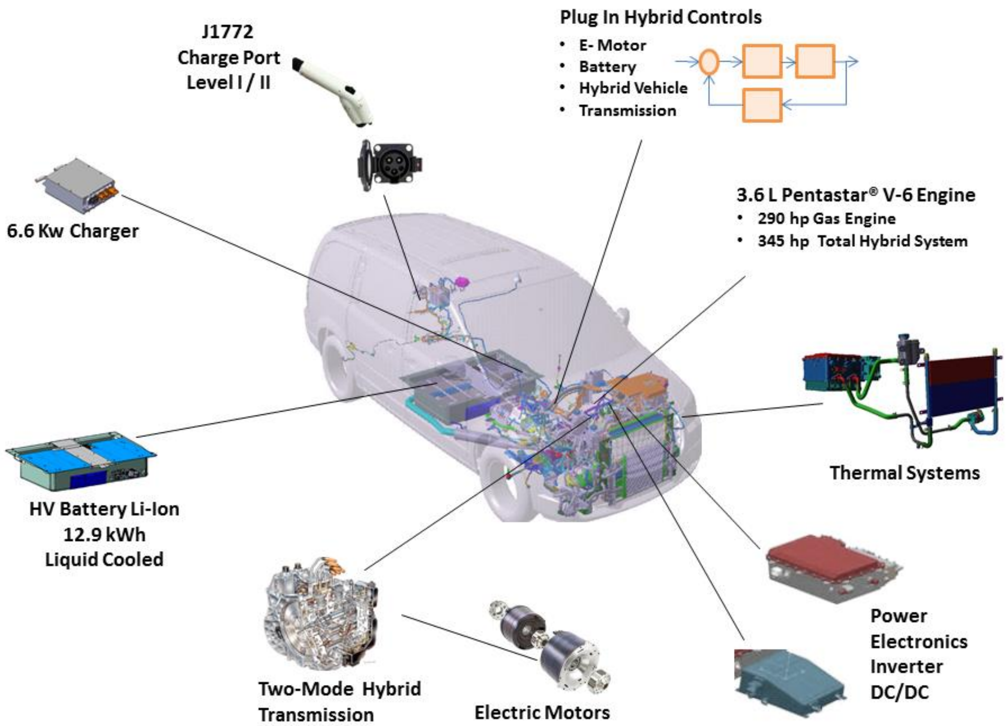


Figure 22: Vehicle integration overview for the Chrysler Town & Country PHEV

Table 10 below provides the technical specifications and key features of the demonstration PHEV minivan as a result of vehicle integration.

Technical Specifications			
HV Battery Technology	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)	53 mpg @ Charge Depleting	**EV Range (City)**	20 miles Phase I
Range	700 miles	**Transmission**	Advanced Two-mode hybrid
Brakes	Regenerative Braking System	**Capacity**	Towing: 1,000 lbs.
Max. Power	290 hp		
Key Features			
• Does not compromise any of the standard minivan utility • PHEV minivan with flex-fuel capability			

Table 10: Technical specifications and key features of demonstration PHEV minivan

3.3 Vehicle Testing Operations

3.3.1 High-Voltage Energy Storage System Testing Operation

During Phase I, seven battery packs were used for testing and 25 packs were used for demonstration PHEVs. Qualification and approval testing for cells, modules, battery management system, electrical and mechanical components, thermal management and mechanicals were conducted prior to packs release. 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, random vibration and other environmental testing (humidity, dust, shock, etc.). In addition, destructive testing of the battery modules with the integrated battery management system was completed.

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 23 on the next page. The target of 20 miles was met in Phase I as the result shows.

Phase I Federal Test Procedures Results

Objective	Target	Status	Procedure	R/G/Y
RANGE	EAER 20 miles	20.8 miles EAER testing results acheived	California Exhaust Emission Standards And Test Procedures, as amended December 2, 2009	GREEN
FUEL ECONOMY	Charge Depleting City -53 MPG (MS8004 Fuel)	**MS 8004 Fuel:** CD CITY Unadjusted: **55 MPG** CD Hwy Unadjusted: 46 MPG CS City Unadjusted: 25 MPG CS Hwy Unadjusted: 34 MPG **E85 Fuel:** CD CITY Unadjusted: 40 MPG CD Hwy Unadjusted: 36 MPG CS City Unadjusted: 18 MPG CS Hwy Unadjusted: 24 MPG	SAE J 1711, Date Published: 2010-06-08. For Test Procedure Guidance. *Reported FE is – Fuel used in CD mode/CD Distance	GREEN

Phase I Real World Results

	Chrysler Town & Country PHEV Status	Background
FUEL ECONOMY & Mileage Accumulation (Real World)	• Charge Depletion: Accumulated Miles – **23,027** – **City**: 33 mpg; **Hwy**: 37 mpg • Charge Depletion / Charge Sustaining: Accumulated Miles – **6,901 (CD) / 26,350 (CS)** – **City**: 26 mpg; **Hwy**: 29 mpg • Charge Sustaining: Accumulated Miles – **66,636** – **City**: 21 mpg; **Hwy**: 28 mpg	• Data taken from 23 partner vehicles deployed throughout the United States • Total mileage : **122,913** (September 2012) • Vehicle fuel economy is based on customer usage and may not be representative of maximum potential fuel economy

Figure 23: Phase I EAER results

It should be noted that Phase II EAER results are not available since the four vehicles built for Phase II were used strictly for internal developmental activities, rather than fleet partner driving testing.

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. All the safety requirements were achieved through the testing modes outlined in Table 11 on the next page.

Speed	Mode	Criteria	Status 12/7/11
multiple	Sensor Threshold Tests	Deployment Strategy	Complete
50 mph	Left Rear 70% Overlap	FMVSS 301, 30	Complete
25 mph	Flat Frontal, UFUM	FMVSS 208	Complete
35 mph	Flat Frontal with BMBF	FMVSS 208, 301, 305	Complete
30 mph	Left Angular	FMVSS 301, 30	Complete
33.5 mph	Moving Deformable Barrier (Left)	FMVSS 214, 301, 305	Complete
35 mph sled	Belted Male Driver	FMVSS 208	Complete
30 mph	Right Angular	FMVSS 301, 30	Complete
30 mph sled	Unbelted Female Driver	FMVSS 208	Complete

Table 11: List of Chrysler Town & Country PHEV FMVSS test modes

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

Testing	Targets and Results	Standard
Emissions	Tier II Bin 5 Compliance (with both MS8004 & E85 Fuels) • Complete and passing for T2 Bin 5 with MS 8004 fuel • E85 testing yielded acceptable levels without margin. Based on testing with prior development test vehicles, SULEV TP emissions requirements were met for 50F test and SC03 cycle.	CFR Title 40: Part 86 – Control of Emissions from New and In-Use Highway vehicles and Engines; Subpart S.

Table 12: PHEV emissions 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 fleet partner activities were always aligned with 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 call between the fleet partner managers and 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, as 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 Chrysler Town & Country demonstrated the ability to significantly reduce petroleum consumption and GHG emissions. To ensure a robust assessment, FCA US LLC deployed 25 minivans 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 24 below illustrates the locations and quantities of all demonstration PHEVs deployed in Phase I. The deployment period for Phase I was from April 2012 to September 2012.

