Ford Motor Company
Final Technical Report on the Escape PHEV Demonstration Fleet

Ford Plug-In Project: Bringing PHEVs to Market
Demonstration and Validation Project

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Team Members:

- **American Electric Power**
- **Consolidated Energy**
- **DTE Energy**
- **Electric Power Research Institute**
- **Hydro-Quebec**
- **National Grid**
- **New York Power Authority**
- **New York State Energy Research and Development Authority**
- **Pepco Holdings, Inc.**
- **Progress Energy**
- **Southern California Edison**
- **Southern Company**

This program was undertaken in response to the US Department of Energy (DOE) Funding Opportunity Number DE-PS26-08NT00360-01 Plug-In Hybrid Electric Vehicle (PHEV) Technology Acceleration and Deployment Activity and involved a collaboration agreement between the Ford Motor Company, the Electric Power Research Institute (EPRI) and eleven North American utilities to demonstrate and evaluate plug-in hybrid vehicles and required charging infrastructure. Ford designed, developed and built 21 advanced technology Escape Plug-In Hybrids (PHEVs) using 2008 MY and 2009 MY Escape Hybrids (HEVs) as donor vehicles. Subsequently 15 of these vehicles were placed with utilities for demonstration: American Electric Power – 1 PHEV, Consolidated Energy – 1 PHEV, DTE Energy – 2 PHEVs, Hydro-Quebec – 2 PHEVs, National Grid – 1 PHEV, New York Power Authority – 1 PHEV, New York State Energy Research & Development Authority – 1 PHEV, Pepco Holdings Inc. – 1 PHEV, Progress Energy – 2 PHEVs, Southern California Edison – 2 PHEVs, Southern Company – 1. In addition 3 Escape PHEVs were provided to the DOE for demonstration and testing and 3 Escape PHEVs were tested and evaluated by the Ford Engineering teams in Michigan, the UK and China. The Ford Escape PHEV program consisted of four overlapping phases.

The results of this project, combined with other development work, led to the introduction of two mass production PHEVs in North America, the Ford C-MAX Energi and Ford Fusion Energi, to be followed by a Ford C-MAX Energi program in Europe. In addition, the Escape PHEV fleet successfully demonstrated the feasibility of bi-directional communication and supported EPRI's development of a fleet charging aggregator simulation tool to assess the potential for vehicle impact on the grid.

Program Goal

The goal of this program was to support efforts to identify a sustainable path toward the successful mass production of plug-in hybrid electric vehicles. This program was designed to demonstrate the feasibility of the technology and to prove-out the vehicle to grid interface.

Principal Program Objectives

Ford Motor Company Objectives:

- Validate and demonstrate plug-in technology on a new, more fuel efficient engine
- Progress battery and controls closer to production intent and demonstrate bi-directional communication and flex-fuel capability
- Design, develop and build 21 demonstration prototype vehicles for utility, government and internal testing
- Collect and analyze vehicle data in fleet operation to direct and augment future PHEV design efforts
- Demonstrate the benefit of using advanced information systems in an intelligent PHEV system

EPRI and Utilities Objectives:

- Support industry and electrification events with demonstration vehicles
- Conduct analysis of in-field results of the Escape PHEVs
- Complete a field demonstration of advanced Smart Meter communications
- Create a model studying plug-in vehicles as a grid resource

Executive Summary

This project is in support of our national goal to reduce our dependence on fossil fuels. By supporting efforts that contribute toward the successful mass production of plug-in hybrid electric vehicles, our nation's transportation-related fuel consumption can be offset with energy from the grid.

Over four and a half years ago, when this project was originally initiated, plug-in electric vehicles were not readily available in the mass marketplace. Through the creation of a 21 unit plug-in hybrid vehicle fleet, this program was designed to demonstrate the feasibility of the technology and to help build cross-industry familiarity with the technology and interface of this technology with the grid.

Since then, however, plug-in vehicles have become increasingly more commonplace in the market. Ford, itself, now offers an all-electric vehicle and two plug-in hybrid vehicles in North America and has announced a third plug-in vehicle offering for Europe. Lessons learned from this project have helped in these production vehicle launches and are mentioned throughout this report.

While the technology of plugging in a vehicle to charge a high voltage battery with energy from the grid is now in production, the ability for vehicle-to-grid or bi-directional energy flow was farther away than originally expected.   Several technical, regulatory and potential safety issues prevented progressing the vehicle-to-grid energy flow (V2G) demonstration and, after a review with the DOE, V2G was removed from this demonstration project.

Also proving challenging were communications between a plug-in vehicle and the grid or smart meter. While this project successfully demonstrated the vehicle to smart meter interface, cross-industry and regulatory work is still needed to define the vehicle-to-grid communication interface.

The important learning from this program includes:

Vehicle Results and Lessons Learned

Lessons learned from any program can include both successes and failures.   The successes validate design concepts and development work, providing confidence in the strategies developed and approach methodology. Failures highlight weakness or opportunities where additional work is needed for longer term robustness. This project has experienced successes and failures both of which are valuable outputs from this project.

The Escape PHEV prototype architecture was based on upgrades to the then existing production Escape HEV architecture. While Ford Engineering focused on the unique PHEV attributes of the prototype, charging and increased electric driving, they also followed rigorous internal engineering disciplines in updating the vehicles thermal management and structural/safety performance. This resulted in successful fleet performance during the more than three years in the field.

The focus of this project was to showcase PHEV technology for demonstration purposes only. The resources and time required to optimize fleet fuel economy were beyond the scope of this project. Despite this, the fuel economy experience by the fleet in aggregate underscored an important aspect to the mass production and market acceptance of electrified vehicles. A significant difference was noted between the fuel economies achieved in-field versus a Ford internal employee study and versus Argonne National Laboratory testing.   Analysis of the data revealed that the utilities were not charging the vehicles regularly and/or for the required period of time to reach full charge. Thus the utilities were not leveraging the full capabilities of the PHEV and were experiencing lower fuel economy numbers than anticipated because of it. If this project had been in the retail market, this would translate to a customer purchasing a product and then discovering they have bought more product than required. Given today's cost and package price-tags for high voltage batteries, this could hinder the market's acceptance of electrification.

NOTE: Ford recognizes the wide variety of customer usages and is working to offer different levels of vehicle electrification to meet these needs. Offering a complete line up of electrification from start-stop systems, to hybrids, to plug-in hybrids, to all-electric vehicles is Ford's customer focused approach toward encouraging electrified transportation solutions.

Human-Machine Interface (HMI) Lessons Learned

Development of the Escape PHEV demonstration fleet included extensive effort in the creation of strategies and software to enhance the driver-vehicle interface. The center navigation screen was updated with six separate PHEV specific displays. Some screens were focused on providing information to the driver depicting items like vehicle power flow or high voltage battery state of charge. Other screens were interactive and allowed the driver to control charging and calculate trip costs.

This project demonstrated that it is possible to charge a vehicle when electricity costs are at their lowest.

NOTE: Both the Ford C-Max Energi and Ford Fusion Energi now offer time-of-use capability which allows customers to charge their vehicles when it's least expensive.

PHEV Potential Efficiencies Lessons Learned

Analysis of the data indicated that for much of the time that the Escape PHEV fleet vehicles were using energy from the grid, the internal combustion engine was also running. This meant that even though plug-in energy was being employed to power the vehicle, energy from fossil fuels was also being consumed. Data indicated that this was a result of many factors including having the air conditioning or heat on, aggressive driving and/or the vehicle being driven at higher speeds.

Strategies to minimize fuel usage require controlling a broad range of parameters. From a vehicle design perspective, the electrification of power pack components can assist in minimizing internal combustion engine time on. When this fleet was built, electric air conditioning was not part of the Escape HEV architecture. Three of the vehicles were updated with electric air conditioning, demonstrating increased engine off times even at greater ambient temperatures. There are other equally critical vehicle design aspects to improving fuel economy including control strategies, calibrations, and weight management.

These factors were beyond the scope of this technology demonstration project but are being aggressively pursued by Ford in the development of production products.

NOTE: Both of the plug-in hybrids that Ford now produces offer electric air-conditioning, electric power steering, and electric cooling pumps which eliminate the need to run the internal combustion engine every time these components are needed. In addition, the on-plug preconditioning feature further reduces the use of the internal combustion engine (and thus fuel) by leveraging energy from the grid to bring the cabin and vehicle to the desired temperature before the drive begins.

From a driver aggressiveness and speed perspective, while the vehicle design cannot control this directly, the HMI can help inform the driver how certain inputs affect the realized fuel economy. Ford's electrified products include many visual coaching tools designed to aid the driver in adapting driving behaviors that deliver desired fuel economies.

Advanced Metering Communications Lessons Learned

While this project demonstrated that vehicle to smart meter communications are feasible, there are still significant issues with the advanced metering interface system. The process of vehicle-to-grid communication involves numerous functional and nonfunctional aspects. These aspects require cross-utility and cross-industry definition and standardization. As this communication handshake is being defined, higher level challenges such as data/network security, communication protocols and interoperability guidelines also need to be overcome. For issues such as 1) the mechanism for smart meter vehicle identification for billing purposes and 2) the ability for one vehicle to join multiple meters to be resolved in mass production solution terms, local codes and standards need to be evolved to a national level.

Final Comments

This report closes out the Escape PHEV Demonstration fleet part of the project that started October 2008 with Ford's response to the DOE Funding Opportunity Number DE-PS26-08NT00360-01. Since that time, Ford has logged more than 800,000 miles of demonstration Escape PHEV operation with ongoing data collection and analysis. 593,114 of the miles traveled were also monitored by Idaho National Laboratories (INL) who received vehicle data and then conducted their own independent analysis of fleet operations. INL's reports on the Escape PHEV demonstration fleet are publically available on the INL AVTA website with summary results from 19,514 charge events and 49,849 trip events (avt.inl.gov/phev.shtml). In addition, during this program Ford has successfully introduced two mass production PHEVs to the North American market. The Ford C-Max Energi was launched in November 2012 and is built at the Michigan Assembly plant. The Ford Fusion Energi was launched in January of 2013 and is built at Hermosillo Stamping and Assembly. Both vehicles are equipped with 7.6 kWh lithium-ion high voltage battery packs built at the Ford Rawsonville Plant in Ypsilanti Michigan and are capable of 120V (7 hrs) and 240V (2.5 hrs) charging. Lessons learned from this project helped support both these product introductions. Therefore, we thank you for this opportunity and we would certainly look forward to future collaboration opportunities.

The remaining objectives of this project are on track to be completed December 2013 and include two workstreams. The first workstream is a production validation evaluation being conducted by the DOE. Two production C-MAX Energi's are being supplied to the DOE for evaluation of the production technology. In addition, vehicle data will be made available to INL for analysis during this evaluation. The second workstream is targeted at demonstrating the benefit of using advanced information systems in an intelligent PHEV system. One of the Escape PHEVs built for the fleet demonstration has been updated to assess the potential for using advanced information systems to further enhance fuel economy, drivability, and other attributes. After these workstreams have been completed, a supplement to this report will be submitted to finalize the additional results (report submission target" 1st Qtr 2014).

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Glossary of Abbreviations

A/C	Air Conditioning
ABS	Anti-Lock Brake System
AMI	Advanced Meter Interface
AVG	Average
AVTA	Advanced Vehicle Testing Activity
BCM	Battery Control Module
BEV	Battery Electric Vehicle (All Electric)
CAN	Controller Area Network
CRADA	Cooperative Research and Development Agreement
CSV	Comma-Separated Values
CY	Calendar Year
DAP	Data Acquisition Platform
DOE	Department of Energy
DTC	Diagnostic Trouble Code
E-85	Ethanol (85% Ethyl Alcohol)
EATC	Electric Air Conditioning
EHB	Electro Hydraulic Braking
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EPA	Environmental Protection Agency
EPRI	Electric Power Research Institute
ERG	Emergency Response Guide
EVSE	Electric Vehicle Supply Equipment
FE	Fuel Economy
FEAD	Front End Accessory Drive
FMEA	Failure Mode and Effects Analysis
FMVSS	Federal Motor Vehicle Safety Standards
FOIA	Freedom of Information Act
GFCI	Ground Fault Circuit Interrupt
HDL	Hybrid Development Lab

HEV	Hybrid Electric Vehicle
HMI	Human Machine Interface
HV	High Voltage
ICE	Internal Combustion Engine
INL	Idaho National Laboratories
IP	Intellectual Property
IT	Information Technology
kW	Kilowatt
kWh	Kilowatt-Hour
Li-ion	Lithium Ion
LOS	Limited Operation Strategy
MAX	Maximum
MIN	Minimum
MPG	Miles per Gallon
MPGe	Miles per Gallon equivalent
MY	Model Year
NVH	Noise Vibration Harshness
PCM	Powertrain Control Module
PHEV	Plug-In Hybrid Electric Vehicle
PLC	Power Line Communication
QOR	Quit on Road
SBA	Simulator Brake Actuator
SOC	State of Charge
SQL	Structured Query Language
TSC	Transmission System Controller
V2G	Vehicle to Grid
V2H	Vehicle to Home
VMT	Vehicle Miles Traveled
VNG	Vehicle Network Gateway
VSC	Vehicle System Controller

Planning & Preparation

High Level Objectives

This project was undertaken as a part of the DOE's Industry – PHEV Technology and Deployment Activity multi-year program. The overall objective of the Escape PHEV project was to identify a sustainable pathway toward accelerated, successful mass production of plug-in hybrid electric vehicles. To address this challenge, a 21 vehicle demonstration fleet was developed to provide both laboratory and real world usage data. The information learned from progressive phases of technology roll-out was incorporated in subsequent vehicle builds. From Phase I to Phase II vehicles underwent updates in battery technology and PHEV-specific features in order to work toward the technology and designs necessary to demonstrate the potential for a production product. In Phase III and Phase IV the vehicles were demonstrated in the geographically diverse fleets of the project utility partners.

Figure 1: Escape PHEV Demonstration Vehicle

- Phase I Objective: Validate and demonstrate plug-in technology on a new more fuel efficient engine. Phase I was completed in the 2009 CY and included the engineering and development of 11 vehicles.
- Phase II Objective: Progress battery and controls closer to production intent and demonstrate bi-directional communication and flex-fuel capability. Phase II was completed in 2010 CY and included engineering, development and delivery of an additional 10 PHEVs with E-85 flexibility.
- Phase III Objective: Demonstrate plug-in technology in fleet operation and perform data analysis. Phase III was completed in 2011 CY and included the completion of the Ford/INL fleet data correlation and algorithm validation.
- Phase IV Objective: Continue vehicle demonstrations from Phase III and demonstrate advanced metering interface. Phase IV was completed in 2012 CY and included the completion of the utility demonstration project.

Collaborations

To accomplish the project goals, Ford Motor Company established partnerships with key stakeholders whose expertise was judged vital to the success of the program. For example, Southern California Edison brought not only utility knowledge, but also over 20 years of experience with charging electric vehicles. EPRI also played a vital role in the project by having the responsibility of forming working groups comprised of nationwide utilities to help fund and participate in the fleet demonstration. Through EPRI's efforts, 10 additional utilities joined the project for a total of eleven participating utilities:

1. American Electric Power
2. Consolidated Energy
3. DTE Energy
4. Hydro-Quebec
5. National Grid
6. New York Power Authority
7. New York State Energy Research & Development Authority
8. Pepco Holdings, Inc
9. Progress Energy
10. Southern California Edison
11. Southern Company

Each utility participated in the demonstration by incorporating 1-2 Escape PHEVs into their vehicle fleets for 3 years.

Figure 2: Escape PHEV Demonstration Fleet Deployment

Vehicle data was collected throughout the demonstration period. Ford Engineering kept 3 of the Escape PHEVs for testing and development work in Michigan, the UK and China. In addition, the DOE actively participated in the fleet demonstration by performing baseline testing on one fleet vehicle during 2009 and then continuing to evaluate the technology on three additional vehicles until year end 2012.

Variances from Original Plan

The program was completed largely as planned at the outset. However there were some changes that happened as a result of build timing, technology capabilities and opportunities to take advantage of emerging technologies that became more prevalent during the demonstration.

Vehicle Deployments

It was originally planned that all vehicles, including three vehicles identified for DOE testing in long term fleets, would be delivered by the 2nd half of 2009. While all vehicle builds were completed in 2009 and the majority of vehicles were delivered to project partners in 2009, the three DOE vehicles were not delivered until 2010. The principle issue related to this late start was the lengthy process of vehicle bailment negotiations between Ford and the DOE. In addition, Hydro-Quebec received two Escape PHEVs, one in 2009 and the other in 2010. With the delay, the project end date was extended from June 2012 to December 2012 in order to compensate for the late DOE fleet testing start.

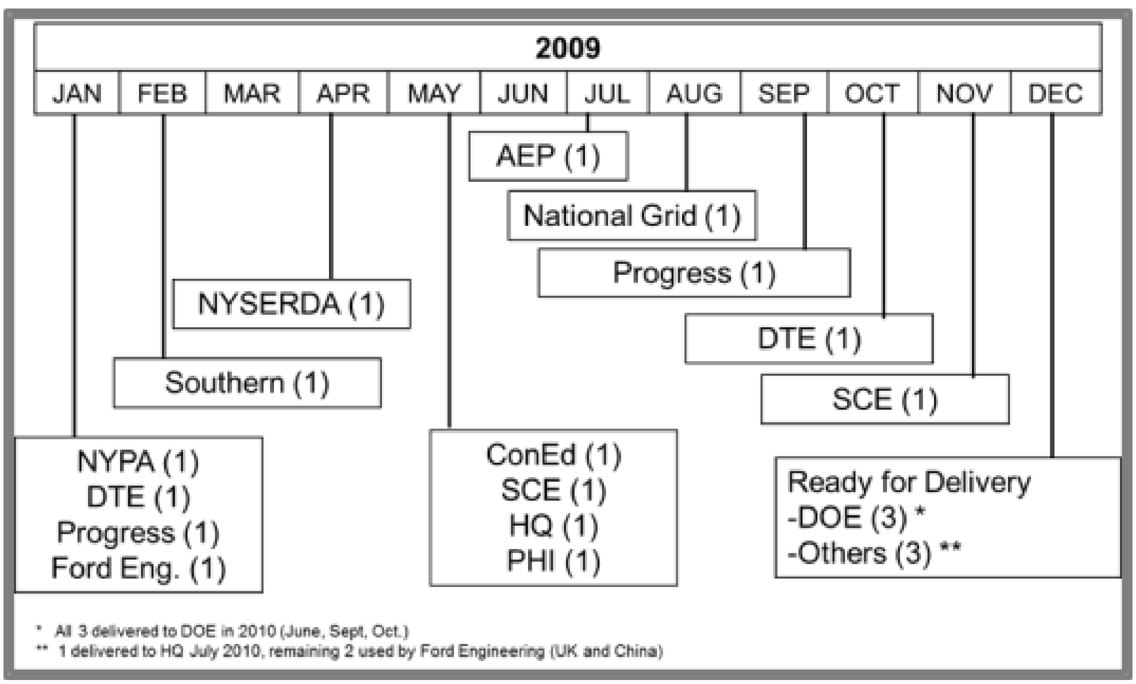

Figure 3: Escape PHEV Fleet Delivery

Bi-directional Power Flow Demonstration Canceled

Vehicle development and demonstration of vehicle to home (V2H) and vehicle to grid (V2G) had originally been planned for one of the Escape PHEV fleet vehicles. V2H is when the vehicle supplies power to the home and there is no connection to the grid (either grid power is unavailable or it has been disconnected). V2G is when the PHEV uses excess power from its high-capacity Li-ion battery to supplement grid utility loads (a connection to the grid exists). In the process of developing one vehicle for the demonstration of V2H and V2G, the Ford Engineering team identified several issues which prevented resolution within project timing and contract constraints. Some of the key issues identified at the time were:

- No off-the-shelf bi-directional inverter meeting engineering and utility requirements was available
- While an off-board inverter combination did not meet desired goals for a public demonstration, back-to-back charger & inverter in-vehicle combinations were large and would consume the rear cargo area, would add weight to the vehicle and were expected to reject heat into the cabin
- A review of regulations indicated potential violations if connected to a building
- SAE J1772 did not support Vehicle/Utility V2H connectivity
- There was no established communication protocol and no clear understanding of ancillary service requirements, regulations and codes to determine communication requirements
- Safety concerns existed including improper building wiring

During a May 13, 2009 meeting, Ford reviewed these issues with the DOE and a decision was reached to cancel the V2H/V2G demonstration. Note: Two-way communication capability was implemented on all vehicles (vehicle-to-meter and meter-to-vehicle).

SAE J1772 240V Charging Compatibility

While the original project requirements specified 120V charging capability, as the project progressed, the advantages of 240V charging were becoming apparent in the marketplace (faster charging) and standards such as SAE J1772 began to be further refined. Utility partners participating in the Escape PHEV demonstration program were asking for their Escape PHEV to be updated so they could demonstrate charging with the SAE J1772 compliant charging stations which were becoming more readily and publically available. Ford Engineering developed a minimal cost approach to making the upgrade which fell within the project spending constraints and the DOE agreed to the program amendment. Updates were begun in 2nd QTR 2011 with DOE vehicles given first priority for the upgrade.

Figure 4: SAE 1772 Compatible Charge Port

The J1772 upgrade was designed to allow the vehicle to charge using a Level II (240V) EVSE as well as to maintain the vehicles Level 1 (120V) charging capability. Since the charge output was limited to 1.4kW, the charging rate did not change between Level I and Level II charging. Project timing and cost constraints did not allow for the packaging, software and cooling strategy development work which would have been required for the design and development of a new, larger charger.

Figure 5: Revised 120V Charge Cord

Ford Engineering created J1772 upgrade kits to be installed at Ford dealerships. The kit consisted of a J1772 charge port assembly, J1772 compatible Level 1 (120V charge cord) and charger assembly which included low voltage charger cooling fans. In the original PHEV design the cooling fans were powered directly by the 120V outlet. With the J1772 connector, however, there was the possibility of the fans meeting either a 120V or 240V outlet. Since there were no available fans that could be powered by both 120V or 240V, the fans needed modification so they were no longer connected directly to the wall outlet.

Figure 6: 1.4 kW Charger with Revised Cooling Fans

To minimize the cost impact, the upgrades were cascaded in a sequenced approached. Utilities were responsible for arranging installation with Ford dealers and returning take-off components in a timely manner. A J1772 upgrade kit was sent to the Ford Dealer identified to complete the upgrade. Then the Ford dealership removed the 120V charge port / charger assembly and returned it to Ford Motor Company using the prepaid shipping label. The dealer would then install the J1772 upgrade kit components while Ford Motor Company would modify the returned take-off components to be included in the next kit to be sent to the next vehicle.

While the upgrade enabled the Escape PHEVs to be charged at public charging locations while continuing to allow charging at home, the upgrade was not fully SAE J1772 compliant. Level II EVSE charging was now possible, however, communications with the EVSE were limited. For example, the EVSE current capacity signal was ignored by the charger. This was judged acceptable for this restricted use, controlled application. The upgrade was completed by 1st Qtr 2012 on all Escape PHEVs except #8.

Increase of All-Electric Driving Speed Capability

The principle objectives of this project were to demonstrate plug-in hybrid technology and bi-directional communication with the utility interface. The Escape PHEV fleet was designed as a demonstration of customer duty cycles related to plug-in electric vehicles. The vehicles used in this demonstration were not optimized to provide the maximum potential fuel economy. However, as the program progressed, Ford Engineering began to review the maximum all-electric speed capability of the Escape PHEV vehicle. Since the demonstration vehicles had been based off of the Escape HEV's, maximum commonality with this architecture had been sought to minimize component changes and meet project cost and timing requirements. Thus, the target all-electric speed was established at the same level as that of the Escape HEV, 40 mph.

Ford Engineering had two primary concerns with increasing the maximum all-electric speed. The first was transaxle durability at this speed which had not been validated. No test data existed regarding failure modes and effects at these speeds. The second concern regarded the lack of a transaxle calibration for engine pull up/down shudder at higher speed. Based on the amount of engineering work required to increase the Escape PHEV all-electric speed, it was determined that updating the entire fleet would push this project over the timing and cost constraints. With DOE approval, in 2010 the Ford Engineering vehicles (PHEV #5, #19 and #20) were updated with a 57 mph all-electric calibration and testing was conducted in-house.

NOTE: Maximum all-electric speed on both the recently introduced Ford C-MAX Energi and Fusion Energi is 85 mph.

Along with the discussion on increasing the all-electric speed, the engineering team investigated adding a switch for battery-only mode. Feedback from partner utilities and drive events had indicated that drivers were interested in being able to control the application of electric-only driving. However, based on the major development work that would be required to implement this, and given the project timing and spending constraints, this action was not pursued for fleet upgrade.

NOTE: Both the Ford C-MAX Energi and Fusion Energi offer this capability when there is plug-in energy available in the HV battery. By toggling through the EV mode button, drivers can chose:

- EV Now: Drive the vehicle in all-electric until the plug-in energy is depleted
- EV Later: Save the plug-in energy and drive like a hybrid until the driver wants to use the energy (for example, drive like a hybrid on the highway and then switch to electric in the city)
- Auto EV: Let the vehicle control strategies decide the optimum all-electric/ICE driving pattern

Addition of Electronic Air Conditioning (EATC)

Similar to the increased all-electric speed discussion above, the Escape PHEV vehicles leveraged the carry-over FEAD driven A/C systems that were in the donor 2008 MY and 2009 MY Escape HEVs in order to minimize fleet development time and cost. This meant that anytime the A/C was requested, the internal combustion engine would be pulled up. The impact on fleet fuel efficiency is apparent when looking at INL's Ford Escape Advanced Research Fleet report for the reporting period Nov 2009 – Dec. 2012. As temperatures increase, the fleet's fuel economy drops

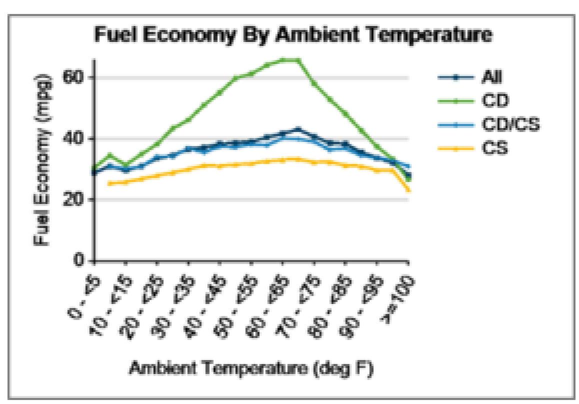

Figure 7: INL's Fuel Economy vs. Ambient Temperature (Nov 2009 - Dec 2012)

off rapidly, most likely reflecting, at least in part, the likelihood that the driver has turned on the A/C. Updating to EATC required wiring and hose changes in addition to installation of a 2010 MY climate control head, instrument cluster and PCM. In addition the PCM strategy required updating and the ABS module had to be re-flashed. With the DOE's approval, the Ford Engineering vehicles (PHEV #5, #19 and #21) were updated with EATC and hot weather testing was completed in Arizona 3rd QTR 2010.

NOTE: All production Ford HEVs, PHEV, and BEVs now offer EATC.

Expansion to UK and China (PHEV #19 and #21)

In June of 2010, the DOE approved a request to deploy one of the Ford Engineering PHEVs to Ford of China (#19) and another to Ford of Europe (PHEV #21). Both vehicles were updated to 230V/50HZ charging capability. This included installation of charger cooling fans, 230V wiring and charge plug upgrades, new charge cords & GFCI and a 230V charging strategy. In the 2011 CY, these two PHEVs were used to demonstrate Ford electrification technologies to the Chinese and European governments as well as to numerous global media and utilities.

NOTE: As discussed later, the Escape PHEV fleet vehicles were equipped with data collectors that used broadband capability to wirelessly send this data to Ford Engineering. However, due to data security concerns in China, PHEV #19 vehicle data was manually downloaded and then manually uploaded to the vehicle data website.

Program Extension - Production Evaluation

In May of 2012, the DOE approved an extension of this program to include DOE evaluation of two production Ford PHEVs after the Escape PHEV demonstration fleet had been completed. Two production C-MAX Energi's are scheduled to be delivered to the DOE. Vehicle data will be collected via the Ford MyFord Mobile system and provided to INL for assessment. Evaluation to be completed December 2013.

Program Extension - Advanced Information Systems

Also in May of 2012, the DOE approved an extension of this program to include the demonstration of using advanced information systems in an intelligent PHEV system to:

- Use cloud based computing and off board information to enhance the fuel economy and drivability of the vehicle
- Maximize EV experience and fuel economy through use of predictive information
- Improve drivability by providing EV mode at the right time and right location
- Determine requirements on external data to obtain vehicle improvements

Results of the Advanced Information Systems work are not covered by this report. Progress is to be monitored via the standard regular Quarterly reports to DOE with final results to be submitted in a final report based on testing completion in December 2013.

Program Management

The Ford Plug-In Project program management plan for detailed work and expectations is laid out in the program Statement of Work which includes the program objectives, scope of work and tasks to be performed. The DOE reviewed these documents and other planning reports that were used to guide the safe and effective execution of the demonstration.

Project Management Plan: The project was planned in four progressive phases of technology roll-out and fleet data collection. Each phase was broken into 5 major tasks with specific sub-tasks or actions delineated under each:

- TASK 1.0: Project Management and Planning
- TASK 2.0: Continuing Improvements for all Builds
- TASK 3.0: Battery Controls and Development
- TASK 4.0: Vehicle Controls and Development
- TASK 5.0: Vehicle Testing, Data Acquisition, Analysis and Reporting

Vehicle Safety Planning: Vehicle safety actions taken by Ford Motor Company included all aspects of the program. In the vehicle design, testing and development Ford employed its standard engineering disciplines including conducting FMEAs, risk reviews and safety assessments. During the build, engineering sign-off books were updated and maintained on each of the 21 vehicles. When delivering the vehicles to the DOE and partner utilities Ford ensured compliance with the US Department of Transportation’s requirements for the transportation of large format lithium ion battery assemblies installed in vehicles. Finally, while in the field, the vehicles were under specific use and service restrictions detailed and agreed to in each vehicles bailment agreement. Contents of these actions are provided in subsequent sections of this report.

Data Reporting Plan: The DOE directed INL to identify data collection parameters and reporting methods with Ford for this project. This plan provided 3rd party neutrality to the DOE and relieved Ford from reporting responsibility to the DOE FOIA impacts**.**

Vehicle Field Service Support Plan: An in-field service support plan was developed to assist dealership technicians in making field repairs. The plan called for Ford Motor Company dealerships which were already certified to conduct Escape HEV repairs to service the Escape PHEVs. Additional training and materials (including a service manual supplement written for the PHEV-specific parts of the vehicle) were detailed for PHEV specific concerns and a Ford Engineering team hot line was specified as the mechanism for determining the extent of the concern and level of assistance required. If the hotline determined that the repairs could not be made at the dealership, plans were in place to transport the vehicle back to Dearborn for service.

Program Safety

Ford Motor Company is committed to the safety of all people associated with the operation of any Ford product, and further to the safe conduct of all activities related to the development and evaluation of electrified vehicles. Specific actions were undertaken with the objective of ensuring that no harm to personnel, property or the environment would happen during the demonstration program. These actions included establishing and maintaining a concept ready risk log, FMEAs, applicable FMVSS compliance assessment, vehicle usage instructions, and an Emergency Response Guide.

Concept Ready Risk Log

During the design and development of the Escape PHEV prototypes, the Ford Engineering team took the program through a rigorous internal management gateway review process designed to confirm concept readiness. As part of this process a project risk log was established. For each risk identified, the team would assign a category type (technical, organizational, legal, or commercial) and then assess the probability of the risk occurring, when it would likely occur, and the potential impact of the occurrence. Based on this, a risk rating was established (high, medium, low) and a lead contact was assigned. For each risk the designated lead was responsible for identifying the appropriate responses or countermeasures and providing status reports until closure.

Failure Mode and Effects Analysis (FMEA)

The Ford Engineering team leveraged the FMEA in validating the Escape PHEV prototype. The FMEA is an analytical process that recognizes and evaluates the potential failure mode, then identifies actions to eliminate or reduce the changes of failure. It is a living document that is continuously updated. Ford leverages this engineering discipline tool on production products. Ford has found that usage of this tool:

- improves the quality, reliability and safety of the evaluated products
- aids in the development of a robust control plan and design verification plans
- identifies critical characteristics and significant characteristics
- reduces product developing timing and cost
- documents and tracks actions to reduce risk

The Engineering team focused the FMEA on the incremental functions of the PHEV over the donor HEV vehicles; on-plug and extended electric drive. The overall objective was to identify and validate safety critical functions as well as critical to performance functions. Validation of these functions occurred at the vehicle level. Note: Separate validation plans were established for the battery design levels.

Based on the FMEA design evaluation a total of 27 controls were identified to be validated at the vehicle level:

- Critical to Safety Functions Validated
    - On-Plug Charge Functions (9 failure modes)
        - Overcharge protection
        - Ground fault protection
        - Leak detection
        - Flammable vapors
        - Contactor control
    - Extended Electric Drive Mode Functions (3 failure modes)
        - Battery CAN message integrity
        - Drive away protection with power cord
- Critical to Performance Functions Validated
    - On-Plug Charge Functions (5 failure modes)
        - Low voltage charging
    - Extended Electric Drive Mode Functions (10 failure modes)
        - Battery CAN Message
        - Sub-System Component EMI/EMC

Ford Engineering also conducted limited operation strategy (LOS) and quit on road strategies (QOR) development work for the high voltage battery and controls. 23 additional validation tests were identified and conducted for the high voltage battery subsystem. By the completion of the design and development of the Escape PHEV all safety critical functions and all battery critical to performance functions had been validated. A pre-delivery drive validation was established to complete the remaining critical to performance function validation for each vehicle before delivery. Note: This validation was performed before any new software strategy or major hardware revision was released to the fleet.

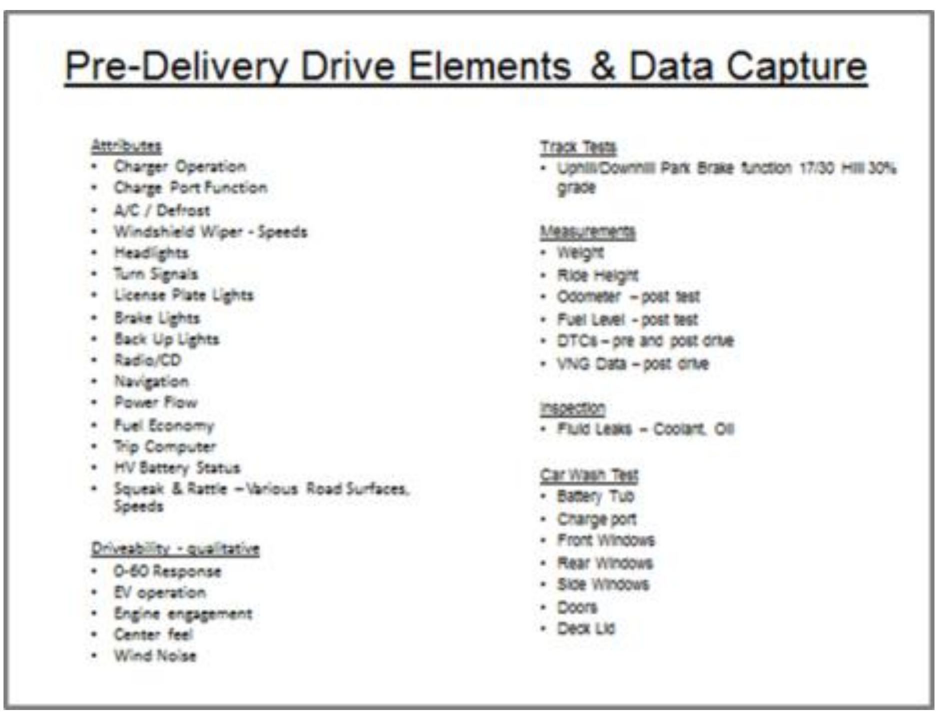

Figure 8: Ford Escape PHEV Pre-Delivery Checklist

FMVSS Compliance Assessment

All 21 units of the Escape PHEV prototypes were based off of production level 2008 MY or 2009 MY Escape HEVs which were fully compliant and certified to all FMVSS requirements. Based on this, and with DOE approval, Ford Engineering targeted four additional validations in addition to the FMEA validations above which focused on the unique PHEV components/attributes. While the prototype vehicles were not official certified, the compliance assessments were based on engineering judgment of internal testing and CAE analysis validations.

EMI Immunity Validation: EMI testing was completed on both a vehicle level and with incremental components testing. Component validation test results were assessed as passing in all cases, including the battery system controller and oil pump controller. Pre-delivery vehicle EMI/EMC validations were also successful.

Emissions Validation: Internal testing showed all vehicles met applicable emissions requirements.

Center of Gravity: Center of Gravity of Escape PHEV was determined to be ~16 mm lower than the comparable Escape HEV.

FMVSS – 55 mph Impact – 70% Offset: CAE analysis confirmed fuel tank and high voltage battery integrity with the addition of Y brace and rear frame and side rail reinforcements.

Figure 9: 3-Legged Crash Brace

Vehicle Usage Instructions

The introduction of the Escape PHEV fleet represented the first time for the majority of drivers that they had driven a PHEV and/or had experienced the charging process. Given the unfamiliarity with the technology at the time, as well as the nature of prototype vehicles, special instructions and restrictions were established for in-field usage of the Escape PHEV fleet.

Supplemental Owners Guide: A spiral bound Plug-In Hybrid Electric Vehicle (PHEV) Supplemental Owners Guide was developed and included in each Escape PHEV. This was to be used in combination with the base HEV owners guide and provided guidance on the unique PHEV features and attributes. Topics covered by the supplemental guide included how to start the vehicle, charge the high voltage battery, and jump start the vehicle. The supplemental owners guide table of contents is provided below:

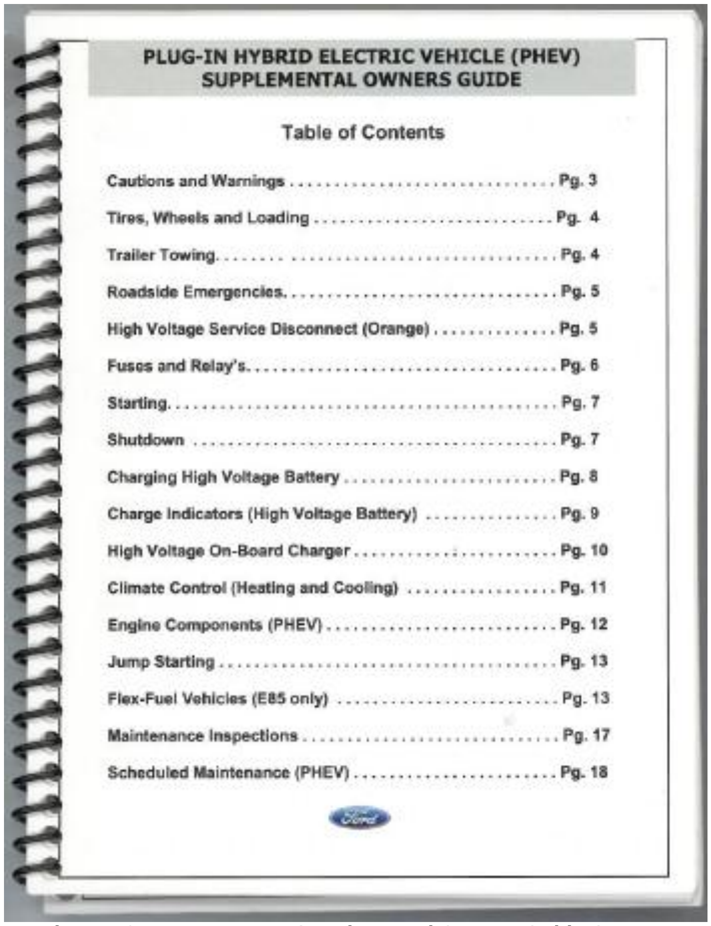
PLUG-IN HYBRID ELECTRIC VEHICLE (PHEV)
SUPPLEMENTAL OWNERS GUIDE

Table of Contents

Figure 10: Escape PHEV Supplemental Owners Guide Content

Quick Reference Card: In addition to the supplemental owners guide, each Escape PHEV was delivered with a PHEV quick reference card. This card provided vehicle start and shutdown instructions as well as emergency contacts and telephone numbers. Also included were instructions on how to charge the vehicle and read the SOC indicator.

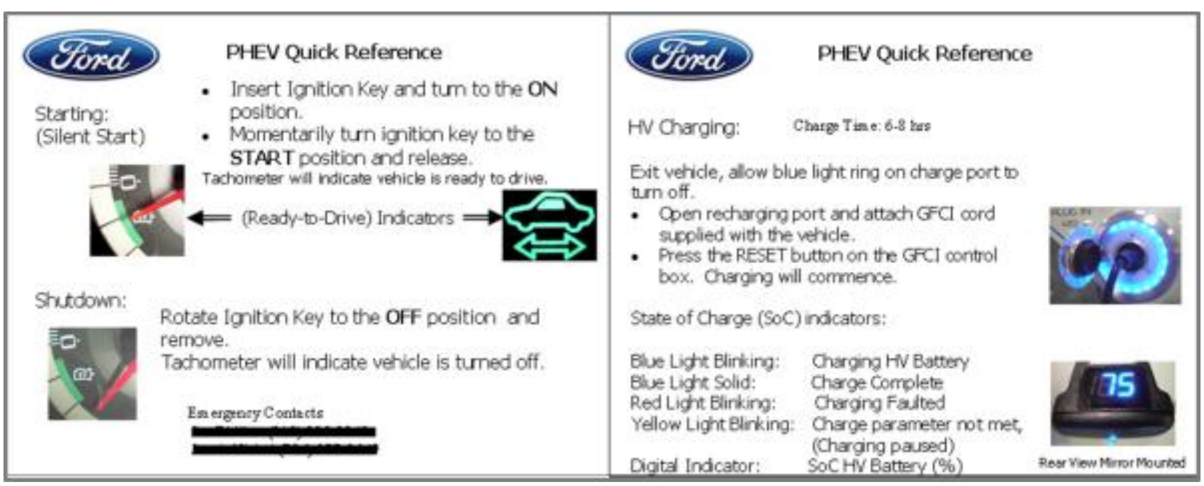

Figure 11: Escape PHEV Quick Reference Guide (Front and Back)

Driver Training: Drivers of the Escape PHEV were provided training to familiarize themselves with the operation and charging of the vehicle. New Driver Information Booklets explained the PHEV features including the location of the high voltage battery and data collection equipment. The booklet also explained how the center navigation screen could be used to display the PHEV specific information screens such as vehicle power flow, high voltage battery state of charge, and charge setting options.

Usage Restrictions: Partnership agreements with utilities receiving an Escape PHEV contained a vehicle usage provision. The recipient was required to utilize the vehicle in accordance with a usage plan that would be developed by the recipient and approved in writing by Ford. These usage plans specified the agreed-to vehicle operation that the Escape PHEV would experience. The plans also required that the recipient would ensure that any drivers of the vehicle review Ford's driver information sheet and that only those authorized by the recipient would occupy or operate the vehicle and associated equipment. Parking, storage, safety & security requirements were also detailed as well as the ongoing data collection and monthly reporting requirements.

Emergency Response Guide: An Emergency Response Guide was developed and published. The guide explained how to quickly identify the Escape Plug-In Hybrid vehicle, the high-voltage electrical and fuel disconnect features, and the Escape PHEV components. Instructions were provided for approaching a damaged high-voltage vehicle, extinguishing a fire, what to do if the high-voltage case had been ruptured and how to move damaged vehicles.

Vehicle Scheduling, Build & Delivery

The 21 Escape PHEVs were built as a progression of PHEV technology consistent with the project phases of first validating the battery/control enhancements (Phase I) and then progressing the battery/control development closer to production intent. Information learned from the earlier phase was incorporated into subsequent vehicles builds. By the end of 2008 the first 11 builds were completed. These units were built with 10.0 kWh battery packs that were assembled by Ford. The first four units were built from 2008 MY Escape HEVs, the next six from 2009 MY Escape HEVs. Major differences between the 2008 MY and 2009 MY Escape HEVs were as follows:

1. Engine changed from 2.3L to 2.5L
2. Transaxle changes primarily addressing NVH
3. Brake System changed from EHB to SBA
4. PCM Software differences (variable valve timing, etc.)
5. HV Battery Changes (signal updates)
6. Wiring Harness Changes
7. Chassis structure modifications (front structure only and change to gas filler pipe for capless fuel)

Each of these Escape HEV MY changes were investigated for potential effects on the PHEV system operation and the appropriate calibration/strategy and hardware/wring modifications were incorporated into the next PHEV builds.

The remaining 10 builds (PHEV #12 - #21) were completed with 11.5 kW battery packs from Johnson Controls SAFT and were completed in 2009. As with the previous builds, Roush Industries was contracted for part of the design/fabrication and vehicle build. The DOE requested that some of the vehicle demonstrate PHEV with E-85 fuel flexibility, so the remaining 10 vehicles were designed to include this capability. Also in 2009 PHEV #1 - #4 were updated with E-85 flexibility.