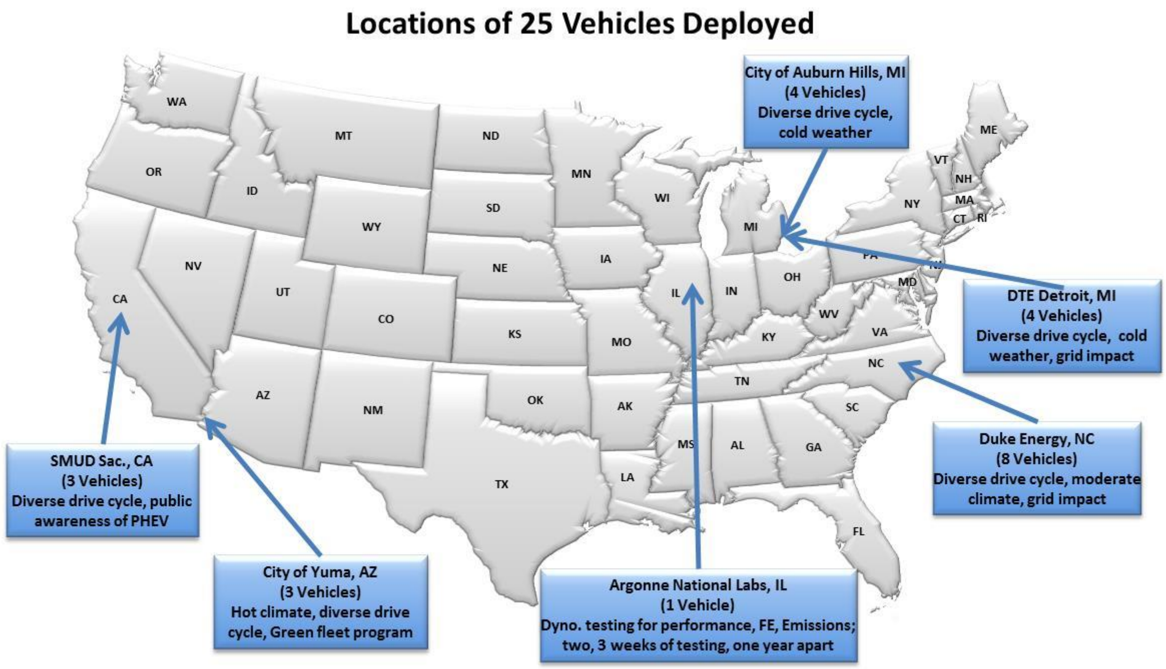


Figure 24: Phase I demonstration PHEV deployment location and quantity details

Details of partner vehicle deployment status regarding date of deployment in Phase I are shown in Table 13 below.

Phase I Partners	# of Vehicles	Date Deployed
FCA US LLC	2	4/12/2012
City of Auburn Hills	4	4/12/2012
DTE Energy (Detroit Edison)	4	4/13/2012
Duke Energy	8	4/18/2012
City of Yuma	3	4/23/2012
SMUD (Sacramento Municipal Utility Dept.)	3	4/24/2012
Argonne National Labs	1	7/27/2012
Total	25	

Table 13: Phase I 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, with an eye on exploring the limits of the system and revealing opportunities for further optimization. Key system monitoring data collected were battery data (voltage, current and temperature), engine operation, and power consumption (including SOC, fuel usage and GHG estimation for each trip). Driver profiling is an attempt to understand how a customer uses a particular vehicle and its functions. 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; and driver aggressiveness (which contributes to power consumption, including vehicle power distribution and pedal distribution).

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 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 25 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 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

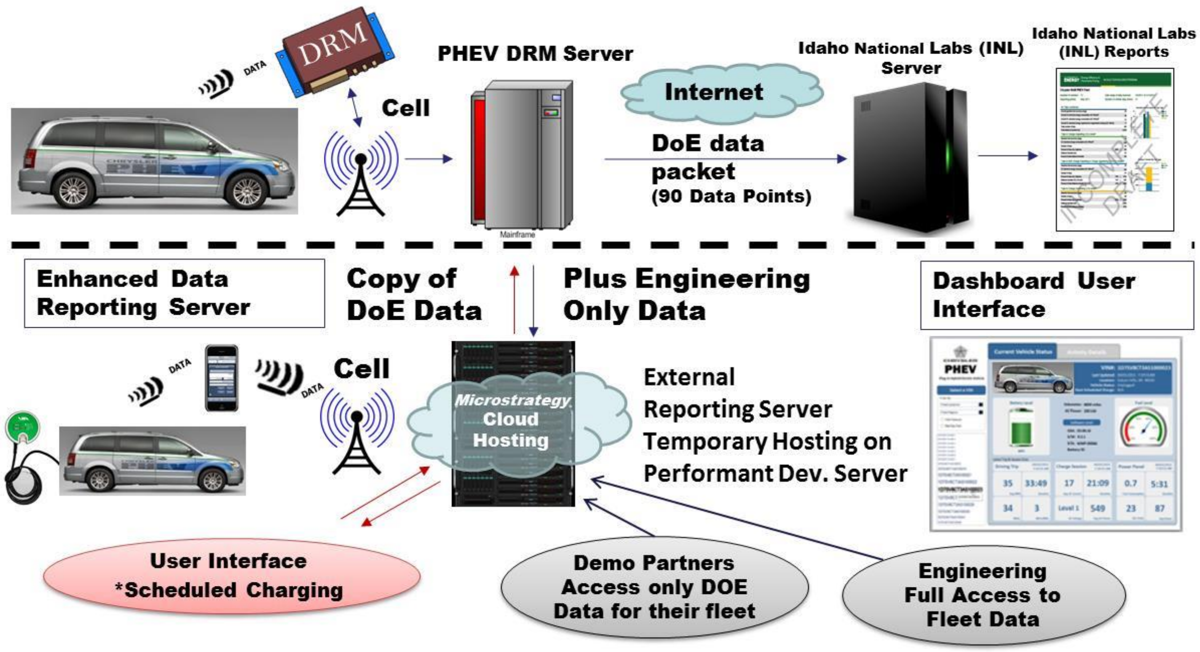


Figure 25: PHEV demonstration data acquisition process

Acquired Data Path (continued reference to Figure 25 above):

- Data passed through the cellular system to a dedicated PHEV server database
- Specific DOE data was passed 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 plug-in hybrid electric minivan. 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, both 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 14 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 14: 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 the Phase I for a portion of the deployed vehicles are shown below in Figures 26 through 28. The data period ranges from April 2012 to September 2012.