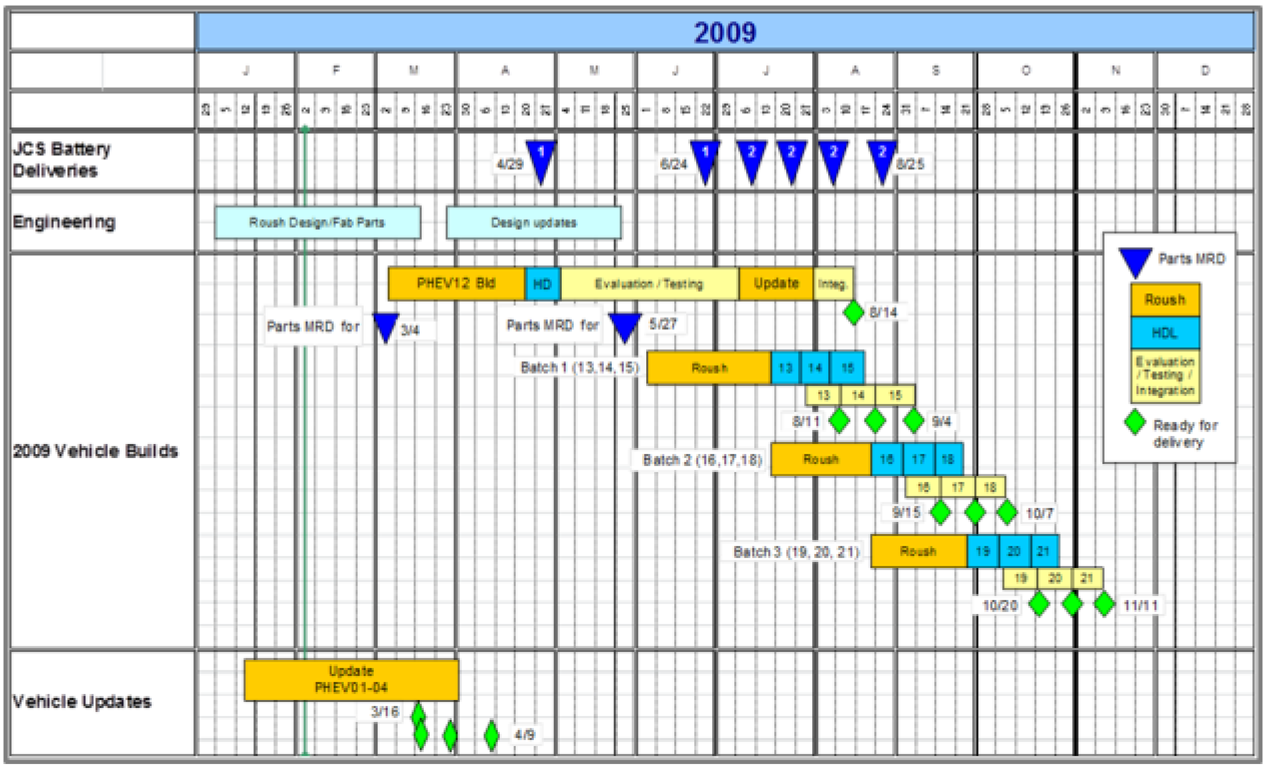

Figure 12: Escape PHEV 2009 Build Schedule

Build Books

Build books were created for each Escape PHEV built. These books included documentation on the vehicle changes made during the upgrade from HEV to PHEV. Instruction and engineering sign-off sheets were included for every system modified:

- Powertrain
- Exhaust System

- Transmission Cooling System, Transmission By-Pass System
- Aux A/C System/Battery Coolant Loop
- Navigation System
- HV Battery System, and Battery Integration
- Interior Trim
- 120V Receptacle
- Electrical System
- Exterior Badging/Engine Cover
- Rear Suspension/Structure
- Fuel System
- Sub-System Control Modules and Bracketry

Also included in the build books were specific vehicle bill-of-materials, vehicle inspection sheets and build service log/vehicle history documentation. A deeper dive on vehicle modifications required is covered later in this report.

Build Variations

Given the progressive nature of design and development of the Escape PHEV fleet and the phased program timing, there were several variations of vehicle within the fleet itself. Software calibrations in the HV Battery Controller, HMI display and Vehicle Control Module were ongoing for each PHEV leading to unique software versions across the PHEVs. From a high level, however, there were primarily four variations of PHEVs in the field.

	Escape HEV Build From		HV Battery		E85	230/50 Hz, 57 mph tip-in Elec AC
	2008 MY	2009 MY	10 kW (in-house)	11.5 kW JCS		
PHEV #01 - PHEV #04	X		X		X	
PHEV #05 – PHEV #11		X	X			(#5 only)
PHEV #12 – PHEV 18, & PHEV #20		X		X	X	
PHEV #19 & PHEV #21		X		X	X	X

Figure 13: High Level Build Variances within Escape PHEV Fleet

Delivery Schedule

The Escape PHEV demonstration fleet vehicle build was completed by the end of 2009, though, as previously discussed, additional modifications such as the conversion to 240V SAE J1772 compatible charging were made post-build. Each vehicle was equipped with an onboard data acquisition system and delivered to the designated recipient.

PHEV#	Customer	Location	Servicing Dealer
1	SCE 1	Pomona, CA	Serviced by SCE
2	Hydro-Quebec 1	Montréal, Québec, CAN	Gabriel Ford 7100 Saint-Jacques Quest Motreal, QC. Canada H5B1H7
3	Pepco Holding Inc.	Washington, DC	Waldorf Ford 2440 Crain Highway Waldorf, MD. 20601
4	American Electric Power	Columbus, OH	Ricart Ford 4255 S. Hamilton Rd. Columbus, OH. 43227
5	Ford Engineering	Dearborn, MI	Serviced by FMC
6	DTE 1	Detroit, MI	Village Ford 23535 Michigan Dearborn MI. 48124
7	NYSERDA	Albany, NY	Metro Ford 3601 State Street Schenectady, NY. 12304
8	NYPA	White Plains, NY	Smith Cairns Ford 900 Central Park Ave. Yonkers, NY. 10704
9	ConED	Astoria, NY	Schultz Ford 80 Route 304 Nanuet, NY. 10954
10	Southern Company Services	Birmingham, AL	Adamson Ford 1922 Second Ave. South Birmingham, AL. 35233
11	Progress 1	Raleigh, NC	Capital Ford 2807 Millbrook Road Raleigh, NC. 27616
12	National Grid	Waltham, MA	Stoneham Ford 185 Main Street Stoneham, MA. 02180
13	DTE 2	Detroit, MI	Village Ford 23535 Michigan Dearborn MI. 48124
14	SCE 2	Pomona, CA	Serviced by SCE
15	DOE 1 (ETEC)	Phoenix, AZ	Camelback Ford 1330 E. Camelback Road Phoenix, AZ. 85014
16	Progress 2	Lake Mary, FL	Greenway Ford 9001 E. Colonial Drive Orlando, Florida 32817
17	DOE 2	Washington, DC	Jerry's Ford 6510 Little River Turnpike Annandale, VA. 22312
18	DOE 3	Morgantown, WV	Superior Ford 1351 Earl Core Road Morgantown, WV. 26505
19	Ford Engineering	Nanjing, China	Serviced by FMC
20	Hydro-Quebec 2	Montréal, Québec, CAN	Gabriel Ford 7100 Saint-Jacques Quest Motreal, QC. Canada H5B1H7
21	Ford Engineering	Dunton, England	Serviced by FMC

Figure 14: Escape PHEV Service Location

In-Field Fleet Servicing

Service Requirements/Training

Specific Ford Dealerships were selected to provide regular maintenance to the Escape PHEVs as well as to conduct any required repairs. These dealerships were selected on the basis of their location to the utility receiving the vehicle. Technicians from the participating dealerships were already Ford certified for hybrid vehicle repairs including high voltage battery work. Plug-In Hybrid Electric vehicle training was provided to these technicians when necessary to address the unique PHEV components. Technicians would interact with the hotline team to diagnose the issue and determine if the repair could be made locally or if the vehicle would need to be returned to Ford Engineering for repair. Vehicle recipients were required by the usage restrictions to service the vehicles at the designated dealerships.

Figure 15: Ford Certified Dealership

In-Field Vehicle Monitoring

Customer Action Team Meetings: Weekly Customer Action Team meetings were hosted by Ford Engineering where partner utilities were able to discuss any service issues or vehicle concerns they were experiencing. As drivers became more familiar with the PHEV vehicles and technologies the need for these meetings became less frequent and they were reduced to bi-weekly occurrence. Participants had access to a shared website where service bulletins, notices and vehicle information were also available.

Onboard Data Collection: Data was collected near real time on the Escape PHEVs while they were in the field. The process and results are discussed later in this paper, but for the purposes of program service, vehicle signals were reviewed by Ford Engineering in the diagnoses of repair issues. The data available enabled the engineer to see what the vehicle was experiencing on a system network basis thus helping in the identification of service issue root causes.

Vehicles Codes and Standards

At the time of this demonstration fleet creation, there were no cross-industry common PHEV definitions. For example, the EPA policy on battery charge depletion had not yet been established for PHEVs at this time. The definition of all-electric range was still being debated and there was no consensed definition of MPGe. SAE J1772 application to PHEV 240V charging was agreed to half-way through this project, long after design parameters had been set and vehicle builds completed.

In addition, customer and market expectations of PHEV performance in the field were non-existent.

It is important to remember that this demonstration of PHEV technology was initiated over five years ago. All design decisions, items like the HV battery size, HMI features, and control strategies, were based on Ford's best engineering judgment at the time.

Program Management & Reporting

Task 5.0 within all four of the project phases established the ongoing requirements of reporting for the Escape PHEV demonstration fleet. The fundamental reporting requirements of the DOE were all met in accordance with the original agreement. All required reports were submitted in a timely and proper fashion.

Quarterly progress reports were issued detailing the activities leading up to production and the preparation of the fleet. These continued as the fleet was deployed and throughout the fleet operation.

Annual program review meetings were held with the DOE program personnel to discuss progress, problems and opportunities in the ongoing effort. These meetings were held both in Dearborn and at DOE sites to provide effective and timely reviews.

Annual merit reviews were supported by Ford with Engineering presenting the project's accomplishments, status and challenges and answering questions related to the project. Reviewers from a wide variety of backgrounds assessed the projects breadth, depth and appropriateness within the goals of the DOE Vehicle Technologies Program activities.

As part of the reporting requirements, the Design, Release and Validation Report on the Johnson Controls SAFT HV Battery System was submitted mid-way through the project. This report was filed as reference information for the DOE.

In addition to the project reporting requirements, the DOE specified that monthly reports be made public on the Escape PHEV operation in the field. INL was directed to work with Ford to identify the data collection parameters and reporting methods. INL brought a consistent data quality, analysis and dissemination methodology. Ford and INL had several discussions regarding how the vehicle data would be made available to INL and the reporting requirements:

- INL was granted access to Ford PHEV Engineering data and reports
- Ford created software to provide data in the INL preferred format and deliver the data securely
- Ford provided INL all data descriptions and vehicle specific software algorithms (where applicable)
- Ford/INL completed their data correlation analysis

As a result of this collaboration, INL produced fleet summary reports on vehicle data received from Ford. These reports followed a 3-page monthly summary report format and included the results of all fleet vehicles aggregated. The reports were made publically available via the AVTA website.

Vehicle Demonstration

Vehicle Description

Figure 16: Completed Ford Escape PHEV

The Ford Escape PHEV demonstration prototype is a hybrid electric vehicle equipped with a rechargeable high-voltage (HV) battery that is discharged during driving to significantly improve fuel economy. Once the charge of the HV battery has been depleted to a preset threshold, the vehicle continues to operate as a standard hybrid electric vehicle.

Overall vehicle specification:

- High Efficiency 4 Cylinder Atkinson Cycle Engine
- 11.5 kWh Li-Ion HV Battery Capacity (PHEVs #12 - # 21. NOTE: #1 - #11 have 10 kWh packs)
- Charging time: 6 – 8 Hours
- Fuel Capacity: 15 Gallons
- Fuel Economy: Up to 30 miles in electric mode for speeds less than 40 mph and dependent on driving conditions
- Weight: 3900 lbs
- Max Speed: 102 mph

Features

- Outstanding fuel economy – especially in real-world city driving
- Two-thirds fewer trips to the gas station
- Overnight recharging from standard home electrical outlet
- Interactive vehicle-to-grid communications
- Engine off operation during low speed driving
- Regenerative braking
- Flex Fuel Option (E-85)

How it works

Ford's strategy for electrified vehicle operating modes is a blended power split. This means that the vehicle can be driven by electric power alone (HV battery), mechanical power (internal combustion engine) or by a combination of both electric and mechanical power (blended operation).

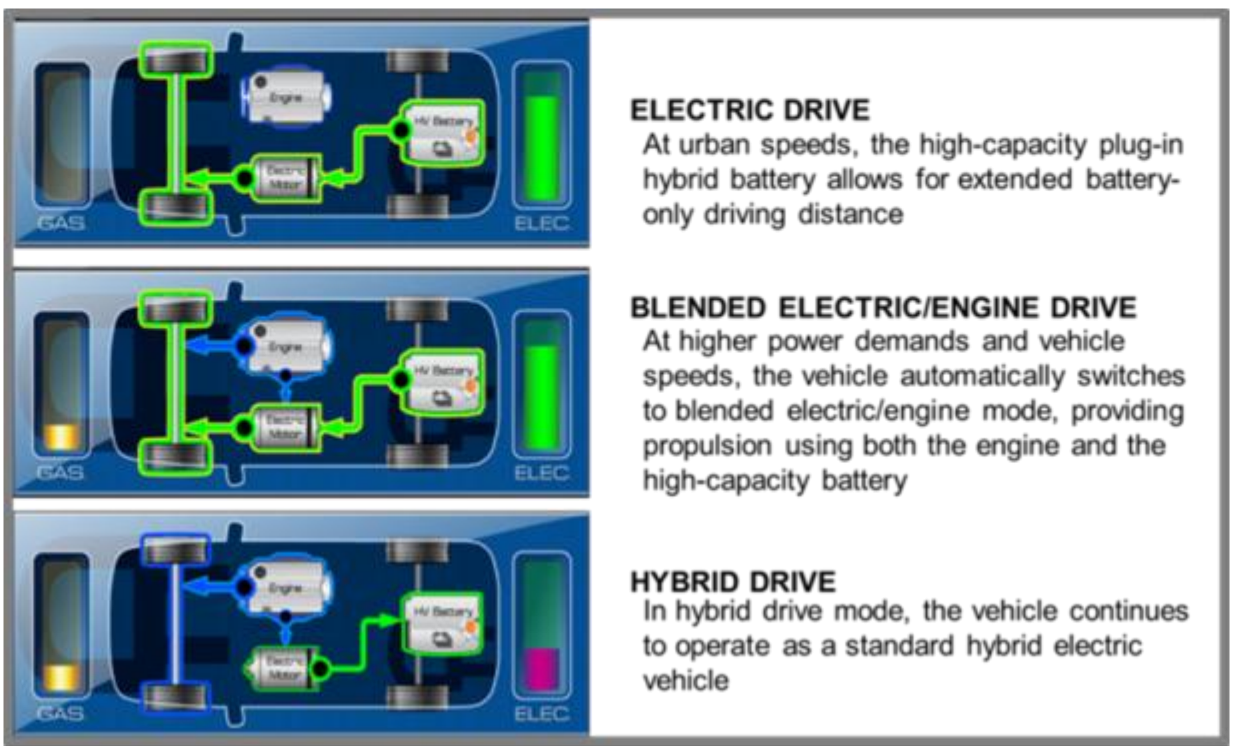

Figure 17: Ford PHEV Powersplit Power Flow

Similar to the production Escape HEV, the demonstration Escape PHEV energy flow from the propulsion system to the wheels is part mechanical and part electrical. The Escape PHEV builds off the standard Escape HEV architecture by the addition of a larger li-ion HV battery which can be charged with energy from the grid as well as by the engine and regenerative braking. The larger HV battery increases the vehicles electric-only capability including an increased all-electric driving range. Thus by combining hybrid electric technology with a larger battery and external charge port which can be plugged into a 120V or 240V outlet, drivers have the capability of offsetting their fuel usage with electricity from the grid.

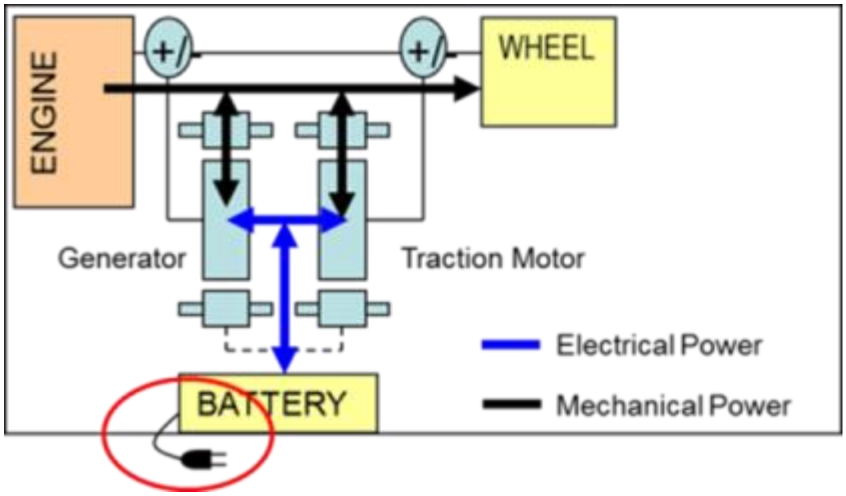

Figure 18: Ford PHEV Powersplit Architecture

In an Escape PHEV starting a trip with a full state of charge (6-8 hours on either a 120V or 240V outlet) energy would flow out of the battery to propel the vehicle. The HV battery state of charge then gradually decreased depending on driving style and conditions. This phase of operation is called charge depletion. In the case of the Escape PHEV, the internal combustion engine would come on during this phase at speeds over 40 mph, when the A/C was turned on or when more power was needed. Once the HV battery reached a specified minimum state of charge, the Escape PHEV began to operate like a typical hybrid. This phase of operation is called charge sustaining. Meanwhile, the regenerative braking system would capture much of the energy normally lost in friction braking and put it back into the HV battery for further spurts of blended or even all-electric driving. The internal combustion engine would also provide energy back to the HV battery.

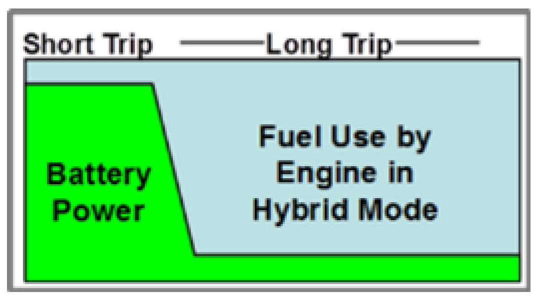

Figure 19: Illustration of PHEV Battery and Fuel Usage

Escape PHEV System Upgrades

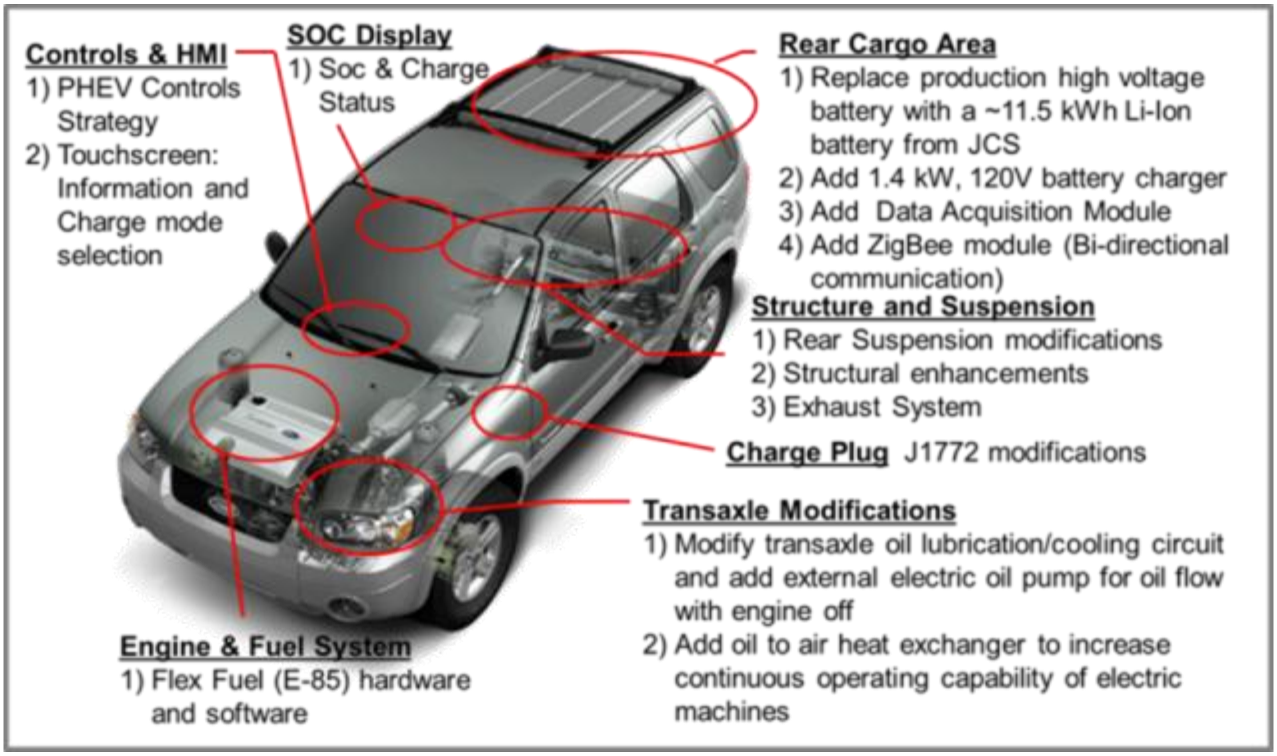

Figure 20: Escape PHEV Modifications

The Escape PHEV demonstration vehicle updates continually progressed as the Ford Engineering team advanced the development of the technology. As design improvements or modifications were established, previously-built prototype vehicles were retrofitted with the enhancements as appropriate. The updates detailed below are a consolidation of the vehicle enhancements representing the completed Escape PHEV design.

Rear Cargo Area

High Voltage Battery: A critical decision in the design and development of the Escape PHEV was the HV battery sizing. This decision directly related to the electric capabilities of the Escape PHEV including the all-electric driving capability. In making this decision, Ford Engineering looked to available vehicle miles traveled (VMT) studies. In 1997, Sierra Research had constructed drive cycles based on vehicle data collected for the EPA in Atlanta GA, Baltimore MD, and Spokane WA. Additional confirming data from the results of a University of California-Riverside study based on instrumented vehicles driven in southern California were also assessed. The VMT studies indicated that the most frequent actual distance driven per day was about 15 miles and that the most mileage racked up was by people driving about 30 miles per day. Considering the charge depletion and charge sustaining operation of the Ford PHEV, and under the assumption that the greatest potential for fuel economy improvement is when the entire capacity of the PHEV is used, the engineering team judged that for vehicles with modest electric ranges, people that drove the battery to full depletion by the end of their daily driving would achieve the best fuel economy / value from their PHEV vehicle investment (assumes at home, overnight charging only.) Based on this, the Ford Engineering team targeted the Escape PHEV to deliver an all-electric range of 30 miles. A greater all-electric range would require a larger HV battery pack, which would be more expensive and would be rarely used by most households.

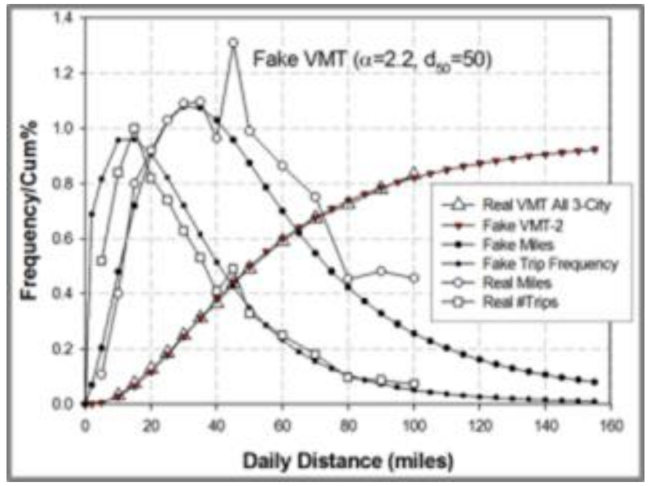

Figure 21: EPA & Sierra Research VMT Model

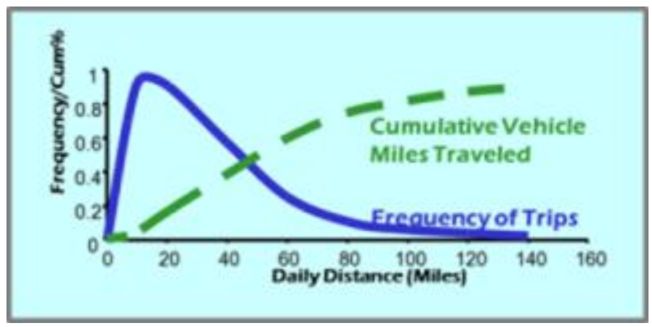

Figure 22: Frequency vs. Daily Distance

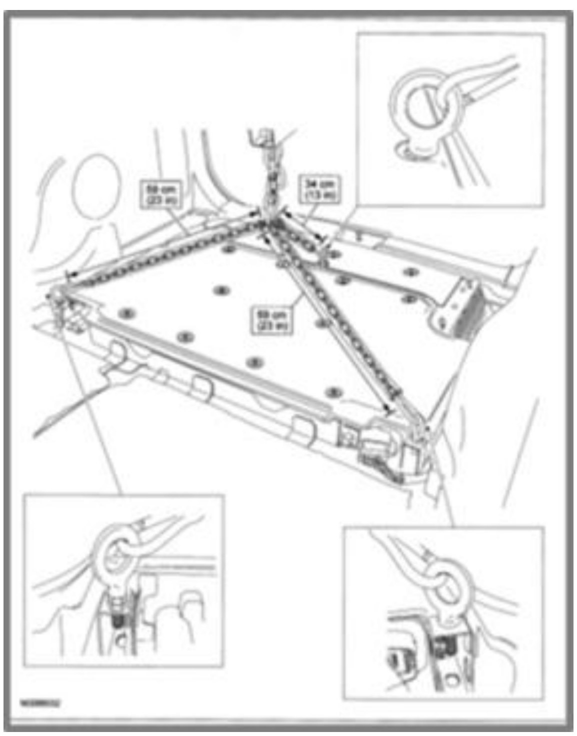

Figure 23: Removal of Donor HEV HV Battery

Installation of the 11.5 kWh HV PHEV Li-ion battery first required removing the production Ni-MH HV battery from the donor Escape HEV. The HEV HV battery was depowered and the necessary trim, ducting, bolts and brackets removed for access. Then the high-voltage cables were disengaged and the pack was lifted out via the specified lift points.

Next the rear floor was removed and a rear floor tub that had been designed to hold the battery was installed. Two battery tub reinforcements were then installed and welded into the rear floor.

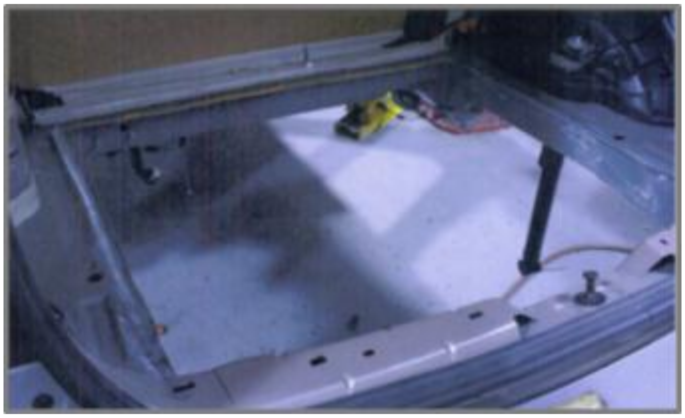

Figure 24: Rear Floor Removal

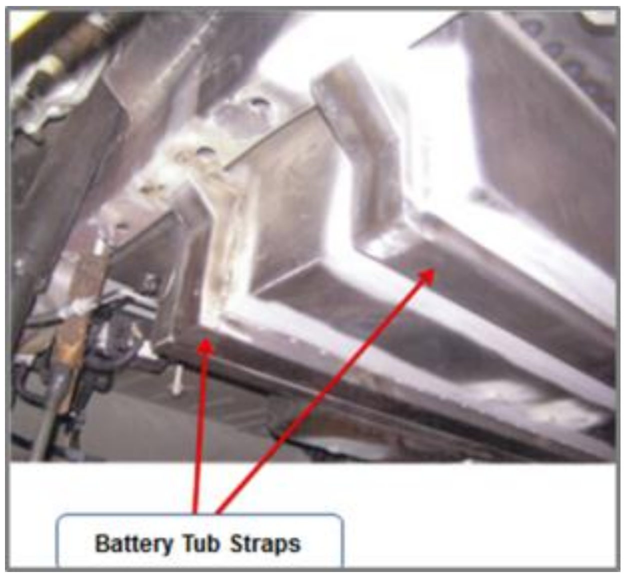

Figure 25: Battery Tub and Reinforcements

The PHEV Li-Ion battery installation also included modifications to the HV wiring and routing. All high voltage wires and connectors were made in the standard, clearly visible orange color.

Figure 26: HV Color Coding

A PHEV liquid cooling loop system was designed as part of the Li-Ion HV battery pack thermal management system. Installation of this loop involved removing the production battery chiller and ducting as well as cutting and removing the rear auxiliary A/C branch which was then welded closed and capped. The battery loop degas bottle, coolant pump (right front frame rail) and filters were then installed/ mounted via brackets and fittings. In addition, coolant lines from the front of the vehicle to the rear were rerouted.

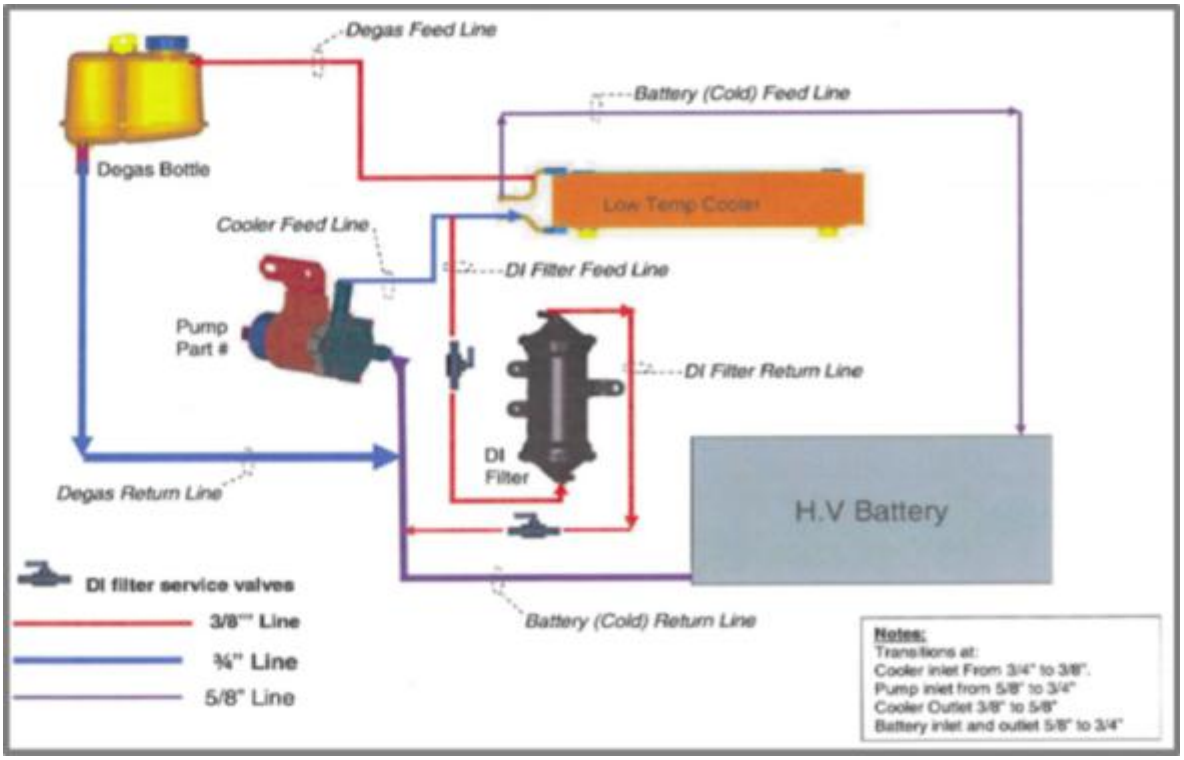

Figure 27: HV Battery Coolant Loop Schematic

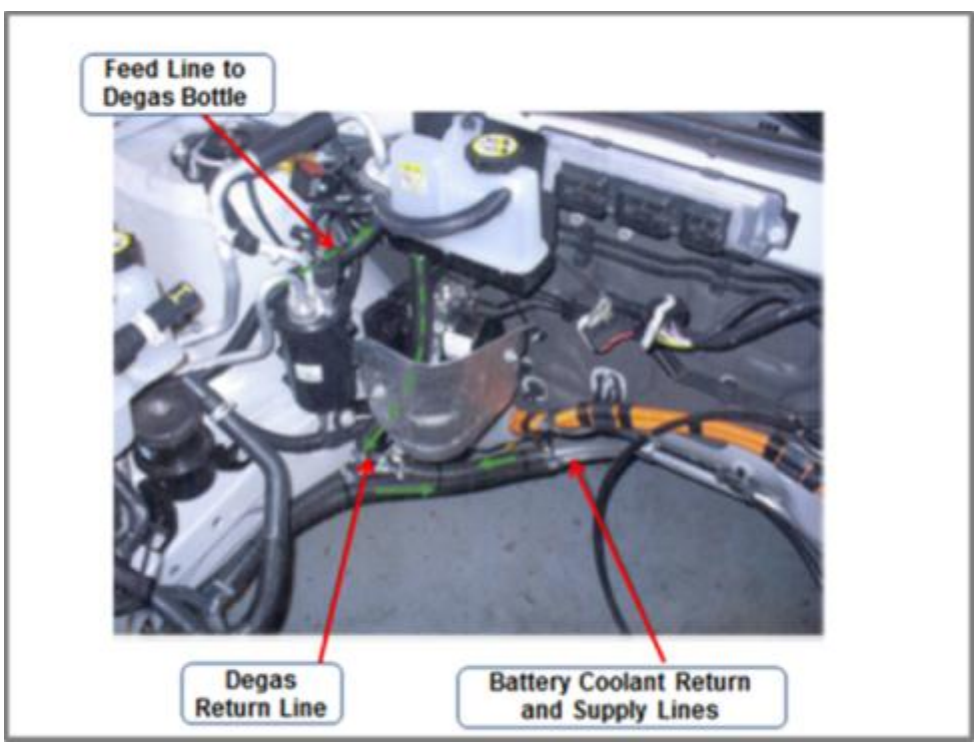

Figure 28: HV Battery Coolant Loop

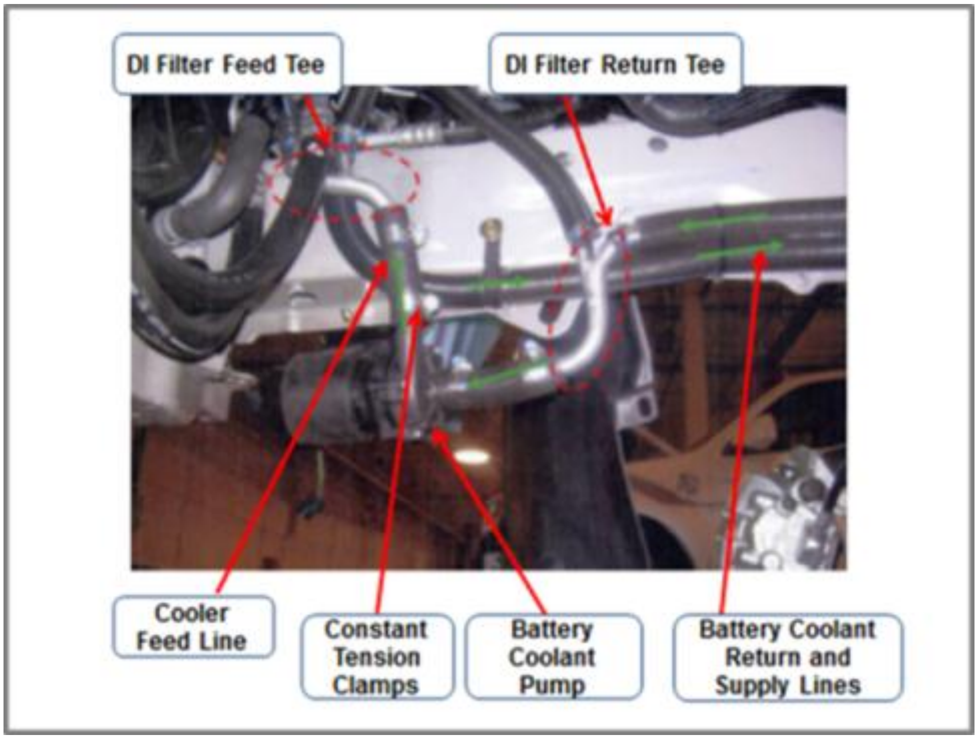

Figure 29: HV Battery Cooling Loop Pump Location

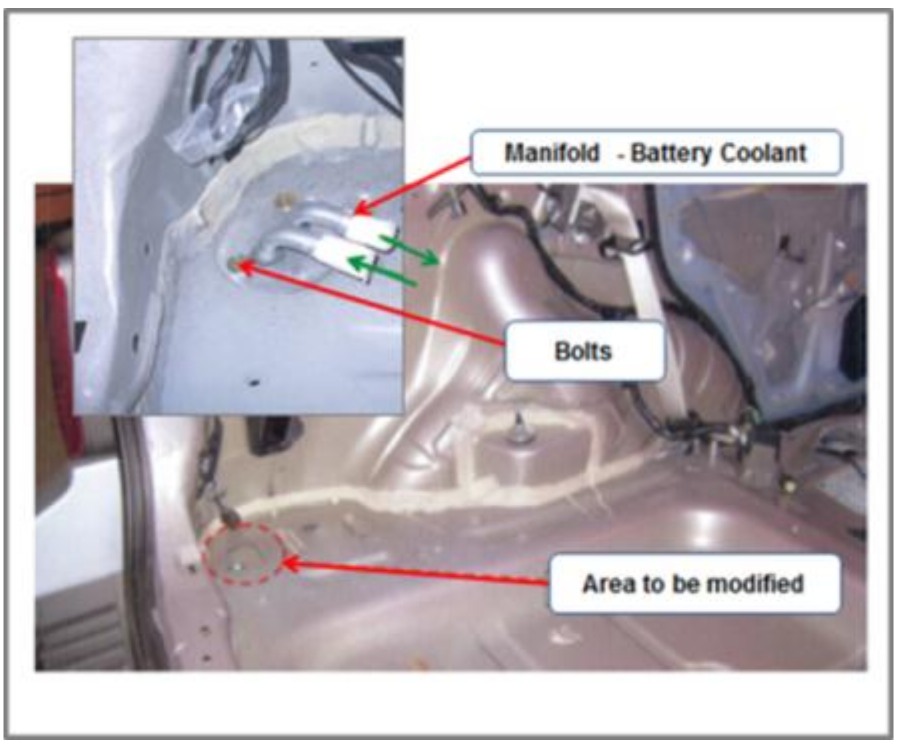

Figure 30: HV Battery Cooling Manifold Location

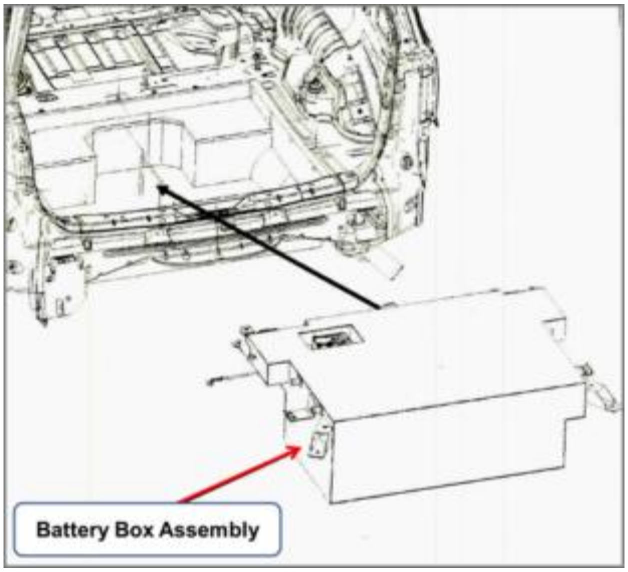

Figure 31: High Voltage Battery Box Location

The HV battery box assembly was installed in the battery tub surrounded by foam inserts.

1.4 kW Charger: In order for the HV battery to be able to accept energy from the grid, a charger was installed in the rear of the vehicle. This onboard 1.4 kW charger converted AC utility power to DC and allowed the battery to reach a full charge (from fully exhausted) in about 6 - 8 hours. The charger was also used to maintain the 12V battery. Installation required modifications to the left rear inner fender and creation of support brackets, as well as installation and electrical connection of the charger itself. The high voltage charger was designed to operate on a normal household voltage of 120V and would typically draw approximately 12 amps max. Thermal management of the charger required development and installation of cooling fans and associated duct work which enabled cooling of the charger using outside air.

Figure 32: Escape PHEV Unique Rear Glass

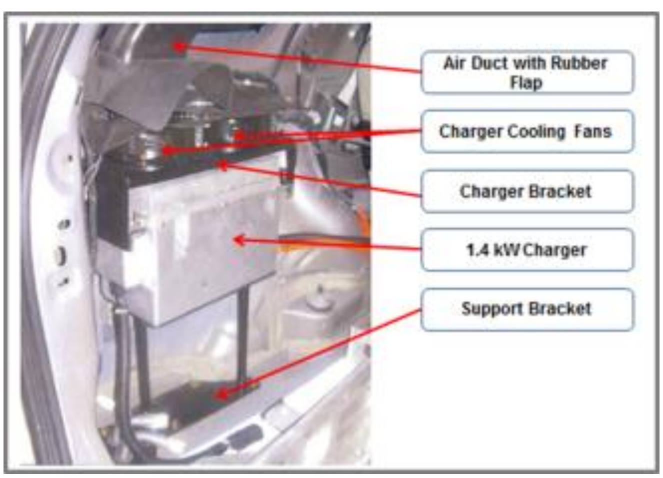

Figure 33: Onboard 1.4kW Charger Location

Note: As previously discussed, charger cooling fans were originally powered by 120V from the input side of the charger. To accommodate the 120V/240V charging the 120V fans were replaced with 12V fans operating from the 12V output of the charger. This resulted in a substantial reduction in fan power consumption because 12V fans are substantially more efficient than 120V fans.

Modules: Rear cargo area package space and brackets were also developed and installed for the VNG and Zigbee wireless modules. The VNG or Vehicle Network Gateway was a data collection device that was used very early in the program on the first 2 PHEVs. It was phased out once the first Data Acquisition Platforms (DAPs) were developed and delivered. Any vehicle originally outfitted with a VNG was upgraded to a DAP. More information on the data collected is available later. The Zigbee wireless module was installed to provide a means of communication with a utility smart meter.

Figure 34: VNG Module and Tire Air Compressor Kit Location

Tire-Inflation Kit: To provide packaging space for the PHEV upgrade components, the spare tire was replaced by a tire-inflation kit which was being used by other production vehicles at the time. It was mounted in the right hand quarter of the cargo area via a specially designed bracket.

Structure and Suspension

Structure: As discussed and shown previously, CAE analysis supported the addition of a 3-legged structural crash brace. Installation of this underbody brace first required the removal of the subframe and wheel knuckles and disconnection of rear drum brake lines. Next front and rear crash strut clevises were welded to the frame. Reinforcements were also added to the left and right hand frames and side rails.