All Trips Combined

Overall gasoline fuel economy (mpg)		26
Overall AC electrical energy consumption (AC Wh/mi)[1]		50
Overall DC electrical energy consumption (DC Wh/mi)[2]		39
Overall DC electrical energy captured from regenerative braking (DC Wh/mi)		28
Total number of trips		10,624
Total distance traveled (mi)		122,913

Trips in Charge-Depleting (CD) mode

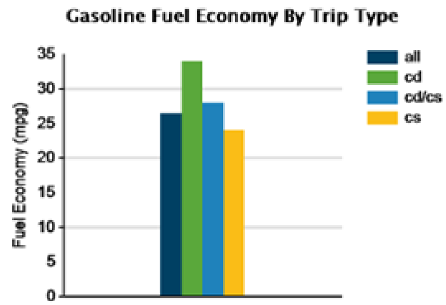
Gasoline fuel economy (mpg)		34
DC electrical energy consumption (DC Wh/mi)[4]		182
Number of trips		3,649
Percent of trips city | highway	93%	7%
Distance traveled (mi)		23,027
Percent of total distance traveled		19%

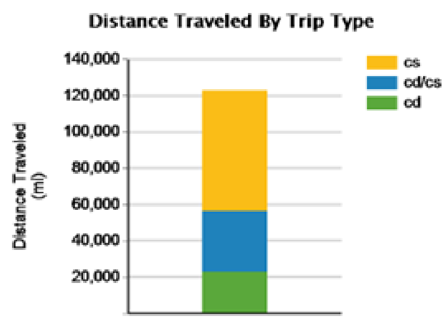
Trips in both Charge-Depleting and Charge-Sustaining (CD/CS) modes

Gasoline fuel economy (mpg)		28
DC electrical energy consumption (DC Wh/mi)[6]		30
Number of trips		1,458
Percent of trips city | highway	71%	29%
Distance traveled CD | CS (mi)	6,901	26,350
Percent of total distance traveled CD | CS	6%	21%

Trips in Charge-Sustaining (CS) mode

Gasoline fuel economy (mpg)		24
Number of trips		5,517
Percent of trips city | highway	87%	13%
Distance traveled (mi)		66,636
Percent of total distance traveled		54%





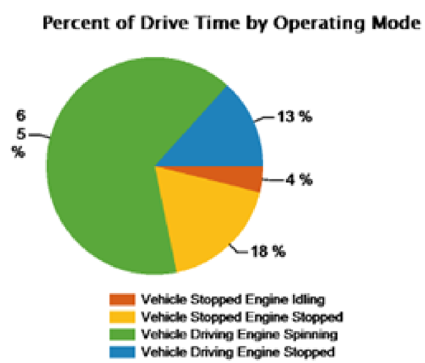
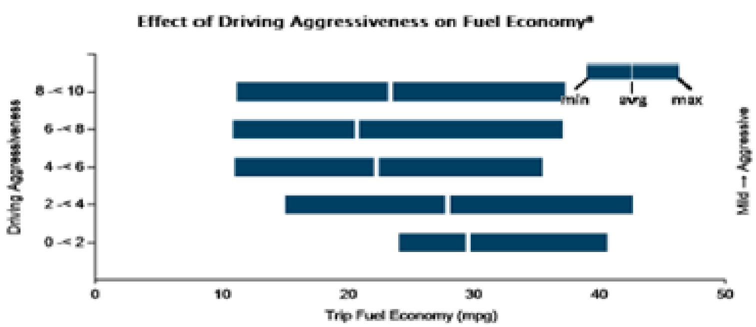


Figure 26: Phase I overall fleet deployment statistics

Trips in Charge-Depleting (CD) mode	City	Highway
Gasoline fuel economy (mpg)	33	37
DC electrical energy consumption (DC Wh/mi)	199	135
Percent of miles with internal combustion engine off	13%	2%
Average trip Agressiveness	5.7	3.5
Percent of miles with air conditioning selected	77%	72%
Average trip distance (mi)	5	23

Trips in both Charge-Depleting and Charge-Sustaining (CD/CS) modes		
Gasoline fuel economy (mpg)	26	29
DC electrical energy consumption (DC Wh/mi)	51	19
Percent of miles with internal combustion engine off	9%	1%
Average trip Agressiveness	5.2	2.7
Percent of miles with air conditioning selected	72%	81%
Average trip distance (mi)	11	53

Trips in Charge-Sustaining (CS) mode		
Gasoline fuel economy (mpg)	21	28
Percent of miles with internal combustion engine off	11%	1%
Average trip Agressiveness	5.5	2.7
Percent of miles with air conditioning selected	81%	87%
Average trip distance (mi)	6	50



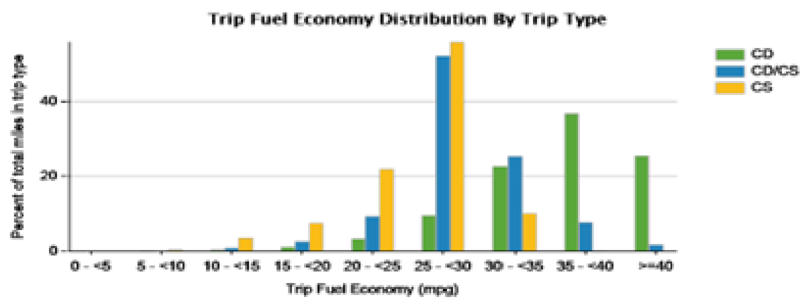


Figure 27: Phase I overall fleet statistics (continued)

Plug-in charging

Average number of charging events per vehicle per month when driven		8
Average number of charging events per vehicle per day when driven		0.6
Average distance driven between charging events (mi)		110
Average number of trips between charging events		9.5
Average time charging per charging event (hr)		2
Average energy per charging event (AC kWh)		5.5
Average charging energy per vehicle per month (AC kWh)		45
Total number of charging events		1,116
Number of charging events at Level 1 | Level 2	74	1037
Total charging energy consumed (AC kWh)		6,113
Charging energy consumed at Level 1 | Level 2 (AC kWh)	416	5,697
Percent of total charging energy from Level 1 | Level 2	7%	93%
Average time to charge from 20% to 100% SOC (hrs) Level 1 | Level 2[3]	13	3.5

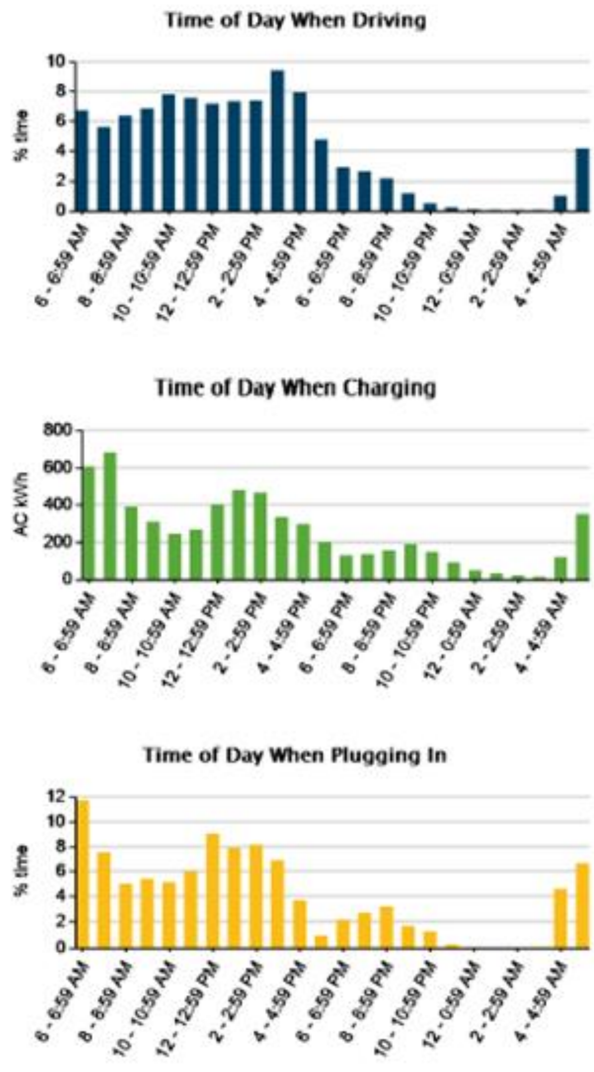


Figure 28: Phase I overall fleet statistics (continued)

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.

Mileage data gathered for each partner in Phase I is shown below in Figure 29 below. The variation in mileage represents the results from diverse geographical locations and types of driving cycles (city and highway).

The demonstration PHEV deployed at Argonne National Lab was primarily for charging equipment research and the vehicle was not extensively driven for the deployment period. Therefore, the recorded mileage data was insignificant and it is not presented here.

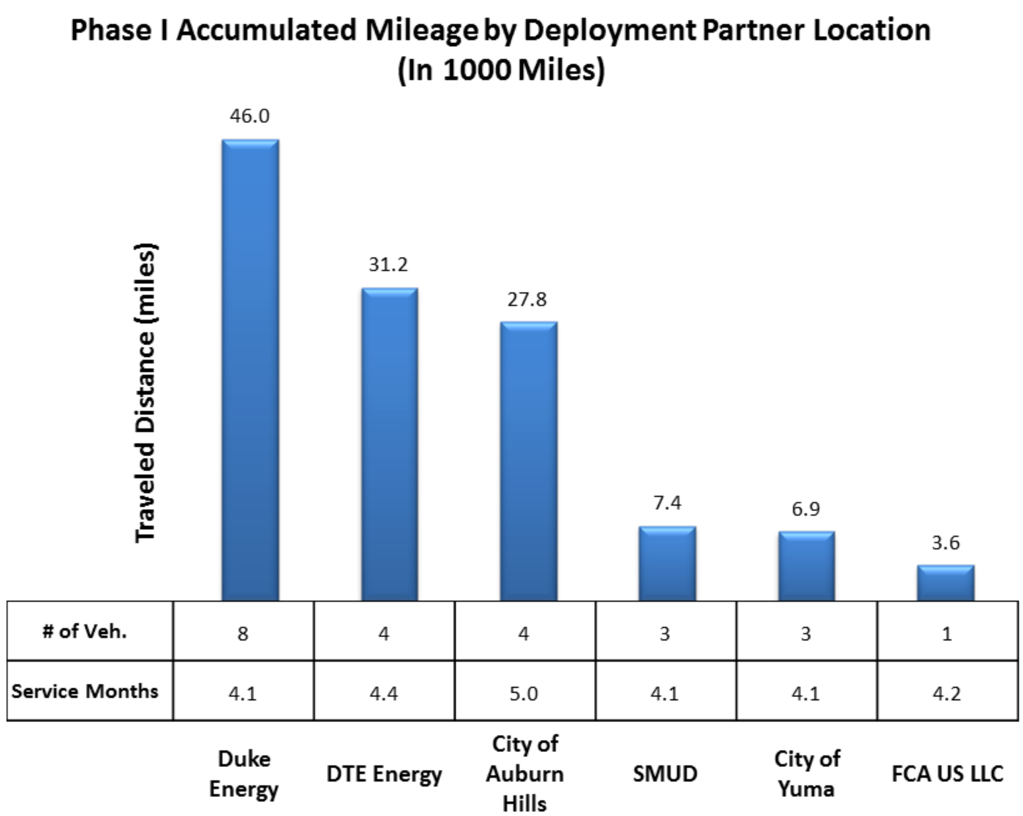


Figure 29: Mileage driven by fleet partners

In addition, charging activity data (shown in Figures 30 and 31 below) was gathered during fleet deployment and utilized for system optimization and determination as a result of charging habits by the end users.

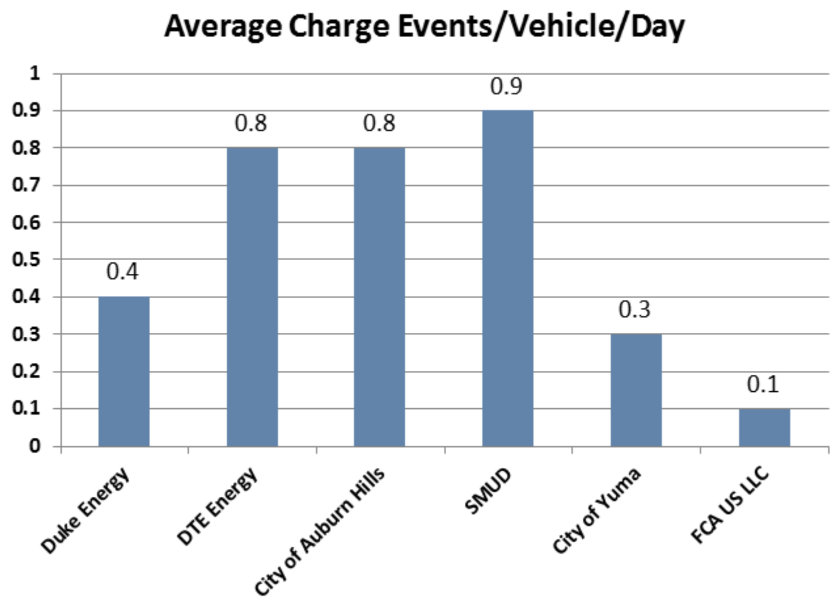


Figure 30: Charging activity statistics by fleet partners

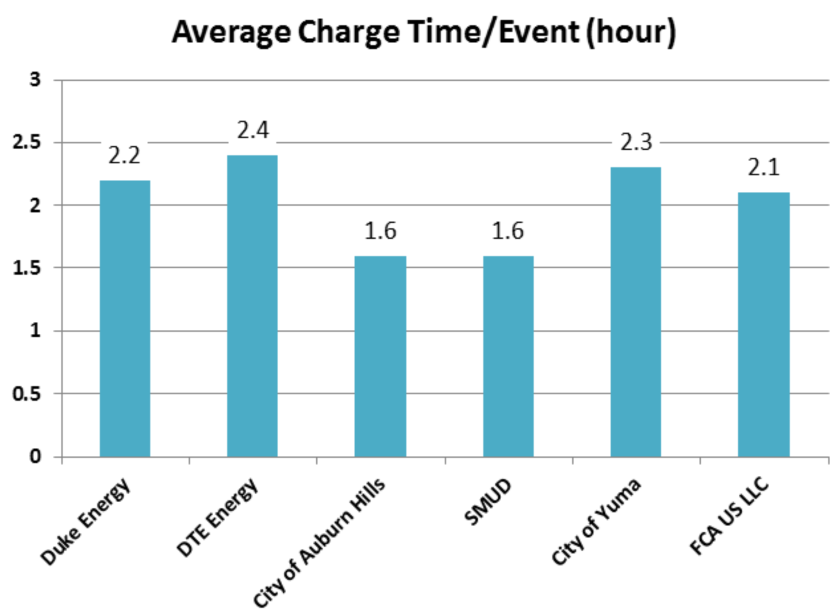


Figure 31: Charge time per event statistics by fleet partner

Data gathered during the deployments was evaluated to determine the charging habits of the end users. Three states of HV battery 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 battery pack charge was depleted throughout entire trip
- CD/CS: Trips when the battery pack 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 battery pack was not depleted during the trip. Vehicle operation is similar to a HEV in this mode

Figure 32 below shows the amount of the time spent in each of the state of HV battery discharge and charge at the times of deployment for Phase I.