Figure 35: Front Crash Strut Clevis

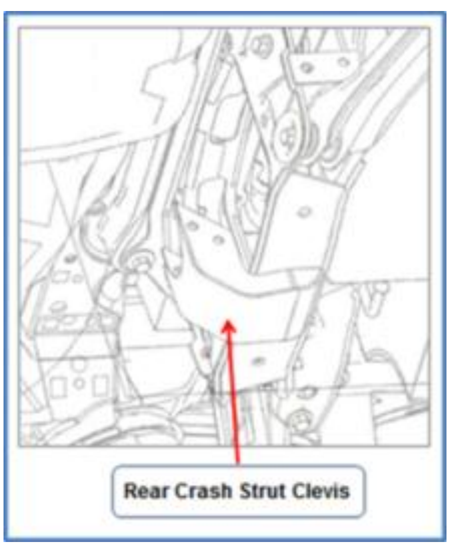

Figure 36: Rear Crash Strut Clevis

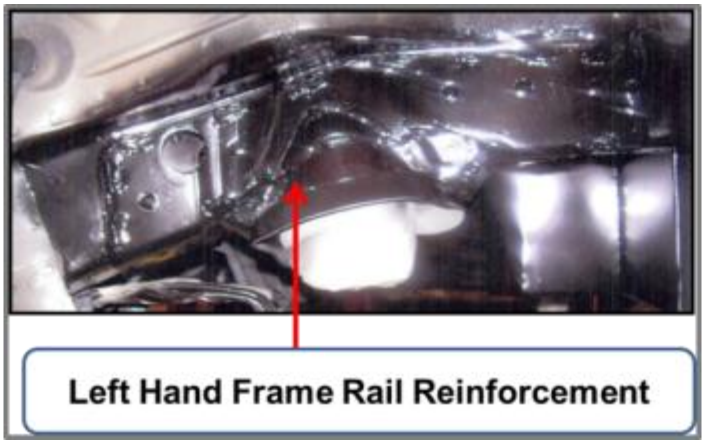

Figure 37: Left Frame Reinforcement

Figure 38: Right Frame Reinforcement

Figure 39: Left Side Rail Crash Brace

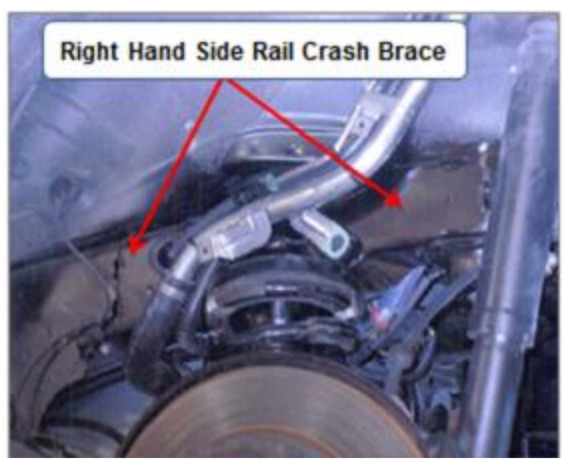

Figure 40: Right Side Rail Crash Brace

Rear Suspension: The Escape PHEV fleet was based off of both 2008 MY (4 units) and 2009 MY (17 units) Escape HEVs. No changes were made to the front suspension on any of the vehicles. There were no changes to the rear suspension on the 2008 MY vehicles. On the 2009 MY vehicles the 4x2 springs in the rear suspension were replaced with production 4x4 springs to compensate for the increased battery weight on the rear axle.

Charge Port

Prior to the J1772 compatible modification previously discussed, each vehicle was equipped with a 120V charge port for plugging into the grid. The front left hand fender was selected for the location to further differentiate it from the fuel fill doors that are most commonly located in the rear quarter panels. The left hand side was selected for convenient access for the driver. Installation of the charge port required removal of the left hand fender which was modified to provide a hole for assembly. The inner sheet metal was also cutout to make room for the charge port wire harness and the outer fender was built-up to make the receptacle flow better with the exterior design of the vehicle.

Figure 41: Original Escape PHEV 120V Charge Port

Roush Industries manufactured the charging receptacles. The machined aluminum part was installed with an illumination ring which would illuminate (blue) when the vehicle was charging. This receptacle was modified and reused in the conversion to 240V J1772 charging compatibility

NOTE: Originally the blue charging ring light came on when the lights of the vehicle were on (even when driving down the road). However it was discovered that certain regional laws/ordinances do not allow blue lights on vehicles when driving, so the light was modified to illuminate only when charging.

NOTE: Both the Ford C-MAX Energi and Ford Fusion Energi charge port locations are on the driver side fender. (All Ford electric vehicles, including the Ford Focus Electric, have this standard port location.)

120V charge cords equipped with a GFCI (Ground Fault Circuit Interrupt) unit were provided with each vehicle and users were instructed that charging should only be completed with this supplied cord. No additional extension cord or adaptors were permitted. The provided 120V 12G (12 gauge wire) extension cords required users to press the GFCI button once the cord was plugged into the AC outlet. This was to reduce loss and reduce vehicle access plug damage by avoiding plugging in of a live extension cord. The vehicle was intended to be charged from a GFCI protected building circuit. In some cases, such as brown out conditions, the vehicle was designed to enter a stand-by condition which then required the user to press the test button on the vehicle charge cord and wait 10 seconds before pressing the reset button to re-initiate charging.

SOC Display

The state of charge (SOC) display was located under the windshield mounted rearview mirror and projected the SOC value through the windshield so that it was visible from outside the vehicle. This display had both a digital reading to provide a percentage of charge completed and a LED light used to indicate status. Users were also instructed that the LED light would indicate the following conditions:

- Blinking BLUE LED light – Indicted vehicle was charging
- Solid BLUE LED light – Indicated that the charge was complete
- Blinking RED LED light – Indicated that a fault had occurred during the charge phase that required attention
- Blinking YELLOW light – Indicated that the either a customer selected charge parameter was not operational or no vehicle to utilities communications was available, and charging had paused

Figure 42: SOC Indicator

Transaxle Modifications

The Escape PHEV transaxle system required updating to address the extended internal combustion off time expected in PHEV operation. A new thermal management strategy was required to provide motor cooling during the faster and longer all-electric driving.

Figure 43: Transaxle Coolant Loop

Electric Oil Pump and Cooling Circuit: The PHEV transaxle lubrication/cooling circuit was modified by the addition of a cooling loop that included an external electric oil pump which was located on the driver's side front engine underbody. This was required to accommodate extended electric motor loads. The powertrain was removed so that the transaxle case could be machined to allow for connection to the new external cooling circuit. The side of the transaxle case was tapped to allow for direct flow into the hydraulic passages from the external cooling circuit which included a cooler, pump and filter. The transaxle required a significant amount of flushing in order to ensure metal chips from the machining process were completely removed prior to the re-installing of the transaxle.

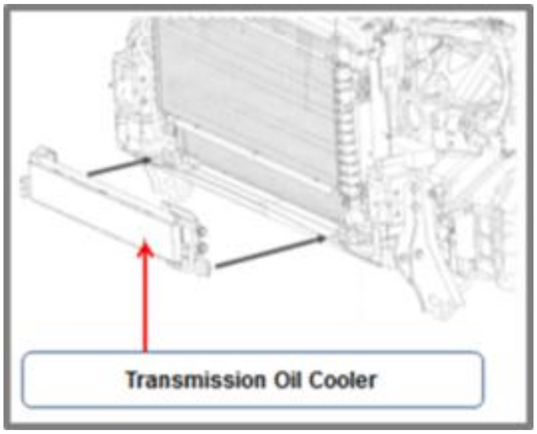

Figure 44: Oil to Air Heat Exchanger

Oil to Air Heat Exchanger: In order to increase the continuous operating capacity of electric machines, an oil to air heat exchanger was added to the transaxle system. This involved integrating and installing a liquid-to-air radiator to cool the transaxle fluid. The fascia was removed to install the transmission oil cooler.

Engine & Fuel System

Flex fuel hardware and software updates were made to the Escape PHEVs based on a request by the DOE that the vehicles be capable of running on E-85. Two E-85 conversion kits were developed by Ford Engineering to convert the PHEVs to flexible fuel vehicles (FFVs) and then supplied to Roush for installation (2008 MY and 2009 MY).

Fuel System Revisions: The major fuel system revisions included use of a production flex fuel pump that was in use on the Ford Explorer and production flex fuel pumps isolators. Wiring modifications were required to make the connections compatible. Other modifications included revisions to the calibration as well as the fuel fill pipe, fuel fill pipe shield and fuel cap (yellow identifier).

Engine Modifications: The engine cylinder head was a modified production head with revised valve seat material, cylinder head gasket and cylinder head bolts. In addition the fuel injectors were replaced with production FFV compatible fuel injectors. Production engine block heater and block heater wiring were also installed. Associated E-85 strategy and calibration were developed and implemented.

Body Electrical Revisions: Body electrical revisions included fabrication of a wiring overlay from ignition to fuel sender which included a protective conduit. Other revisions included a revised fuel label indicating ethanol fuel or unleaded gasoline only.

Exhaust System: The ICE exhaust system was rerouted and a heat shield was added to the resonator.

Controls & HMI

PHEV Controls Strategy: In establishing the control strategy for the Escape PHEV, Ford Engineering focused only on those functions which were incremental to the donor Escape HEV: on-plug charging and extended electric drive. On-plug charging included developing control strategies for the onboard charger, BCM and interface plug. The onboard charger needed to deliver plug energy to the high voltage battery, 12V battery and BCM.   Sub-net CAN messaging was established between the onboard charger and BCM and the BCM would then manage the HV battery charge contactor control. A strategy was also needed for the interface plug to provide charge indication.

Extended electric driving also involved the BCM. New BCM and VSC strategies were required for charge depletion driving. In addition, main-net CAN messaging between the TSC and electric oil pump was required to provide oil flow during ICE off.   Software modifications were also required to allow silent key start on 2009 MY vehicles.

In the development of the control strategies, Ford Engineering considered the input signals (HV plug power, communications via CAN, etc.) as well as noise factors (degradation over time, high road vibration, temperature, etc.). They then balanced these against identified control factors (feedback control architecture, component grade and rating, etc.) to determine how to achieve the ideal function output and how to avoid potential error states. This process involved a rigorous and detailed analysis of PHEV operations and included in-depth assessments on the impact of everything from the individual component characteristics to system and vehicle interactions. The analysis included 10 input signals, 81 potential noise factors, and 40 control factors. Desired ideal functionality included 15 function descriptions for on-plug charging and 7 function descriptions for extended electric drive mode. 23 potential error states were identified and protected against for on-plug charging and 12 identified for extended electric driving. All control concepts were validated prior to being implemented on any vehicle.

HMI - Touchscreen: Another key area of development for the Escape PHEV fleet was the human machine interface (HMI). This would define how the driver interacted with the vehicle and establish the mechanism for how the driver would be provided information on the vehicles state and operation. It would also allow the driver to provide inputs to the vehicle to control this operation.

The HMI strategy was developed based on a three-day face-to-face discussion between Ford Engineering and the utility partners. Based on Ford’s vehicle expertise and the utilities grid and customer charging experience, potential use case scenarios were created for the Escape PHEV in the field. Based on this, an extensive wish list was developed for vehicle capabilities and HMI functionality.   This list was assessed against technology capability (including safety) and project cost and timing constraints resulting in a smaller priority list of features which included items such as value charging and critical peak charge interruption. From this prioritized list, the Ford Escape HMI was developed. This list was also used to help define the ongoing vehicle data to be collected and the information that would be exchanged with the utility during charging. Vehicle data collection and utility communications are discussed later.

In-vehicle messaging was developed that supported the creation of the prioritized HMI. Each Escape PHEV was equipped with a center stack navigation screen. The display screens were modified to show PHEV specific information. The main menu was designed to provide users six different menu choices: Instant Fuel Economy, Average Fuel Economy, Power Flow, HV Battery, Trip Computer, and Charge Settings.

Figure 45: Escape PHEV NAV Screen PHEV Main Menu

Figure 46: Escape PHEV Instantaneous Fuel Economy

The instantaneous fuel economy screen indicated the present fuel consumption, displayed in bar chart and numerical MPG value. The average fuel consumption was also displayed as a horizontal bar on the same scale as the instantaneous fuel consumption. When the engine was off the MPG value was replaced by the text "Engine off" and the graphical bar would reach top of image.

The average fuel economy screen indicated historical fuel economy for both the current drive and previous drive events of the vehicle. Fuel economy was displayed in a bar chart form, displaying bars in 1 minute increments for the previous 15 minutes, in a rolling display populating the screen from left to right every minute with the oldest bar disappearing to the right. The average fuel consumption was displayed across the chart.

Figure 47: Escape PHEV Average Fuel Economy

The Power Flow screen showed the energy flow from the powertrain components with arrows indicating the direction and line thickness indicating the magnitude of the energy flow. Possible flows were:

- battery to the motor to the wheels
- ICE to the wheels
- ICE to the motor
- ICE to the motor to the battery
- The wheels to the motor to the battery

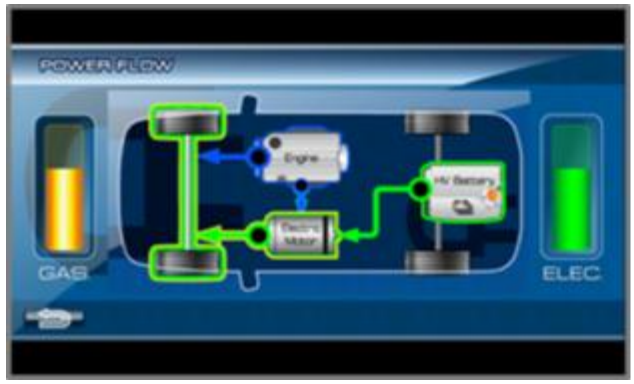

Figure 48: Escape PHEV Power Flow

Figure 49: Escape PHEV HV Battery SOC

The HV Battery screen indicated the amount of energy in the battery, displayed in bar chart form and numerical percentage, and labeled as battery state of charge. In addition, the screen displayed text indicating whether the vehicle was in charge sustaining or depletion mode. Different modes were displayed in unique colors.

The trip computer screen was used to estimate the current trip costs and cost savings achieved through plug-in hybrid operation versus non-plug-in operation. Users could input the cost of electrical energy and gasoline. The screen also allowed the user independently reset each of two trip accumulator calculators. Information from the last drive was saved upon key-off.

Figure 50: Escape PHEV Trip Computer

Figure 51: Escape PHE V Charge Settings

The charge setting screen provided the customer the opportunity to customize the HV battery charge process. This screen allowed the customer to modify charge selection parameters such as energy price in order to manage the overall battery charging process. The user could schedule the time that the vehicle would charge on a regular basis with different time selections possible for weekdays and weekends. Users could also elect to allow the utility to interrupt the vehicle charge event during charging

NOTE: The Ford C-MAX Energi and Fusion Energi now offer a production solution similar to the Escape PHEV HMI demonstration of charging on the basis of energy price. Value charging allows Ford customers to reduce their electricity costs by taking advantage of off-peak or reduced rates from their utility without a complicated set-up process. In addition the current production vehicles have similar displays as that developed for the Escape PHEV for instantaneous fuel economy, historical fuel economy, and charge setting times.

Vehicle Markings

Engine Cover: The Escape PHEV engine cover was modified to clearly indicate that this was a PHEV. The engine cover included both Ford's Road and Leaf logo and the words PLUG-IN HYBRID.

Figure 52: Escape PHEV Engine Cover

Badging: The exterior of the Escape PHEV had badges located on the left and right front doors. In addition the rear lift gate displayed a "Plug-In Hybrid" nameplate that had been machined in brass letters and then chrome plated. Finally distinctive wraps were designed for the vehicle which included the words "Plug-In Hybrid".

Fleet Maintenance Review

Escape PHEV maintenance was scheduled every 10,000 miles to be completed by the participating Ford dealer. Each maintenance included an oil change, filter replacements, a tire rotation and a multiport inspection. 67 scheduled maintenances were completed during the 800,000+ miles logged by the fleet:

PHEV Scheduled Maintenance	10K	20K	30K	40K	50K	60K	70K	80K	90K	100K
Change engine oil and replace oil filter	X	X	X	X	X	X	X	X	X	X
Replace DI filter assy.	X	X	X	X	X	X	X	X	X	X
Replace engine air filter			X			X			X	
Inspect tires for wear and measure tread depth	X	X	X	X	X	X	X	X	X	X
Rotate tires	X	X	X	X	X	X	X	X	X	X
Inspect brake pads, shoes, rotors, drums, brake lines and hoses and parking brake		X		X		X		X		X
Inspect engine and Motor/electronics cooling system and hoses		X		X		X		X		
Replace engine coolant and Motor/electronics coolant										X
Inspect steering linkage, suspension and if equipped half-shafts, drive shaft and ball joints		X		X		X		X		X
Inspect exhaust system and heat shields		X		X		X		X		X
Inspect accessory drive belt.										X
Replace spark plugs.										X
Change High Voltage Battery Coolant					X					X

Figure 53: Escape PHEV Maintenance Schedule

Given the nature of prototype vehicles, a detailed assessment on fleet maintenance data was determined to be of minimal benefit.

Overall, and especially considering the prototype nature of the fleet, the Escape PHEVs performed exceptionally well in the field with numerous software updates and only minimal hardware repairs required. Some of the more common PHEV-related issues experienced were as follows:

- VSC: The vehicle control software required updates to make it more robust to low ambient temperatures and high battery SOC operation
- HV Battery: The initial HV battery temperature sensors had multiple issues and reported out of range battery temperature values. The root cause turned out to be a splice located at a harness bend which failed due to fatigue stress
- PCM: The PCM software required modification to improve the cabin heating and cooling strategy (no electric A/C or heat)
- 12V Battery – Multiple vehicles experienced dead 12V batteries and the root cause was identified as the increased load from additional PHEV systems and modules. The regular 12V HEV battery was replaced by a deep cycle battery
- Navigation: The fleet started with a prototype level FordWorks Navigation system which would lock up and not display PHEVs screens. When the production system was available vehicles were updated.
- Data Acquisition (DAP): The original DAP wake up system caused system lock-up requiring the system to reboot to address issue. DAP hardware and software were updated

Major repairs were minimal and included resolution of 2 oil leaks and 4 transmission fluid leak occurrences.

Education and Outreach

One of the purposes of the Escape PHEV demonstration fleet was to progress the public dialogue on the electrification of transportation. A significant part of this was to get people familiar with the PHEV technology and what it could offer. To that end, the Escape PHEVs were used to participate in public education and outreach events supported by Ford and the utility partners. Between 2008 and 2012 the vehicles were used in hundreds of events across the nation either as static display units or participating in ride and drives. And with the expansion to Europe and China, the Escape PHEV became part of global demonstration events as well. In total, the Escape PHEV supported over 300 public outreach activities – from major auto shows, to high school educational displays, from government occasions to utility events.

Conclusions and Recommendations

The Escape PHEV vehicle design, development, build and delivery was successful in demonstrating that PHEV technology can provide consumers the ability to offset some of their transportation fuel usage with energy from the grid. Although not optimized for fuel efficiency, this 21 unit fleet consistently demonstrated greater all-electric driving capability than its donor regular hybrid vehicles.

Lessons learned by the Ford Engineering team were incorporated into production solutions on the Ford C-MAX Energi and Ford Fusion Energi; two mass produced commercially available products. These solutions range from maximizing all-electric speed capability to providing drivers the ability to select their electrification mode.

The next part of this report focuses on the vehicle data that was collected from these vehicles in the field and an assessment of this data. Also discussed are the results of efforts with the utility partners in employing these vehicles to demonstrate plug-in technology and to progress vehicle to grid communications (smart meter) work.

Vehicle Testing and Data Analysis

Vehicle Data Plan

Onboard DAP

All Escape PHEVs were equipped with data acquisition platforms (DAPs) which collected and transmitted vehicle data while driving and charging. DAP data collected included 89 measured parameters such as vehicle longitude, vehicle latitude, ambient temperature, battery temperature, motor temperature, speed, engine on/off, A/C on/off, odometer reading, drive event start/end times, charge event start/end times, and battery state of charge. Raw data was collected at a frequency of 1 Hz with selected "vital" signals received as MIN, MAX and AVG to avoid aliasing. The DAP data collection process was designed to provide an overview of vehicle operation useful for statistical analysis on a fleet or individual vehicle basis.

AC_Energy_Used	Contactor_Control_Req	MessageFileCount
AC_Operating	Contactor_status	MIL_Light
Ambient_Temp	Cust_Pref_Allow_Utility_Interrupt	ModemSignal
AverageBandwidth60Seconds	Cust_Pref_Enable_End_Chg	Motor_Torque_Desired
Balance_Charge	Cust_Pref_Enable_Rate_Chg	Odometer
Batt_Cell_Skin_Temp	Cust_Pref_Enable_Time_Chg	Odometer_count
Batt_cooling_Pump_cmd	Cust_Pref_End_Chg_Time	OutboundQueueCount
Batt_Failure_Sig	Cust_Pref_Price_Chg_Thresh	Park_Brake_Status
Batt_Mode	Cust_Pref_Time_Chg_WkDay	PHEVDataIndex
Batt_Temp	Cust_Pref_Time_Chg_WkEnd	PRNDL_Position
Batt_Voltage	DAPVersion	Ready_Light
Battery_Current	Discharg_Power_Limit	SavedMessageCount
Blink_Yellow_SOC	dtBroadcast	SmartMode
BPO	dtGPS	SOC_Display_Red
Brk_Pdl_Depressed	dtRTC	Throttle_pedal_position
CaptureDiskUsage	Engine_cool_temp	Time_Offset
CaptureFileCount	Engine_on	TimeChanges
Cell_Temp_MAX	Engine_torq_desird	Total_Torque_request
Cell_Temp_MIN	Exterior Temp (subnet)	Trans_Inverter_Temp
Cell_Voltage_MAX	Ford_HV_Battery_SOC	Trans_Motor_Temp
Cell_Voltage_MIN	Fuel_alcohol_prcnt	Trans_oil_Pump_Speed
Charg_Power_Limit	Fuel_flow	Trans_Oil_Temp
Charge_Counter	Fuel_tnk_Level	Trip_Counter
Charger_Current_Demand	GPS3DAltitude	Vehicle
Charger_Fault	Ignition_Switch_Position	Vehicle_Mode
Charger_Input_Current	JCS_HV_Battery_SOC	Vehicle_Speed
Charger_Input_Voltage	Latitude	VIN
Charger_Output_Current	Longitude	WirelessActive
Charger_Output_Voltage	LOS	WirelessSystem
Charger_Temp	MessageDiskUsage	

Figure 54: Raw Data Collected by Escape PHEV DAP

Broadband Access

The mechanism for providing near real time access to the vehicle data being collected was accomplished through the sourcing of two suppliers. One supplier managed the broadband on-vehicle data acquisition and transfer. The other supplier handled the on-vehicle data organization and web-based access. The vehicle data collected by the DAP was received via broadband wireless network and then sent to be archived in a collection server (Iowa City). From there, the data was relayed to a website server (Dallas) where it was saved in a SQL database which was backed-up nightly (Farmington). Authorized users then had access to the vehicle data through the web.