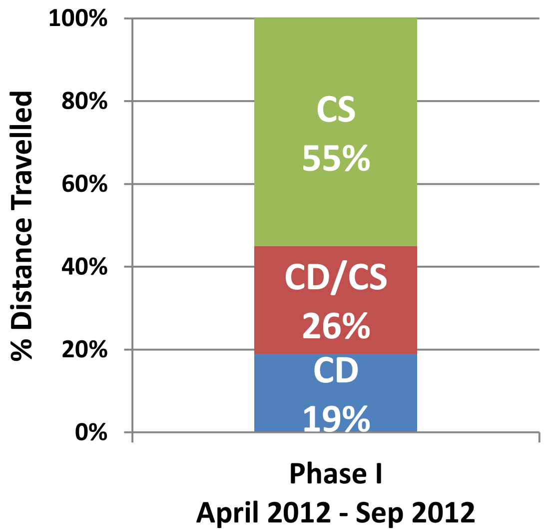


Figure 32: Phase I fleet distance traveled comparison in CD, CD/CS & CS modes

5.4 Internal Development Fleet Results

After Phase I demonstration, four minivans were fitted with upgraded energy storage systems. They were redeployed at the FCA US LLC engineering center for internal development activities. The deployment period for Phase II was from December 2013 to December 2014.

These four minivans were used for the following major areas of development for PHEV characteristics. The engine was replaced in two vehicles with the series production PHEV design-intent 3.6L Atkinson cycle engine.

Engine Auto Start/Stop and Drivability

- Auto starts and stops were performed to develop a base calibration for the Atkinson cycle engine
- In addition, there was an emphasis on cold auto starts to develop fueling strategy to support emissions development
- Basic drive tests performed with the new engine to determine effects to engine speed-control calibrations under various vehicle maneuvers to ensure engine would function sufficiently to perform emissions work noted below

Emissions

The two minivans retrofitted with the Atkinson cycle engines were also used for PHEV emissions proof-of-concept development vehicles. Additionally, the vehicles were outfitted with aged 150,000-mile catalysts with various levels and combinations of Platinum Group Metals (PGM).

- **Goal:** This proof-of-concept emissions development was performed to determine if the Atkinson cycle engine could meet SULEV30 emissions standards without secondary air
- **Results:** The Atkinson engine met SULEV30 emissions standards with the elimination of secondary air system with selected level and combination of catalyst PGM loading. This serves as validation for the upcoming production minivan PHEV

In addition to the four Chrysler Town & Country minivans buit during Phase II of this project, two PHEV prototype concept vehicles for continued early development of PHEV systems for future FCA US LLC platforms were also built. These two production-intent vehicles were utilized for each of the tasks below from mid-June 2014 through mid-October 2014, when the first prototype vehicles became available.

Specific Production Intent Technical Advancements Realized

- First checks of the Engine Control Module (ECM) and Hybrid Control Processor (HCP) interface allowing for:
  - Successful main contact closure of the high-voltage energy storage system
  - Reception of signals at the HCP from the storage system controller
- Initial checks of transmission speed/torque relationship calibrations
- Electrically variable transmission e-motor position sensing in vehicle environment to optimize the timing of the delivery of electrical torque to the vehicle powertrain
- Initial verification of new ECM and HCP software interface for effective start/stop control

Production Prototype Build Enhancements

- Direct system troubleshooting experience to apply during the prototype builds
- Developed and validated tests for vehicle functional requirements
- Detailed review of the PHEV high-voltage energy storage system connectors
- The FCA engineering team developed and tested software tools, instrumentation and vehicle parameter monitoring systems

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 33 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.

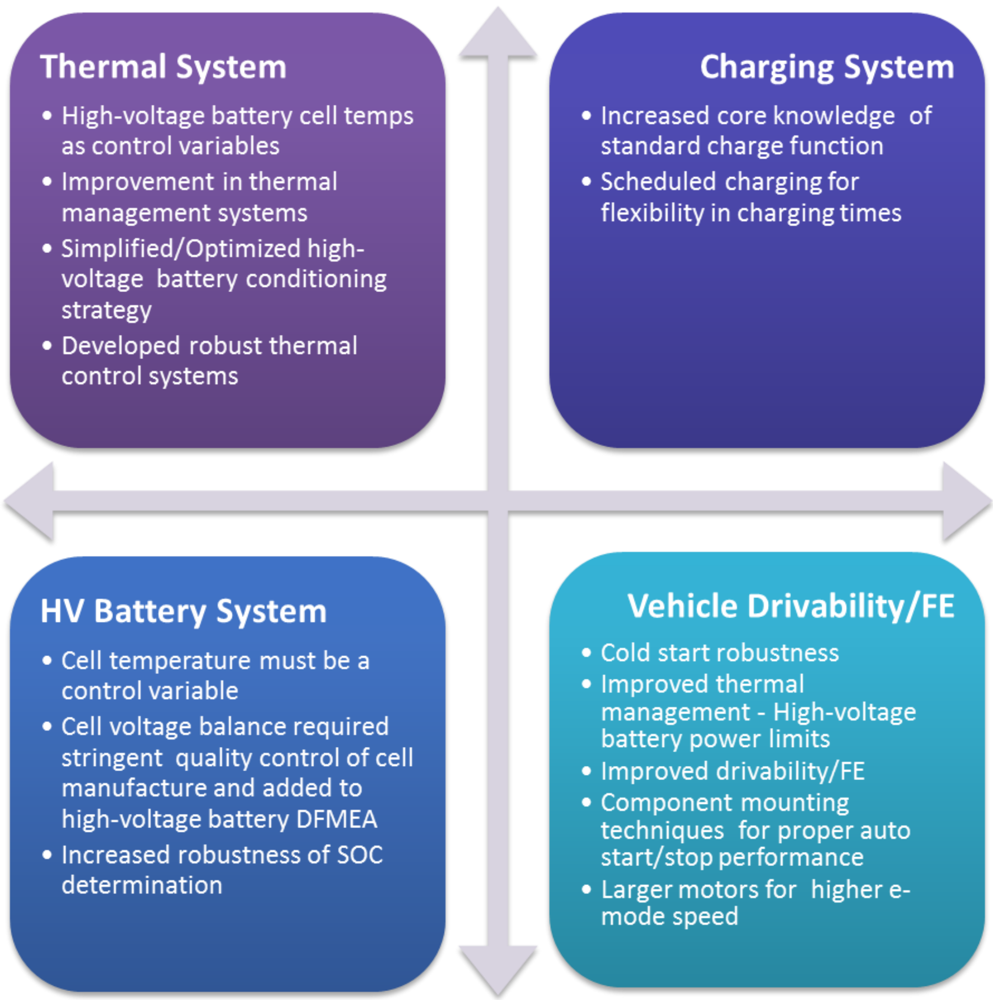


Figure 33: Lessons learning process from four major systems/areas

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 battery 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