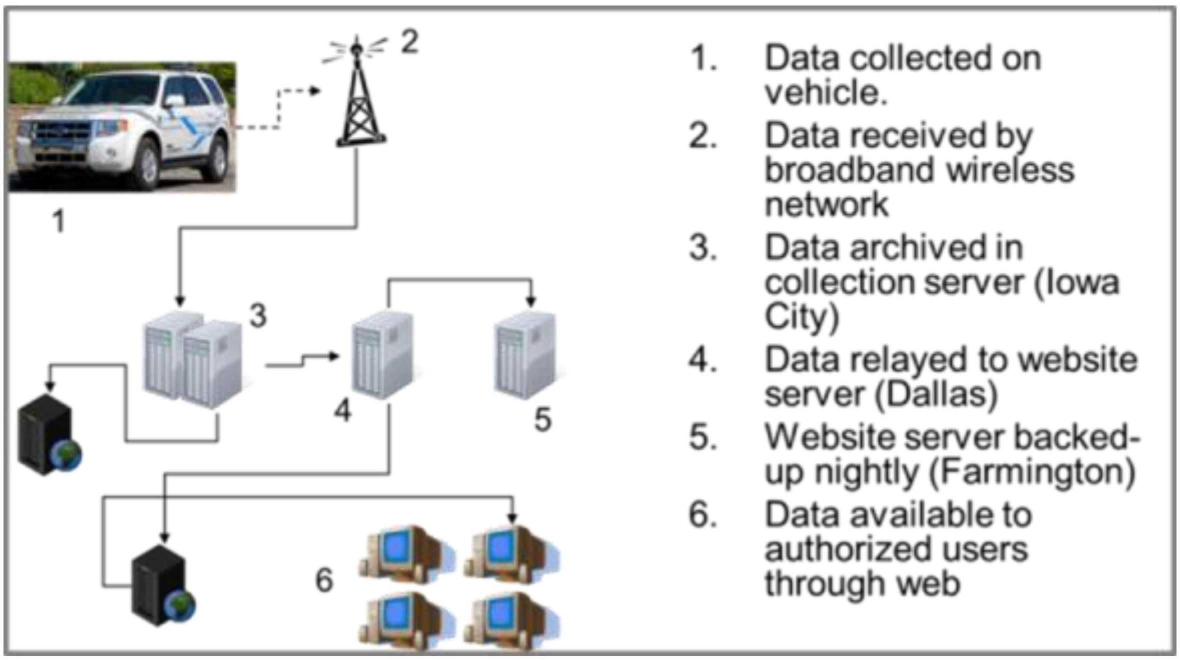

Figure 55: High Level Data Flow

Due to the broadband collection and transmission of vehicle data, authorized users had near real time access to the vehicle data. However, in the field, there were occurrences where an Escape PHEV would temporarily lose accessibility to a broadband network (parking structures, no-service areas). When this occurred the vehicle would continue collecting and storing the data for transmission as soon as a network was available.

Website Data Processing

The vehicle data website was capable of processing incoming data on a minute-by-minute basis to allow for the creation of reports near real time. Reports available included an overall fleet report for the partners, an overall fleet report for Ford, and individual vehicle reports for Ford and the partners.

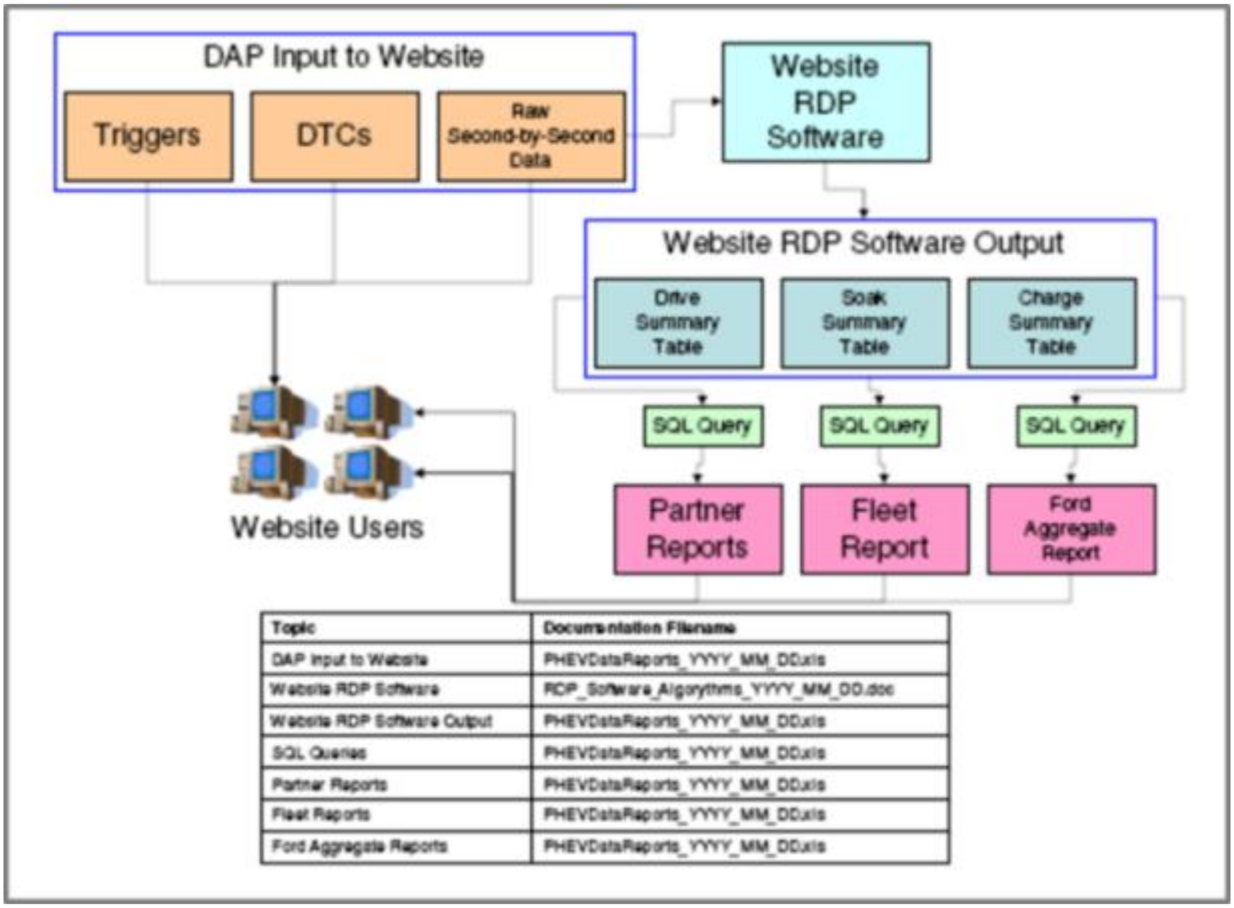

Figure 56: Website Data Processing

Once users accessed the website they essentially had access to five screens:

- Home Screen: Provided access to screens below and displayed vehicle location, operational state and faults (in the last 24 hours)
- Documents Screen: Provided access to vital service and program documents including the vehicle service manual, safety information (MSDS) and shipping information
- DTC Screen: Provided ability to sort DTCs by date range. Website determined download times and provided the data instantly or sent an email to the user when ready
- Raw Data Download Screen: Provided ability to select and sort raw data by date range. Website would determine the download times and provided the data instantly or sent an email to the user when ready
- Vehicle/Fleet Reports: Users could request a summary report of the entire fleet or of a specific vehicle. Report summaries included fuel economy, total number of trips, miles traveled, miles traveled in charge depletion, miles traveled in charge sustaining, number of charges, time of charges and other items

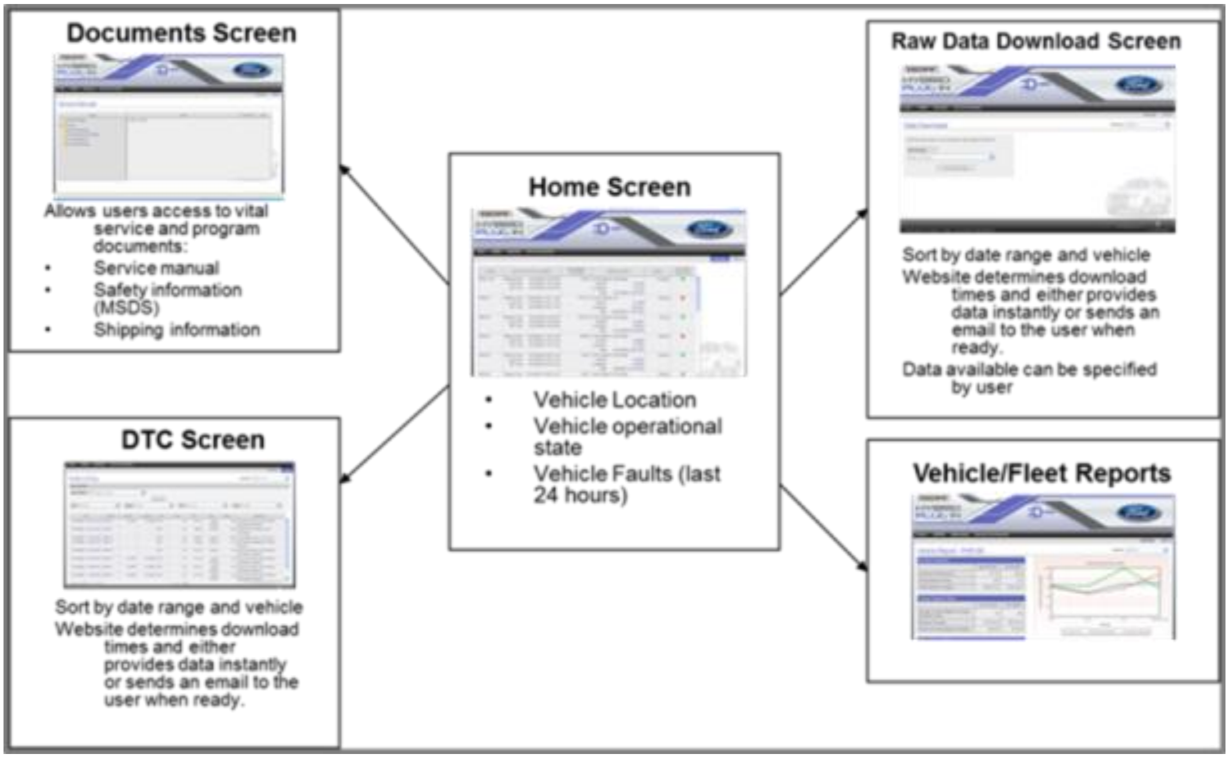

Figure 57: Website Overview

Website/Data Security

On-Vehicle Data and Transfer Security: Only system diagnostic data was available from the vehicle and this data was encrypted during transfer to the website. In additon unsernames and passwords were required for manual data extraction.

Website Data Security: The website was compliant with Ford's IT precesses and requirements. In additon server achitecutre was redundant and nightly tape back-ups were performed.

INL Data Transfer

As previously discussed, all Escape PHEV fleet data was made available to INL for analysis and reporting. The data was encrypted prior to being tranmitted to INL. When the data was received, INL would unencrypt it for analysis and then generate fleet summary reports. These reports followed a 3-page format and included the results of all fleet vehicle aggregated. Starting in 2011, INL began publishing monthly, annual, and life-to-date reports on the public AVTA website.

Data transfer to INL occurred monthly via multiple CSV files per vehicle. Data quality assurance processes were implemented to ensure tranfer completion. The data resided at INL in a restricted-access server enclave behind multiple firewalls. Per the CRADA, data will not be shared with the DOE or other national laboratories without written permisson from Ford.

Vehicle Data

The INL publically available reports are located at "http://avt.inl.gov/phev.shtml" and include both monthly and annual fleet summary reports. Monthly publications report the overall fleet gasoline fuel economy for all trips, for those trips in charge depletion, those in charge sustaining and those in both modes. The number of trips, trip distance and trip intensity are also reported along with other parameters such as the percentage of miles driven with the ICE off. Summaries of charging events are also available. The annual fleet summary reports include most of the above plus a graph illustrating the effect of ambient temperature on the fleet realized fuel economy.

Since these reports have been publically available for over two years, this discussion is focused on two items specific to the Escape PHEV fleet experience.

Infrequent & Incomplete Charging

On a fleet average, the HV battery SOC at the beginning of a drive event was 57%. Only about one-fifth of the time did a vehicle begin a drive event with a fully charged HV battery (90% or greater). In addition about 40% of all trips started with a HV battery SOC of 40% or less.   Looking at the charge events revealed that the vehicles were left to charge for an average of around 2 hours and that during this time the HV battery's SOC increased about 27%.   This pattern of short, infrequent charges resulted in the fleet vehicles routinely operating with low SOC, limiting the ability to realize the potential benefits of the PHEV system.

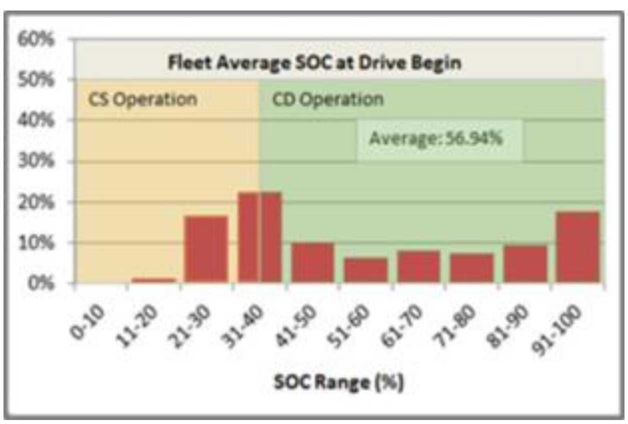

Figure 58: Average SOC at Drive Begin

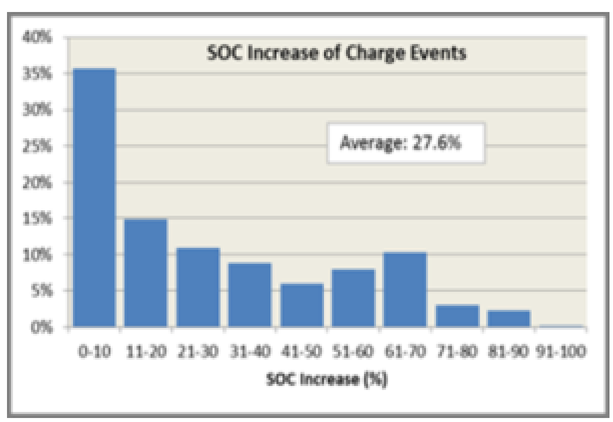

Figure 59: SOC Increase Per Charge Event

When the fleet was designed, the 6-8 hour charge time was judged acceptable based on an assumption of overnight charging. If the vehicles had experienced regular overnight charging, greater charge depletion miles would have occurred. However in the field, the vehicles were being charged primarily during the day. When partner employees took the vehicles home, they were either unwilling or unable to charge them there.

Figure 60: Charging, Driving, Charging Start Time

In addition, roughly two-thirds of all charge events had 40 miles or less accumulated before recharging. If the average charge event time had been expanded to allow full charging, charge depletion operation would have increased thus increasing the amount of plug-in energy consumed.

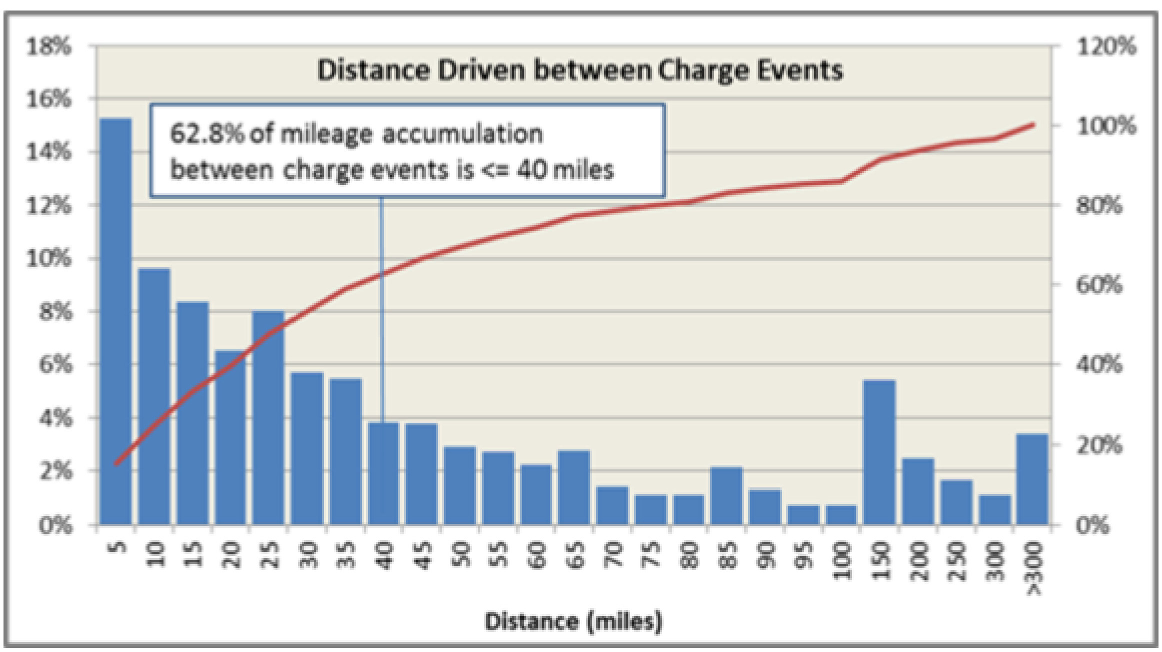

Figure 61: Distance Driven Between Charge Events

NOTE: Both the Ford C-MAX Energi and Ford Fusion Energi offer 240V charging capability with a 3.3 kW onboard charger which allows a full charge in 2.5 hours.   In addition, both offer preconditioning capability while on-plug; a feature that had not been developed for the Escape PHEV demonstration fleet. Leveraging grid energy to bring your vehicle to the desired cabin and operating temperature allows for even more fuel displacement.

Internal Ford Study

After a review of the fleet data with project partners, two of the utilities managed to increase their charging times and corresponding charge depletion driving.   While this resulted in their fuel economy improving 30-40%, a look at the data showed that 85% of the miles driven in charge depletion had the engine on, likely due to demands for climate control, aggressive driving, and/or being driven at higher speeds

To further explore the impact of usage on the Escape PHEVs, Ford Engineering conducted an internal study on three of the returned Escape PHEVs. Seven Ford employees were given the opportunity to drive an Escape PHEV home overnight for one to two weeks. These employees drove approximately 40 miles a day (28 to 51 miles) and were able to charge overnight at their homes. The vehicles were filled with regular unleaded gasoline.

Time maps depicting vehicle usage were compared for the overall fleet against this internal study. On a daily basis, in 15 minute intervals, driving (green), charging (blue) and soaking patterns were compared.

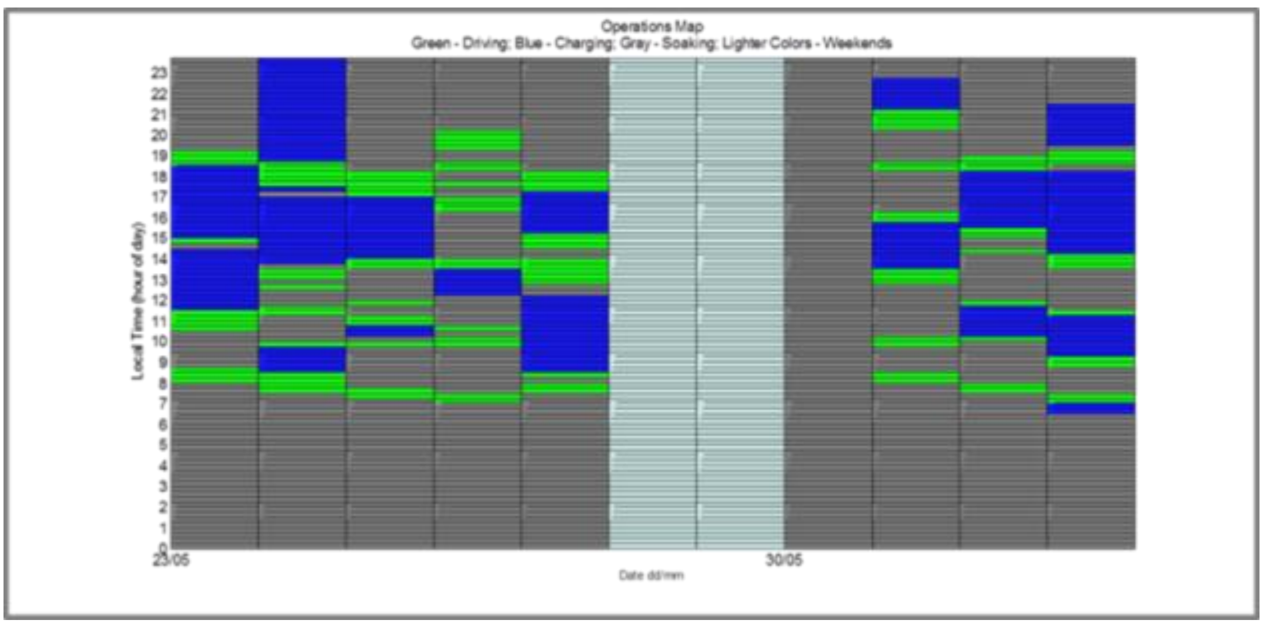

Figure 62: Aggregate Fleet Daily Usage Pattern

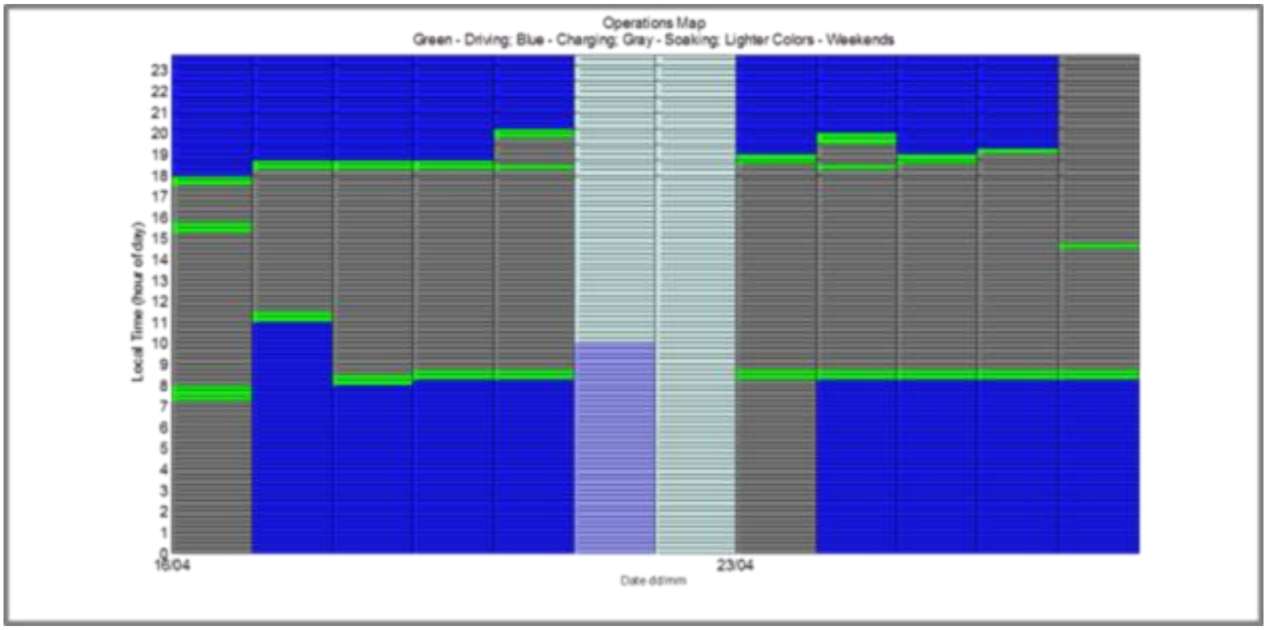

Figure 63: Ford Internal Study Daily Usage Pattern

By charging regularly overnight, the Ford internal study participants experienced an average fuel economy of 65 mpg, 80% better than that experience by the fleet. One “super-user” Ford internal participant arranged to charge the test vehicle during the day as well. He achieved 99 mpg; nearly triple the fuel efficiency experienced by the fleet.