Battery thermal state time

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

6.1.2 Charging System

Standard charging has increased core competency and design efficiency

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

- 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

6.1.3 High-Voltage Battery System

Cell temperature used as a control variable

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

SOC calculation strategy combining current/OC voltage

- SOC determination strategy utilized both current integration for energy removal and reference open circuit voltage to provide robust and accurate SOC level estimation
- Current integration was calculated using current values measured by current sensors
- Real-time open-circuit voltage was determined by a circuit model inside battery 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 and reduced stress on the HV battery

Improved drivability and fuel economy

- Gained insights into the effects of engine torque accuracy on system torque performance

- Used larger motors in the Two-Mode Hybrid system to achieve higher vehicle speeds with engine off
- This reduced unnecessary battery usage and perceived torque disturbances during transient events, such as vehicle launch at a traffic light
- The fuel economy effect is difficult to isolate but directionally beneficial

Improved thermal management systems

- Refined torque path strategy to improve drivability with limited battery power limits

Identified proper mounting design

- 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, made them qualified to develop and demonstrate PHEV technology in this project.

6.2.1 Electrovaya Inc.

Major Tasks and Accomplishments

There were five major tasks for Electrovaya Inc. during the project. The details of each task and the related accomplishments are discussed in the Table 15 on the next page.

	Planned	Actual
Task 1	Demonstrate and evaluate advanced plug-in hybrid electric vehicle technologies across a range of geographic, climatic and operating environments, with an eye to accelerating the production and market penetration of PHEVs.	Thirty battery packs were delivered to Chrysler from September 2011 to March 2012.
Task 2	Battery system design and development of a lithium-ion SuperPolymer battery pack for the minivan PHEV.	The design included 96 lithium-ion cells (35Ah each) connected in series to create a 355V system. Cells were grouped into modules for mechanical retention and electrical control. Pack capacity was 12 kWh. A liquid cooling system was designed that was able to maintain temperature uniformity within 4°C throughout the pack.
Task 3	Delivery of seven prototype development battery packs for testing and verification by Chrysler engineering.	Seven prototype battery packs were built: five were delivered to Chrysler, while the remaining two were kept at Electrovaya.
Task 4	Delivery of 25 demonstration battery packs for use in the Chrysler minivan PHEV demonstration fleet	Twenty-five minivan PHEV’s were built using the battery packs from Electrovaya. The vehicles were distributed for testing to six different fleet operators throughout the United States.
Task 5	Analyze and aggregate data from the demonstration vehicles.	Drive data from vehicles shows an actual average fuel economy of 26 mpg, a significant improvement over the 20 mpg (EPA combined city/highway) fuel economy for a conventional 2012 Chrysler Town & Country minivan.

Table 15: Electrovaya's summary of project goals and accomplishments

6.2.2 MAHLE Behr USA

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 the Table 16 below.

<table>
<tr><th></th><th>Tasks</th><th>Accomplishments</th></tr>
<tr><td>Task 1</td><td>Review interface of the battery thermal management system with the high-voltage battery supplier's internal thermal management system. Design a capable vehicle-level thermal system.</td><td>Updated the minivan 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 US 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</td></tr>
<tr><td>Task 2</td><td>Enhance and refine system understanding of battery thermal management on a PHEV and of the interaction of the various systems.</td><td>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</td></tr>
</table>

Task 3	Model the thermal systems in BISS (Behr Integrated System Simulation) software 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 16: 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 minivan produced controllable traction forces from minimum to maximum under different battery temperatures, ambient temperatures and vehicle speeds, as shown in the “Demonstration PHEV Fleet Deployment” section
- 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 battery model

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

- Manual Charging
- Scheduled Charging

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
    - Four urban locations on the Southwest and East Coast, as well as the Midwest
- The deployment location climates ranged from northern Midwest cold, moderate mid-East Coast to hot in the Southwest

7.2 Development vehicle verification objectives

Confirm vehicle functional objectives

Phase I

- The fuel economy objective was improvement over the conventional minivan at 20 mpg combined city and highway. During Phase I:
    - The real-world fuel economy in CD mode combined city and highway was 34
    - The real-world fuel economy in CD/CS mode combined city and highway was 28
    - The real-world fuel economy in CS mode combined city and highway was 24
- Compliance to impact requirements was met, as noted in section 3.3.3

Demonstrate drivability and safety

Phase I

- The fleet partners drove the vehicles in excess of 122,000 total miles in six months total deployment time for Phase I
- There were no drivability safety issues

Phase II

- Performed basic drive tests with the new engine to determine effects to engine speed control calibrations under various vehicle maneuvers
- Ensure engine would function as intended to perform emissions work noted below

Prove emissions targets can be achieved

Phase I

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

Phase II

- The Atkinson engine met SULEV30 emissions standards with the elimination of secondary air system with selected level and combination of catalyst PGM loading. This serves as validation for the approach that will be adopted for the upcoming production minivan PHEV

7.3 Fleet demonstration objectives

Profile vehicle usage

During Phase I, each vehicle was tracked on a monthly and aggregate basis using the Idaho National Labs DOE data as noted in 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
- Charging activities:
    - 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 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 daily work activities at the demonstration partners in Phase I for a total of over 122,000 miles

Confirm that conditions for viable mass productions can be met

- The base vehicles, MY 2011 Chrysler Town & Country minivans, were production-based vehicles
- The thermal system employed, though unique, was comprised of mass-production components
- The HV battery was prototype in nature, but production versions for other FCA US LLC production platforms (BEV Fiat 500e and upcoming minivan PHEV)
- Used the lessons learned from the HV battery in this vehicle for successful series-based integrations

Quantify the benefits to customers and to the nation

- 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

1. 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.

7.4.2 Project Patents

List of patents applied during the entire project funding period is shown below in Table 17 below.

Patent Application USPTO Serial No.	Patent Application Title	File Date at USPTO	DOE Program
13 / 593,589	Electric-drive tractability indicator integrated in hybrid electric vehicle tachometer	19-Sept-2011	IDR – Minivan PHEV
13 / 160,561	Adaptive powertrain control For plugin hybrid electric vehicles	15-June-2011	IDR – Minivan PHEV

Table 17: List of project patents

7.5 Project Tasks Performed

Task 1- Project Management:

Project management established a clear communications protocol, through meetings and documentation to ensure that all partners were closely engaged and working together toward a shared solution. There were seven key tasks during the course of the project, which was managed through a robust governance structure. Project management ensured that milestone reports, as well as periodic technical status updates, program management plan (PMP) updates, and risk management plan (RMP) updates were provided in a timely manner to the DOE.

PHEV Development, Build and Launch

Task 2- Project preparation and planning:

Subtask 2.0- Project preparation and planning: Ensured that all pre-build requirements were established and executed

Subtask 2.1 – Supplier selection and component sourcing: Ensured that suppliers were selected for all components and were capable of meeting functional and timing requirements

Subtask 2.2 - Perform vehicle packaging: Ensured that 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 - Perform system simulation: Simulated key systems prior to vehicle builds

Subtask 2.6 - Develop test and build plans: Determined vehicle level test plans and build schedules

Subtask 2.7 - Order base vehicles: Ordered carrier vehicles for development vehicle and demo builds

Subtask 2.8 - Establish the material required date (MRD) for development vehicle build: Determined the MRD for the parts

Task 3- Initial development builds:

Subtask 3.0- Initial development builds: Procured all components required for the development vehicles

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

Subtask 3.2 - Prototype parts tooling and manufacturing: Kicked off tool orders for components and builds

Subtask 3.3 - Prototype parts logistics: Determined shipping method for all components

Subtask 3.4 - Material staging: Ensured parts were available and placed as required; perform vehicle builds

Subtask 3.5 - Verify basic drivability: Confirmed basic functionality required to drive vehicle

Subtask 3.6 - Conduct ride and drive event: Provided opportunity for key stakeholders to evaluate the vehicles and provide feedback

Subtask 3.7 - Conduct hot weather, cold weather and other development testing: Ensured that vehicles functioned as intended in hot and cold climatic conditions; this included engine, transmission and battery-pack bench testing

Task 4- Supplier readiness review:

Subtask 4.0- Supplier readiness review: Ensured suppliers were ready to deliver all components; 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 deliver 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:

Subtask 5.0- Pre-demonstration builds: Ensured that 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 cold development tests: Performed component and system level testing. Ensured that vehicles function 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 shipping method for all components

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

Subtask 5.8 - Material staging for demo 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

Task 6- Demonstration fleet build and customer readiness:

Subtask 6.0- Demonstration fleet build and customer readiness: Built the demonstration fleet of 25 minivans; ensured customers were prepared to receive fleet vehicles

Subtask 6.1 - Build demonstration fleet: Built demonstration fleet of 25 minivans and upgraded the development vehicles from Phase II with latest software

Subtask 6.2 - Prepare demonstration testing sites for vehicle delivery: Ensured daily charging strategy was established and communicated, and charging infrastructure was in place for all users. Also ensured that roles and responsibilities for usage and data collection and analysis at partners 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 the demonstration partners on vehicle operation and safety through on-site 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; they were given hands-on training by the mobile on-site demonstration support team. Many of the Chrysler dealers were already trained and certified to service production HEV vehicles

Subtask 6.6 - Deliver demonstration vehicles: Delivered demonstration vehicles to the selected demonstration partner locations

Vehicle Demonstration

Task 7- Ongoing Vehicle Operations:

Subtask 7.0- Ongoing vehicle operations: Ensured vehicles were utilized and functioned as intended

Subtask 7.1 - Vehicle operations: Vehicles were driven according to mileage requirements confirmed with the demonstration partner across pre-defined 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

Subtask 7.4 – Complete fleet vehicle demonstration: Returned and de-commissioned demonstration vehicles. Removed components for engineering analysis and/or recycling

Task 8- Data collection and analyses

Subtask 8.0- Data collection and analyses

Subtask 8.1 - Collect data: System monitoring and vehicle data were collected on an ongoing basis

Subtask 8.2 - Data analyses: The data collected from the demonstration vehicles was analyzed to verify the development objectives; data was shared with DOE to better understand vehicle behavior and gain insight on consumer usage patterns and vehicle performance

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 and GHG emission reductions

Advanced Energy Storage System Development

Task 9 – Advanced Energy Storage System Development

Subtask 9.1- Advanced battery development and integration: Integrated an advanced battery pack into the vehicle

Subtask 9.2 – Development vehicle build and testing: Performed vehicle development and software calibration updates

Subtask 9.3 – Internal Chrysler vehicle build and testing: A subset of vehicles from the demonstration fleet was retrofitted to accept the upgraded battery pack. The vehicles were engineering development vehicles

Subtask 9.4 – **Vehicle build and testing with upgraded powertrain and battery Technologies**: Two vehicles were added to the development fleet and retrofitted with advance electrified driveline transmission, battery pack, and power electronic technologies

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. They showcase FCA US LLC's commitment and ability to commercialize critical automotive technology. The lessons learned from this DOE project were utilized to facilitate the development the Fiat 500e BEV and the upcoming minivan PHEV program.

FCA US LLC also has strong track record in the energy/environmental arena and 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, 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.

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 minivans 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 minivans, 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 U.S. 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 (battery 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 34 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.

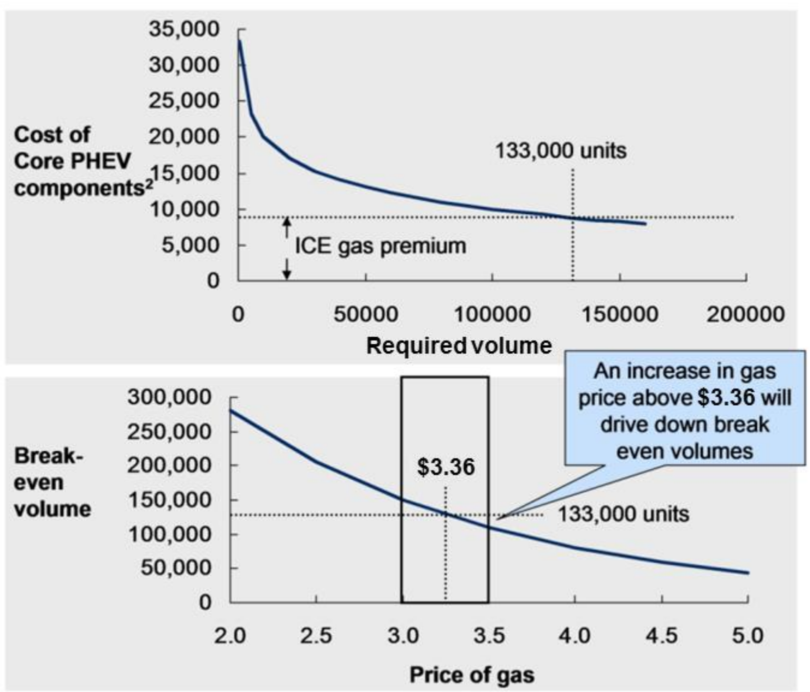


Figure 34: Estimated PHEV total cost of ownership break-even volume[1]

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

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

breakeven volume for production would reduce to 80,500 vehicles. In addition, if the 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 created FTE (Full Time Equivalent) U.S.-based high technology green jobs including FCA US LLC engineers, program management and technical support resources. The year-over-year numbers are shown in Table 18 below.

	2009 / 2010 Pre-Award 13 Months	2010 3 Months	2011 12 Months	2012 12 Months	2013 12 Months	2014 12 Months	2015 3 Months
FCA US LLC	12	19	22	14	3	3	1

Table 18: Year-over-year FTE hours

In addition to these jobs, there were many more jobs provided by the fleet partners, 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 to 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 19 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 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 19: Commercialization risks and mitigation plans

8.4 Estimated Impact on Fuel Consumption and GHG Emission

Through project demonstration of the Chrysler Town & Country PHEV minivans, great improvement of real-world fuel economy has been observed. Table 20 below provides the statistics of the average fuel economy under different vehicle operation models in Phase I.