Comparison of the fuel efficiencies achieved by the fleets versus those obtained in the Ford internal study and through testing (section below) underscore the need to deliver technology that is aligned with usage patterns. At a high level, the two most significant factors affecting fuel efficiency are the vehicle and how the driver uses the vehicle. The wide variety in fuel efficiencies achieved indicates how important usage patterns are to minimizing fuel consumption.

NOTE: Ford Engineering is working to deliver electrified products that provide optimal fuel economy for a wide variety of customer usages. By matching the level of electrification with expected usage (Start-Stop, HEV, PHEV, or BEV) customers are given a choice to optimize their individual electrified transportation experience on the basis of cost and fuel efficiency. This flexibility is consistent with the holistic objective of reducing dependence on fossil fuel in the mass market.

Vehicle Testing

Per the INL test plan, Argonne National laboratories conducted baseline dynamometer fuel economy testing over the EPA standard urban drive (UDDS) and Highway (HWFET) drive cycles on one Escape PHEV. Results are available on the AVTA website (http://avt.inel.gov/phev.shtml). Baseline testing was done with E-85 which typically results in 20-25% lower FE than regular gasoline. Fuel economy in charge depletion with A/C off was reported at 119 mpg. Fuel economy in charge sustaining with A/C off was found to be 33.8 mpg, which is comparable to the donor Escape HEV mpg.

Communications

Advanced Metering Interface (AMI)

Another area of vehicle testing involved vehicle to grid connectivity. When the initial design parameters of the prototype Escape PHEVs were being established, wireless technologies seemed to be the most likely avenue for vehicle to smart meter communications and several utilities had work in progress for wireless communications with their respective smart meters. Ford Engineering thus designed, developed and implemented the hardware and software necessary to support a wireless field demonstration of communications between the vehicle and smart meter. All Escape PHEVs were equipped with ZigBee wireless capability and initial field tests were started. Initial communications testing experienced noise issues with RF interference being caused by radio towers and other ZigBee devices. Software modifications were made to decrease the sensitivity. Shortly after that, however, direction within communications development changed, and with SAE J1772, PLC was established as the industry standard. Ford Engineering worked with the utilities to establish an interface method so that the vehicles could support communication testing.

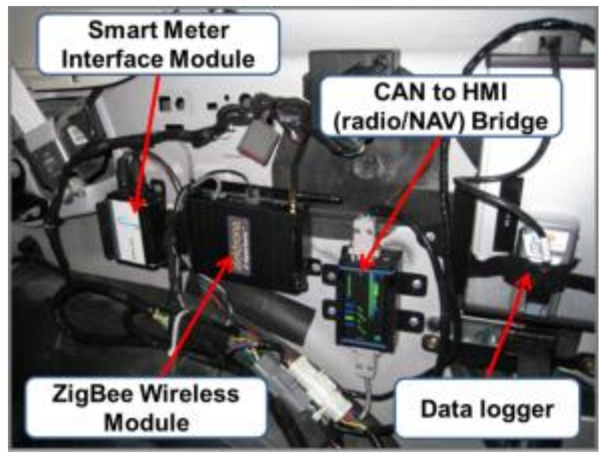

Figure 64: Communication Modules

EPRI - Communications Interface

(Provided by John Halliwell, EPRI, 942 Corridor Park Blvd. Knoxville, TN 37932)

EPRI worked with Pathway Technologies and a collaborating utility to upgrade the ZigBee interface on the vehicle. The ZigBee gateway module firmware was updated to support certificate based authentication based on SE 1.0. The vehicle then supported test and production certificates. The results of this effort were that the vehicles demonstrated response to price signals from the AMI. Due to limitations of the AMI however, the vehicle would not acknowledge a demand response event. The AMI system tested did not allow sending of a negative duty cycle value as required to control the vehicle. SE 1.0 does allow for negative duty cycle values. The issue was addressed with the AMI system vendor, however it could not be resolved within the timing and cost constraints of this project.

Another issue raised was that the vehicle did not have the ability to join multiple meters. One potential way to support joining multiple networks, such as at a work and a home location, would require that the vehicle user interface be upgraded, allowing the user to select from multiple meter connections. The vehicle system would need to maintain security keys and other information such that the vehicle would reconfigure its settings to match the meter it wants to join. This would require extensive modification of the vehicle HMI display and as such was outside the scope of the project.

EPRI - Fleet Aggregator Tool

(Provided by Robert Entriken, EPRI, ***rentrike@epri.com****)*

EPRI created a fleet aggregator simulation tool to analyze how valuable a PHEV could be as a grid resource. During the analysis, the tool first ensures each vehicle in the simulated fleet has sufficient battery energy for its scheduled transportation purposes before analyzing the entire fleet's potential to provide energy to the grid. The tool works as an aggregator, collecting many small resources (the individual vehicles) and presenting them to the bulk electricity system as a single, large, and potentially distributed resource. EPRI has indicated that the above tool has been completed, and will be used in future EPRI research endeavors.

NOTE: Study is also required to quantify impact on vehicles of expansion beyond regular transportation patterns (example: increased battery cycling).

EPRI – On-Road Fleet Analyses

(Provided by Christine Lee EPRI, clee@epri.com and Doug Saucedo, EPRI, dog@evosyseng.com)

As part of this project, EPRI conducted two analyses of the Escape PHEV fleet data. The first report assesses the impact that different factors can have on fuel economy and battery usage (for example, route type), In this assessment the benefits of electrification are clear with the report showing that the Escape PHEV technology did use electrical energy to displace the use of more expensive fuel. The second report analyzes drive operations and discusses the factors influencing energy consumption. Both of these reports are available in the appendix.

Intellectual Property (IP) and Publications

IP

Some inventions may have been developed during this work, but specific patents have not yet been identified.

Publications

All Escape PHEV publications have either been made available on the AVTA public website or submitted to the DOE.

- In 2011, INL began publishing publically available monthly and annual reports entitled the *Ford Escape Advanced Research Vehicle* on their AVTA website (avt.inl.gov/phev.shtml).
- Ford PHEV Fleet Quarterly Reports – DOE
- Annual Ford PHEV Project: Bringing PHEVs to Market Merit Review Presentations – DOE
- Annual Ford PHEV Project: Bringing PHEVs to Marketing Industry PHEV Technology Acceleration and Deployment Activity Reports - DOE
- Annual Ford PHEV Project Budget Reviews – DOE
- EVS26, Los Angeles California, May 6-9, 2012 Paper #2360162: Ford Escape PHEV On-Road Results from US DOE's Technology Acceleration and Deployment Activity. Co-authored by INL (Richard "Barney" Carlson, Matthew Shirk) and Ford Motor Company (Julie D'Annunzio, Christopher Fortin) – previously submitted to the DOE

Accomplishments

Successfully designed, developed, built and delivered a 21 unit Escape PHEV fleet to demonstrate plug-in vehicle technology.

Collaborated with 11 different utilities across North America and EPRI in facilitating a deeper understanding of the current and future potential impact of PHEVs on the grid.

Provided a platform for advanced feature development to further increase the capabilities of future PHEVs.

Established a data acquisition system where vehicle data was collected in-field during fleet operation and then transmitted and made available in a near real time manner project partners.

Collaborated with INL to provide the vehicle data in a safe and reliable manner. INL has publically reported their summary results on ~600K miles; including ~50K driving and ~20K charging events.

Demonstrated the significant potential that electrification has to displace gasoline consumption in personal public transportation - including over 100,000+ miles traveled in all-electric mode.

Participated in over 300+ nationwide public outreach activities helping to build public awareness PHEV technology and facilitate public discussion on electrification.

Successfully demonstrated vehicle to smart meter communications with an Escape PHEV responding to price signals from the interface.

At the end of the Escape PHEV fleet demonstration, the vehicles had travelled over 800,000+ miles.

Began advanced information systems in an intelligent PHEV demonstration to further enhance the fuel economy and drivability of the vehicle – results to be reported upon completion in December 2013.

Leveraged the lessons learned in this DOE-sponsored program to support the introduction of two mass production PHEVs in NA and announced plans for a PHEV introduction in EU. In process of sending two Ford C-MAX Energi's for DOE evaluation of the production solutions.

Conclusions and Recommendations

In this final report regarding the Escape PHEV demonstration fleet part of this project, the lessons learned and experiences gained from the design and development and then utility fleet usage under the DOE program have been presented. During this program the Escape PHEV fleet accumulated over 800,000 miles and supported over 300 public and outreach events. Through regular fleet usage, static displays and ride & drive events these PHEVs assisted in establishing a cross-industry understanding of what a plug-in vehicle is and how it operates.

The data accumulated from the Escape PHEV demonstration fleet operation has been made available to INL. INL has analyzed the vehicle data from nearly 600,000 miles of operation and shared their summary results publically. The work and analyses have demonstrated that PHEV technology is a viable option for vehicle propulsion from a functional and performance basis and is ready for safe production and usage in the mass market. In fact, since the inception of this project nearly 5 years ago, Ford has introduced two mass production PHEVs and a BEV. Other OEMs are also bringing plug-in vehicles to market.

While the optimization of the vehicle-related PHEV technology has moved into the production arena and is being realized through increased MPG and MPGe results, there is still work to do in defining the potential fuel economy improvements possible through the leveraging of advanced information systems. The final phase of this project includes an assessment of cloud based computing and off board information to maximize the EV experience through the use of predictive information. Results to be reported when completed in December 2013.

Beyond this project, another key area where further work is required is within the communication between plug-in vehicles and the grid or smart meter. This project successfully demonstrated the communication interface between a vehicle and smart meter through the vehicle acceptance of price signals from the interface. However, broad industry consensus on the PHEV-grid handshake needs to be developed. Cross utility and automotive OEM communications standardization is necessary. Industry and regulators need to work together to identify regulations, standards, and building codes that need to be modified or added to create a single national regulatory framework.

Appendix – EPRI: Analysis of Factors Influencing Fuel Economy and Battery Usage

(Christine Lee EPRI, clee@epri.com)

Results

DATA FILTERING

While real world data can potentially introduce error into any data analysis, the basis of this investigation will be focused on the impact that different factors have on the average trend of fuel economy and battery energy consumption. Thus, data filtering was implemented to reduce the potential for noise and measurement error prior to analysis of factors influencing fuel economy and battery energy consumption. To control for consistency of driving behavior, PHEV05, PHEV17, PHEV18, PHEV19, and PHEV21 were removed from analysis. These vehicles displayed multiregional driving, that is, across North America or travel to international locations, so controlling for location would be difficult to account for.

Additional data filtering involved removing events that fell outside the scope of analysis. The following criteria were used for event removal:

- Fatal Errors: These include events that are affected by CAN Bus transmission errors or instances where full vehicle operation is limited. These also include events labels as impossible trips, where the duration was longer than 8 hours or the distance was greater than 500 miles.
- Key On/Off: These include events with either zero duration or distance. Key on/off events are interesting for emissions studies, but this is not the focus of this analysis.
- Short Trips: These include events that are shorter than 5 minutes or less than 0.1 miles. These event are generally considered too short for driving events and may be due to reparking the vehicle. These events are interesting for looking at the effects of startup only, which is discussed below, but not for the analysis of driving trends.
- Outside Region: These include events that are potentially outside the study region of interest. In this case, the study region of interest encompasses the area where the vehicle would typically drive for the participating utility. For example, this generally excludes trips where the vehicle was delivered from Detroit for participants whose service territory was not in the state of Michigan.

Ultimately, 43.3% of events were removed due to data filtering. While the reduction in number of events appears large, this does not pose a significant loss in useful driving data. The loss in driving metrics is minimal: 3.4% of miles, 4.2% of gallons of fuel, and 4.8% DC Wh of battery energy. On the other hand, the loss in hours of operation is not trivial at 27.3%. In conjunction with the minimal loss in driving metrics implies that the data filtering is removing non-driving related behavior. Thus, the data filtering for noise reduction is justified. Additional breakdowns of the data filtering are provided in Figure 75 located at the end of this article in the Additional Figures section on page 74.

INFLUENCING FACTORS

Eight variables will be investigated to determine the impacts that they have on average fuel economy and average battery energy consumption. These eight variables are grouped into four factors to determine the effect that each variable has on each other. For each of the factors, one variable was chosen to be divided into discrete categories of interest. Within each of these categories, the other paired variable was binned into small intervals. Once the categories and intervals are defined, the average fuel economy or average battery energy consumption is computed. In this analysis, fuel economy will be defined by two different rates: miles per gallon and fuel consumption in terms of gallons per 100 miles. Battery energy consumption will be defined as DC kWh per 100 miles.

The purpose of pairing the variables is to approximate real world driving behavior impacts on fuel economy and battery energy consumption. While the 8 variables could be studied in isolation, it is not common for this to occur in real world driving. This is apparent in Figure 76, Figure 77, Figure 78, and Figure 79 (Additional Figures: pp. 74-75) where the number of trips per variable category typically varies across the intervals of the other variable of interest. The four factors and their variables of interest are defined below:

- Start Up: This factor is defined by looking at categories of time since last trip over intervals of trip duration. For analysis of startup effects, short trips were included in the analysis. For all other factors, short trips, as defined in the Data Filtering section, were not included.
- Environment: This factor is defined by looking at categories of air conditioning (AC) use over intervals of average ambient temperature.
- Driver Aggressiveness: This factor is defined by looking at categories of average acceleration over intervals of average driving speed.
- Route Type: This factor is defined by looking at categories of average driving speed over intervals in percent time idle.

These four factors will be evaluated in two different ways. The first evaluation method looks at how these factors affect the average trend of fuel economy and battery energy consumption. This type of analysis will give better understanding of what drive behaviors are more economical in terms of fuel and battery use. This information can be used to better inform PHEV drivers of more optimal driving practices to maximize their gain from using a PHEV. This information will also benefit utilities by providing driver behavior impacts on a per vehicle basis. The second method of evaluation looks at the degree to which each of these factors affects the benefits of electrification. For this comparison, the analysis was divided into two categories: charge depletion only and charge sustain only trips. The benefits of electrification are determined by looking at the average savings in fuel and battery use when comparing charge depletion vs. charge sustain operation.

The following sections will individually look at the four factors and the trend they exert on average fuel economy and battery energy consumption. After that, there will be a section discussion the benefits of electrification. A very important note to keep in mind is that the focus of this analysis is to conduct a demonstration of what the potential impacts of driver behavior are on PHEV operation. While these impacts are measured in terms of fuel economy and battery energy consumption, the focus should not necessarily be on the magnitude of these values, but how they compare with each other. Regardless of PHEV model, every vehicle will have its own set of engine control strategies and powertrain to accessory load methodologies.

START UP

In terms of driver behavior, the choice of driving duration and frequency can impact the efficiency of the mechanical and electric propulsion of the vehicle. Figure 76 (Additional Figures: pg. 74) illustrates some generalizations of trip breakdown in terms of startup. Trips that were 30 minutes in duration or less made up 72.3% of the total trips; trips that were 10 minutes in duration or under made up 26.9% of the total trips. While the majority of trips occur within at least a day of the last trip, 4.0% of trips take place after more than a day had elapsed. Despite this small percentage, it will be shown later that this choice to drive infrequently can have a significant impact on fuel economy and battery energy consumption. The most frequent category of trips (47.0%) are those that have had at least 30 minutes to a under a day elapse before having been driven again. These benchmarks are important talking points for the trend analysis discussion for Figure 65 and Figure 66.

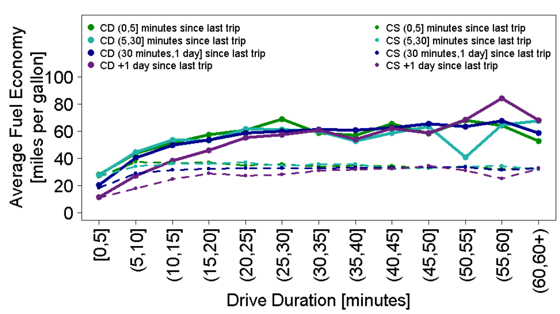

Figure 65: The Effect of Startup on Fuel Economy

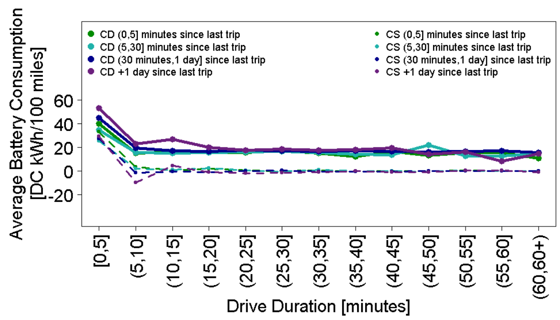

Figure 66: The Effect of Start Up on Battery Energy Consumption

Figure 65 and Figure 6666 show the average fuel economy in miles per gallon and the average battery energy consumption in DC kWh per 100 miles in terms of startup variables. The startup variables are categories of time since last trip over intervals of trip duration. The time since last trip categories are defined in the legends of Figure 65 and Figure 66 and the trip duration intervals are defined on the x-axis. For these figures, as well as subsequent figures in the influencing factors discussion, the thicker, solid lines represent charge depletion (CD) operation and the thinner, dashed lines represent charge sustain (CS) operation. In both figures, it is clear that regardless of CD or CS operation, driver behavior in terms of duration and frequency can have differing impacts on fuel economy and battery energy consumption.

Specifically in Figure 65, regardless of time since last trip, it takes about 30 minutes for the fuel economy to reach a stable level around 60 miles per gallon in CD operation. The time duration to a stable level fuel economy is slight shorter for CS operation; about 20 minutes to reach a little under 40 miles per gallon. This ramping up of the miles per gallon is an important general trend with respect to the aforementioned 30 minute or less benchmark because it encompasses nearly three fourths of the total trips. Despite the ramping effect on miles per gallon due to duration for all categories of time since last event, the time since last event does have a significant impact on the average initial starting value (the 0 to 5 minute duration interval) of miles per gallon within the first 30 minutes of duration. This difference in initial starting value is not distinct until at least 30 minutes to under a day have elapsed and is most impacted when the vehicle has been sitting for more than a day since it had last been driven. This effect is true in either CD or CS operation, and it is interesting to note that the initial starting values for both CD and CS start at the same points. However, the convergence to a stable miles per gallon level for all four categories happens slightly sooner for CS operation.

Figure 66 tells a similar story as Figure 65, however the impact of driver behavior on battery energy consumption is not as widespread as it was for fuel economy. The main difference is that the CD initial values (at the 0 to 5 minute duration range) do not start at the same points as the CS initial values. Despite this difference, the largest consumption of battery energy for initial starting values occurs when the vehicle has not been driven for over a day in CD operation. While it is clear that there is a spike in battery energy consumption for both CD and CS operation with regards to start up, this levels out by 10 minutes trip duration to around 20 DC kWh/100 miles for CD and nearly zero for CS. This dissipation in startup effects by 10 minutes trip duration for battery energy consumption accounts for about a quarter of total trips. Compared to the nearly three quarters of trips that have their fuel economy affected by startup, the effects for battery energy consumption are relatively small.

As with any mechanical powertrain, there will be start up effects that affect fuel economy. However, these effects can be diminished by driving the vehicle often. If the vehicle cannot be driven often, the driver can choose to plug in the vehicle such that it is always available for operate in CD mode since the increased fuel economy ramps up faster when operating in CD mode. The startup effects for battery energy consumption quickly dissipate once the vehicle has been driven at least 10 minutes.

ENVIRONMENT

In terms of driver behavior, the choice to use air conditioning can impact the efficiency of the mechanical and electric propulsion of the vehicle. Figure 77 (Additional Figures: pg. 75) illustrates some generalizations of trip breakdown in terms of environment. The majority of trips (83.9%) occur between the 20 to 85 °F range. In general, air conditioning use is not frequent; nearly half (53.5%) of all trips do not use it and this percentage jumps to three quarters (76.3%) of all trips if low air conditioning use is included. It is interesting to note that high air conditioning use is not prominent until the 70 to 75°F range. From that ambient temperature range and up, high air conditioning use makes up at least 30% or more of trips in each interval. The percent of trips that use high air conditioning when it is 70°F or warmer is 16.9% of the total trips. Despite this small percentage, it will be shown later that this choice to use high air conditioning when it is at least moderately hot outside can have a significant impact on fuel economy and battery energy consumption.

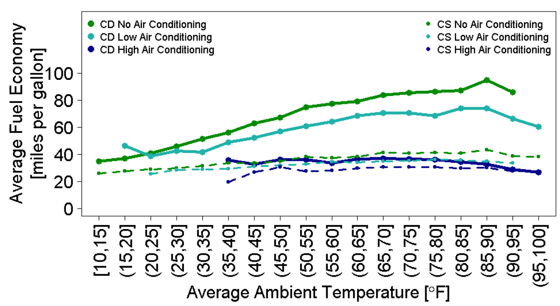

Figure 67: The Effect of Environment on Fuel Economy

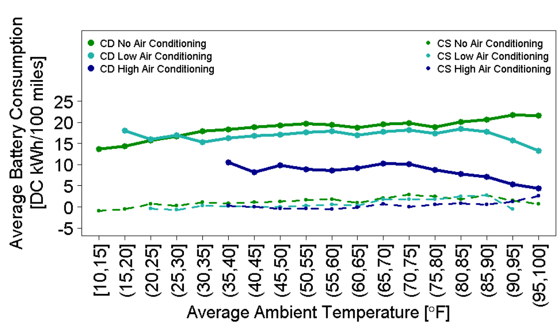

Figure 68: The Effect of Environment on Battery Energy Consumption

Figure 67 and Figure 68 show the average fuel economy in miles per gallon and the average battery energy consumption in DC kWh per 100 miles in terms of environment variables. The environment variables are categories of air conditioning (AC) use over intervals of average ambient temperature. The AC use categories are defined in the legend of Figure 77 (Additional Figures: pg. 75) and the average ambient temperature intervals are defined on the x-axis of Figure 67 and Figure 68.

Figure 67 shows an increasing trend in miles per gallon for both no and low air conditioning categories over the ambient temperature interval when in CD operation. The increase in miles per gallon is likely due to increased lubrication and decreased fluid viscosity that aids the mechanical powertrain. This improvement in miles per gallon for no and low air condition use is not strictly increasing, after 70^{o}F or warmer the miles per gallon benefit levels off and starts to decrease in CD operation. An important observation to note is that the high air conditioning category does not benefit from the increased ambient temperature. In fact, it spans the same 20 to 40 miles per gallon region as CS operation, converging to the CS counterpart as the temperature increases past 70°F or warmer. CS operation has a similar ordering of air conditioning categories as CD operation, but within a narrower region than the CD values.