Trips in Charge Depleting (CD) mode	City	Highway
Gasoline fuel economy (mpg)	33	37
DC electrical energy consumption (DC Wh/mi)	199	135
Percent of miles with internal combustion engine off	13%	2%
Average trip Agressiveness	5.7	3.5
Percent of miles with air conditioning selected	77%	72%
Average trip distance (mi)	5	23
Trips in Charge Depleting and Charge Sustaining (CD/CS) mode		
Gasoline fuel economy (mpg)	26	29
DC electrical energy consumption (DC Wh/mi)	51	19
Percent of miles with internal combustion engine off	9%	1%
Average trip Agressiveness	5.2	2.7
Percent of miles with air conditioning selected	72%	81%
Average trip distance (mi)	11	53
Trips in Charge Sustaining (CS) mode		
Gasoline fuel economy (mpg)	21	28
Percent of miles with internal combustion engine off	11%	1%
Average trip Agressiveness	5.5	2.7
Percent of miles with air conditioning selected	81%	87%
Average trip distance (mi)	6	50

Table 20: Phase I fuel economy statistics

Figure 35 on the next page illustrates the combined average city and highway fuel economy in Phase I. The EPA fuel economy ratings for the base gasoline 2011 Chrysler Town & Country are also shown in the chart for detailed comparison.

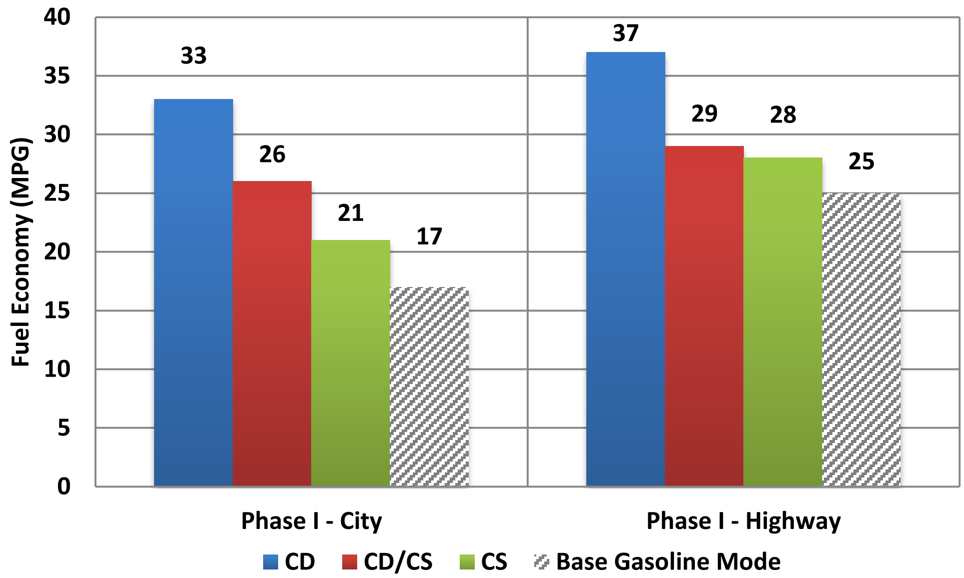


Figure 35: Phase I average city and highway fuel economy

In summary, the fuel economy improvements are as follows:

Phase I & II combined average fuel economy – City

- Charge-depleting mode – 94% increase versus base vehicle
- PHEV Charge depleting/Charge sustaining mode – 53% increase versus base vehicle
- PHEV Charge sustaining mode – 24% increase versus base vehicle

Phase I & II combined average fuel economy – Highway

- PHEV Charge depleting mode – 48% increase versus base vehicle
- PHEV Charge depleting/Charge sustaining mode – 16% increase versus base vehicle
- PHEV Charge sustaining mode – 12% increase versus base vehicle

Greenhouse gas (GHG) emission reduction can also be calculated according to fuel consumption reduction, because of 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 estimated annual greenhouse gas emission per vehicle in different driving modes can be calculated and are shown in Figure 36 on the next page.

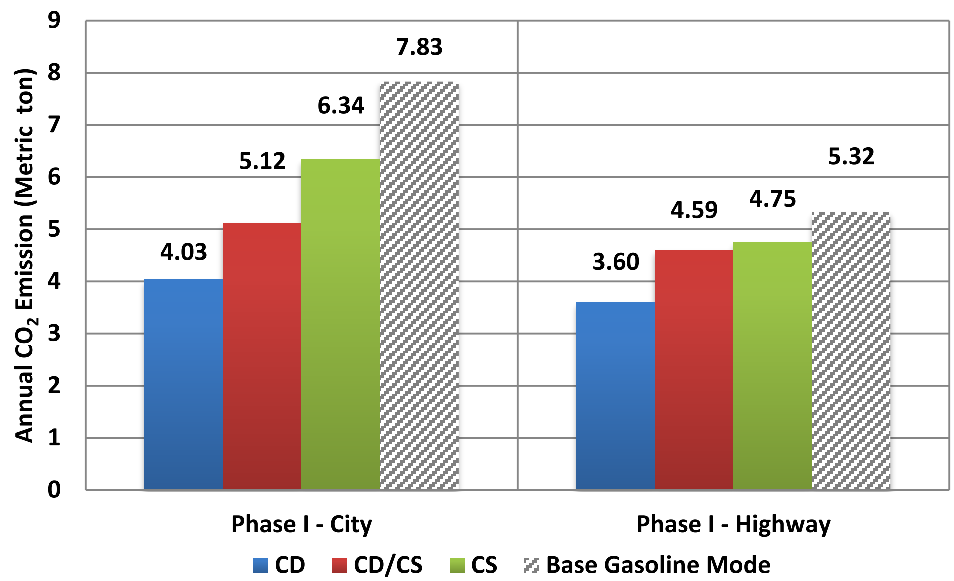


Figure 36: GHG emission per vehicle per year

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

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

- PHEV Charge depleting mode – 49% decrease versus base vehicle
- Charge-depleting/Charge-sustaining mode – 35% decrease versus base vehicle
- Charge-sustaining mode – 19% decrease versus base vehicle

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

- Charge-depleting mode – 32% decrease versus base vehicle
- Charge-depleting/Charge sustaining mode – 14% decrease versus base vehicle
- Charge-sustaining mode – 11% decrease versus base vehicle

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 developed PHEV minivans successfully demonstrated PHEV20 (20-mile equivalent all electric range) capability and flex-fuel (E85) compatibility with PHEV technology. 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.

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

The Chrysler Town & Country PHEV project met the key objectives and metrics outlined in the DOE funding opportunity DoE-PS26-08NT00360-01.

References List

[1] U.S. Department of Energy Technology Program, "Battery Test Manual for Plug-In Hybrid Vehicles, Revision 2, INL/EXT-07-12536," December 2010.

[2] G. DasGupta, "Electrovaya Summary Technical Document for use in DOE Application," Electrovaya Inc., May, 2009.

[3] U.S. Energy Information Administration (EIA), "Short-term Energy Outlook (STEO)," in *EIA Indipendent Statistics & Analysis*, January 2015.