DRIVER AGGRESSIVENESS

In terms of driver aggressiveness, frequent and high periods of acceleration during low average driving speed trips is considered highly aggressive behavior. This less-than-optimal driving style can impact the efficiency of the mechanical and electric propulsion of the vehicle. Figure 78 (Additional Figures: pg. 75) illustrates some generalizations of trip breakdown in terms of driver aggressiveness. Although the categories of average acceleration are evenly split into thirds over the total number of trips, the distribution of high average acceleration trips is skewed among the driving speed intervals. Within the 10 to 35 miles per hour intervals, high acceleration trips make up 30% or more of the trips. Slower speed trips, 30 miles per hour or less, make up about half of all trips. The 30 miles per hour benchmark is an interesting transition point for the impact of driver aggressiveness on fuel economy and battery energy consumption.

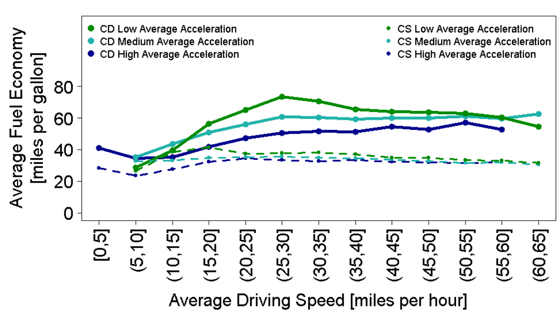

Figure 69: The Effect of Driver Aggressiveness on Fuel Economy

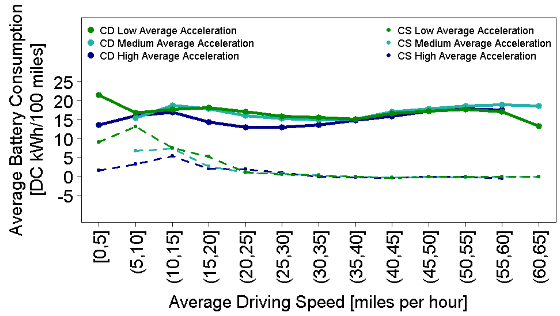

Figure 70: The Effect of Driver Aggressiveness on Battery Energy Consumption

Figure 69 and Figure 70 show the average fuel economy in miles per gallon and the average battery energy consumption in DC kWh per 100 miles in terms of driver aggressiveness variables. The driver aggressiveness variables are categories of average acceleration over intervals of average driving speed. The average acceleration categories are defined in the legend of Figure 78 (Additional Figures: pg. 75) and the average driving speed intervals are defined on the x-axis of Figure 69 and Figure 70.

Figure 69 shows that for all three categories of acceleration, the improvement in fuel economy increases with increasing speed, stabilizing after about 40 miles per hour. This may be due to the possibility that slower trips (15 miles per hour and slower) are often shorter in duration and do not allow enough time for engine warm up to reap the full benefits of fuel economy. Regardless, the increase in fuel economy generally reaches a peak at around 30 to 35 miles per hour. At this point, the increased speed exerts more stress on the mechanical powertrain. However, the increase in stress does not continuously decrease the fuel economy, the drop is small and then simply levels off around the 50 to 60 miles per gallon range for CD operation. Regardless of speed, low average acceleration provides the best fuel economy in both CD and CS operation. Lower acceleration wastes less fuel because the driver is not adding significant additional stress to the vehicle’s powertrain. Thus, around 30 to 35 miles per hour with low acceleration seems to provide an optimal operating level for fuel economy.

A similar story is seen in the battery energy consumption of Figure 70 when it comes to an optimal point of operation. For CD operation, all three levels of average acceleration show a drop in battery energy consumption during the same average speed intervals that reflects an increase in fuel economy. This not only shows that there is an optimal speed range for the mechanical powertrain, but also a similar optimal speed range for the electrical powertrain as well. Like Figure 69, Figure 70 also shows some increased resource use in under 30 miles per hour speed range. This effect is not strong for CD operation. However, CS operation shows a sharp decrease in battery energy consumption during the 0 to 30 miles per hour interval. This may be due to the possibility that slower trips are often shorter trips, so the engine is still subject to start up control strategies. This may also be due to the greater potential impact of regenerative braking during low-speed events.

ROUTE TYPE

In terms of route type, trips with low average driving speed and high percentages of idle time are considered delivery routes or congested traffic. Trips with medium average driving speed and medium percentages of idle time are considered urban or city driving. Trips with high average driving speed and low percentages of idle time are considered highway driving. The choice of route type can impact the efficiency of the mechanical and electric propulsion of the vehicle. Figure 79 (Additional Figures: pg. 75) illustrates some generalizations of trip breakdown in terms of route type. In general, the breakdown of trips by speed is evenly split into thirds of the total trip count. However, the distribution of trip speeds is not even among the percent time idle intervals. Of the 34.5% of total trips that are high speed, nearly all of them (31.9% of total trips) fall within the 25% time idle interval or lower. For trips that are idle 50% or more of the time, slow speed trips make up at least two thirds of the trips per idle interval.

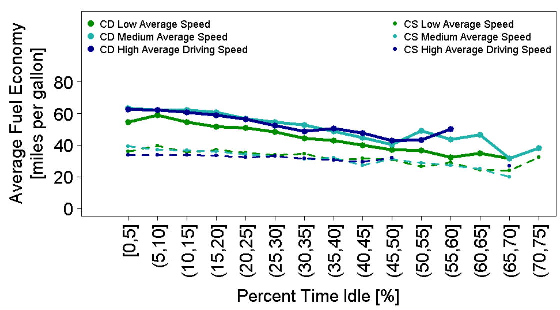

Figure 71: The Effect of Route Type on Fuel Economy

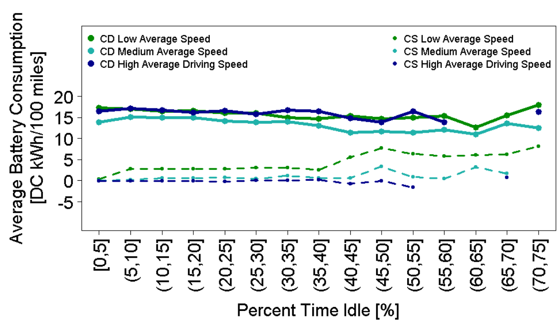

Figure 72: The Effect of Route Type on Battery Energy Consumption

Figure 71 and Figure 72 show the average fuel economy in miles per gallon and the average battery energy consumption in DC kWh per 100 miles in terms of route type variables. The route type variables are categories of average driving speed over intervals of percent time idle. The average driving speed categories are defined in the legend of Figure 79 (Additional Figures: pg. 75) and the percent time idle intervals are defined on the x-axis of Figure 711 and Figure 72.

Figure 711 shows a consistent decrease in fuel economy as the percent time idle increases. This trend is easily explained; if the vehicle is using fuel and not going anywhere, this will drive the fuel economy down, regardless of CD or CS operation. While the distinction between speed categories is not clear for CS operation, the downward trend for low average speed appears to be the lowest in terms of fuel economy for CD operation. The same explanation for low speed impacts provided in the driver aggressiveness section possibly holds true for route type as well: low speeds are possibly associated with shorter duration trips and thus subject to engine warm-up. The downward trend in low speed fuel economy in CD converges to the CS range once the percent time idle exceeds 50% or more.

The explanation of Figure 72 involves some of the results found in the driver aggressiveness section for CD operation. For CD operation, the low and high average speed categories are indistinct, but the medium speed category is consistently lower than either the low or high speed category. This reduction in electrical energy consumption is coincident with the range of the medium speed category: 23 to 34.7 miles per hour. This medium speed range covers the optimal 30 to 35 mile per hour speed range that was discussed earlier in the driver aggressiveness section. Recall that this range was considered optimal because of the reduction in stress on the electrical powertrain. For CS operation, low speed trips yield the highest battery energy consumption, possibly due to the startup strategies discussed earlier in other sections. This increase is especially apparent once the percent time idle goes higher than 40% of the time.

BENEFITS OF ELECTRIFICATION

While the previous four sections explain the nuanced impacts that different factors can have on fuel economy and battery energy consumption, one distinct message is clear: in all cases, the benefits of electrification are clear. To showcase these benefits for every influencing factor, fuel consumption in gallons per 100 miles and battery energy consumption in DC kWh per 100 miles were used as metrics of comparison when comparing electrified operation (charge depleting) with standard hybrid operation (charge sustaining). To aid in the discussion of the benefits of electrification, Figure 73 and Figure 74 provide summaries of the comparison of charge depleting vs. charge sustain operation.

	Average CD vs CS Difference	Average CD vs CS Difference	Average CD vs CS Difference	Average CD vs CS Difference
Start Up	(0, 5] minutes since last trip	(5, 30] minutes since last trip	(30 minutes, 1 day] since last trip	+1 day since last trip
Gallons/ 100 Miles	-1.1	-1.0	-1.3	-1.6
Environment	No Air Conditioning	Low Air Conditioning	High Air Conditioning	--
Gallons/ 100 Miles	-1.2	-1.4	-0.6	--
Driver Aggressiveness	Low Average Acceleration	Medium Average Acceleration	High Average Acceleration	--
Gallons/ 100 Miles	-1.1	-1.2	-1.0	--
Route Type	Low Average Driving Speed	Medium Average Driving Speed	High Average Driving Speed	--
Gallons/ 100 Miles	-0.8	-1.3	-1.2	--

Figure 73: Summary Table of Average CD vs. CS Difference in Fuel Consumption

	Average CD vs CS Difference	Average CD vs CS Difference	Average CD vs CS Difference	Average CD vs CS Difference
Start Up	(0, 5] minutes since last trip	(5, 30] minutes since last trip	(30 minutes, 1 day] since last trip	+1 day since last trip
DC kWh/ 100 Miles	13.7	14.4	17.3	19.3
Environment	No Air Conditioning	Low Air Conditioning	High Air Conditioning	--
DC kWh/ 100 Miles	17.4	16.4	8.0	--
Driver Aggressiveness	Low Average Acceleration	Medium Average Acceleration	High Average Acceleration	--
DC kWh/ 100 Miles	14.2	15.6	14.2	--
Route Type	Low Average Driving Speed	Medium Average Driving Speed	High Average Driving Speed	--
DC kWh/ 100 Miles	11.3	12.2	16.4	--

Figure 74: Summary Table of Average CD vs. CS Difference in Battery Energy Consumption

Figure 73 shows a summary of the fuel consumption comparison between charge depleting and charge sustaining operation for the four influencing factors. For each row of influencing factor, the average difference between CD and CS fuel consumption was computed per category across the entire interval range for that factor. To interpret these values, a positive value for the average difference between CD vs. CS means that CS operation had a relatively better fuel consumption than CD operation. A negative value for the average difference between CD vs. CS operation means that CD operation had a relatively better fuel consumption than CS operation. The impact of Figure 73 is clear: regardless of the influencing factor, on average, CD operation uses fewer gallons of fuel per 100 miles than CS operation. This relative difference is influenced by the type of influencing factor and category. The weakest benefits in decreased fuel consumption were demonstrated for route types with low average speed and for environments where air conditioning use is high. The strongest advantage of CD operation over CS operation were seen in startup when the vehicle was left for 30 minutes or more, when air conditioning use is minimal, and in route type when the vehicle was driven at a medium speed. It was earlier discussed how this medium speed category provided an optimal level of operation.

Figure 74 shows a summary of the battery energy consumption between charge depletion and charge sustain for each of the four influencing factors. For each row of influencing factor, the average difference between CD and CS battery energy consumption was computed across all the intervals of that category. A positive value of CD vs. CS battery energy consumption means that battery energy was consumed and a negative value of CD vs. CS battery energy consumption means that battery energy was regenerated. Figure 74 provides further support for the results found Figure 73. For every category of decreased fuel consumption, there were relatively higher, positive values of battery energy consumption. This means that electrical energy was used to displace the use of more expensive fuel, which can be a benefit of electrification.

Additional Figures

DATA FILTERING

	Raw Total	Fatal Error	Key On/Off	Short Trips	Outside Region	Removed Total	Percent Loss	Final Total
Trips	59422	2326	5975	16634	780	25715	43.3%	33707
Dates	10274	73	282	887	266	1508	14.7%	8766
Miles	540892.9	5047.9	227.6	5785.3	7415.8	18476.5	3.4%	522416.4
Hours	21255.6	4632.0	299.0	613.2	268.2	5812.4	27.3%	15443.1
Gallons	14169.6	136.2	54.6	240.9	168.9	600.6	4.2%	13568.9
DC Wh	37441.5	257.5	58.4	754.3	728.9	1799.1	4.8%	35642.4

Figure 75: Summary Table of Data Filtering

OPERATIONAL BEHAVIOR

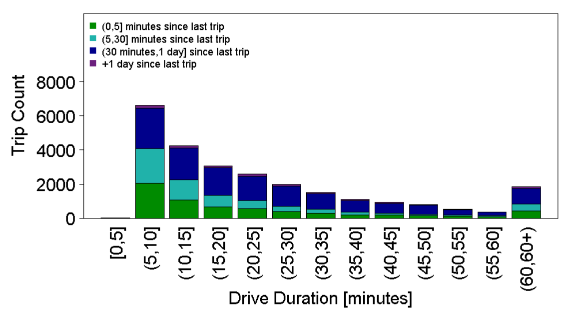

Figure 76: Breakdown of Trips by Start Up

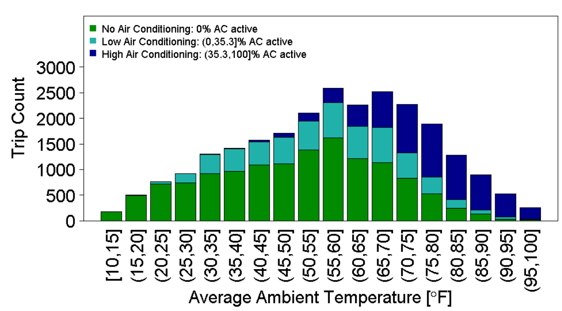

Figure 77: Breakdown of Trips by Environmental Factors

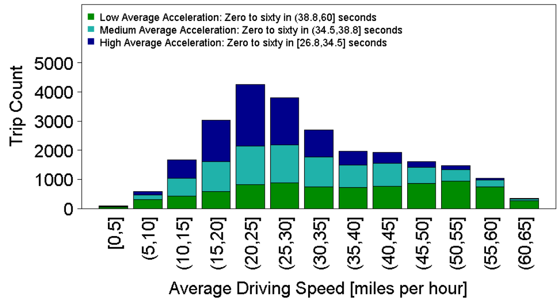

Figure 78: Breakdown of Trips by Driver Aggressiveness

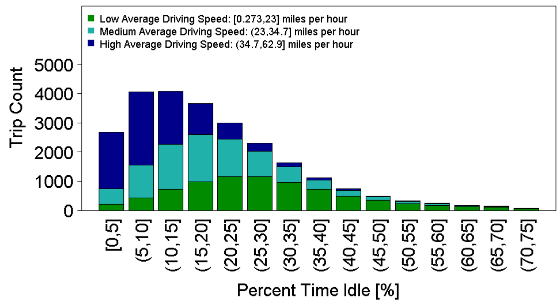

Figure 79: Breakdown of Trips by Route Type

Appendix – EPRI: Drive Operation Analysis – Factors Influencing Energy Consumption

(Doug Saucedo, EPRI, dog@evosyseng.com)

Results

The results presented are based on vehicle data recorded between April 2009 and April 2012.

DRIVE OPERATIONS ANALYSIS

The drive events are evaluated by discussing the stable energy consumption and factors influencing energy consumption.

STABLE ENERGY CONSUMPTION

The stable energy consumption was evaluated for the aggregated fleet. This strategy is based on methods to benchmark blended type and EV-capable plug-in hybrid electric vehicles (Duoba et al, 2008; Duoba et al, 2009).

The SEC lines presented are based on the distance-weighted average fuel and battery energy consumption observed across trip-type, time-of-week, and season. For convenience fuel consumption is referred to as FC and battery energy consumption is referred to as BC. Non-average influences can shift the results presented.

Trip-types were defined by drive events reporting average speeds less than or equal to 42 mph and trips with average speeds greater than 42 mph. The two sets were labeled as city and highway trips and are **not** equivalent to Environmental Protection Agency city and highway controlled test procedures. Instead, these designations are used for convenience of splitting trip types. A combined trip-type was also defined which provides the distance weighted average energy consumption reported by the city and highway trips.

Time of week is defined by weekday (Monday through Friday) and weekend (Saturday and Sunday).

The seasons are defined by four groups: Spring (March through May), summer (June through August), fall (September through November), and winter (December through February).

Each FC and BC value is used to create an ordered pair for net, charge-depleting, and charge-sustaining operation. The net operation is the distance weighted average of charge depleting and charge sustaining operation. The charge-depleting and charge sustaining ordered pairs are then used to estimate the parameters of a line that connects them (Figure 80**Error! Reference source not found.**).

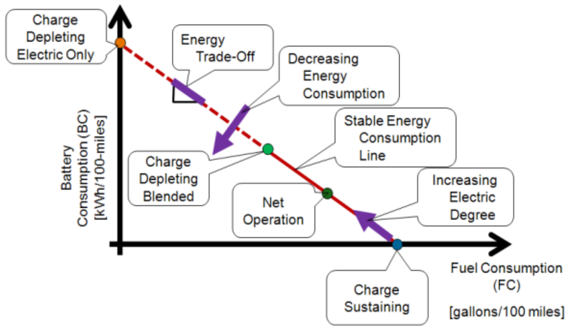

Figure 80: Stable Energy Consumption Characteristics

Energy consumption points closer to the origin represents lower energy consumption driving. Lower energy consumption is typically associated with lower vehicle speed, driver aggressiveness, and mild environmental conditions (Carlson et al, 2012). Other factors play a role and will be discussed in detail.

The line connecting the charge-depleting and charge-sustaining distance-weighted average operating points provides additional information about the energy-trade-off between fuel and electricity use in the vehicle:

- Charge-Depleting, Electric Only Battery Consumption (BC_E)
  - Extrapolated ordinate-intercept
- Charge-Sustaining Fuel Consumption (FC_S)
  - Interpolated abscissa-intercept
- Energy Trade-Off (ε)
  - The additive inverse for the slope of the SEC line (slope = - ε)
- Charge-Depleting Blended (ξ_d) and Net (ξ_n) Electric Degrees
  - Fraction of total energy consumed derived from battery energy using the energy-trade-off as an equivalence ratio between battery energy and fuel (Figure 81: Equation 1)
  - Depletion electric degree represents the fraction of total energy sourced from the battery while the vehicle is known to prioritize battery depletion.
  - Net electric degree combines charge-depleting electric degree with the operator's charging habits.

$$\xi = \frac{BC}{\varepsilon \cdot FC + BC}$$

Figure 81: Equation 1

Method Limitations and Estimate Details

This method has limitations in that many external factors influence the FC and BC consumed. The coarse filtering applied to the data to produce the following results does not separate the majority of these influences. Instead, the results present the distance weighted average within an operating group given the additional unfiltered influences.

The result's significance will depend on the distance available for analysis. The majority of distance travelled is observed on weekdays. The distribution of distance travelled appears relatively uniform across seasons. Highway miles travelled are reported slightly greater than city miles travelled. Note that the combined miles is the sum of city and highway miles travelled and the sum of combined miles is the total miles available for analysis (Figure 82).

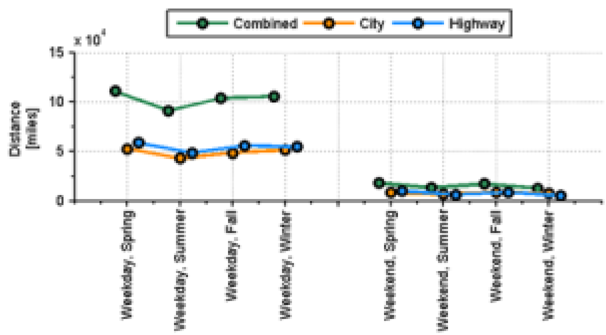

Figure 82: Distance Travelled by Trip-Type, Time-of-Week, and Season

The weekday seasons contain roughly 50,000 miles per season and trip-type. The weekend seasons contain roughly 7,500 miles per season and trip-type. The relatively low distance sampled for weekend events will result in an elevated noise potential. The weekend results are provided for discussion but should be weighted accordingly.

The distance weighted average net, charge-depleting, and charge-sustaining operating points are plotted along with the SEC line. The indicated net fuel and battery energy consumption is scattered underneath the lines to demonstrate the variation in energy consumption observed on a per-event basis (Figure 83).

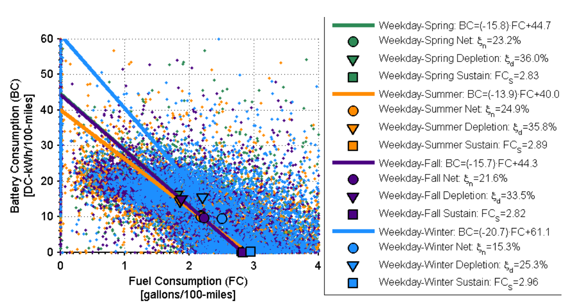

Figure 83: Fleet-Aggregated, City SEC Lines by Weekday and Seasons

The results for city operation demonstrate a broad variety of fuel and battery energy consumption. All electric operation is observed with operating points located along the ordinate. The cloud of operating points around the SEC lines demonstrate considerable noise stemming from influencing factors not captured by simply dividing the data by route-type, time-of-week, and season.

The SEC line parameters are reported within the legend for each weekday-season. The lines report the energy trade-off as the negative slope. The electric degree is reported for charge-depleting and net operation. The charge-sustaining fuel consumption is also reported as FC_S.

For the city results, the SEC lines for spring, summer, and fall are relatively similar with a minor difference in the observed energy trade-off for the fall. The SEC line for winter is noticeably different with elevated fuel consumption and larger energy-trade-off. This indicates that winter city driving events require more electricity to displace liquid fuel. Overall, the energy trade-off varies between 13.9 and 20.7 DC-kWh/gallon in the summer and winter, respectively. The charge-depleting, electric-only result suggests between 40.0 and 61.1 DC-kWh/100-miles between summer and winter, respectively.

The charge-sustaining fuel consumption is observed between 2.82 and 2.96 gallons/100-miles (35.5 mpg and 33.8 mpg) in the fall and winter, respectively. The depletion electric degrees vary between 25.3% and 36% in winter and spring, respectively. The net electric degrees are reported between 15.3% and 24.9% in the winter and summer, respectively.

The highway trip-types show a distinctly different scatter. Few events register as all-electric and the variation around the SEC lines is greatly reduced (Figure 84)

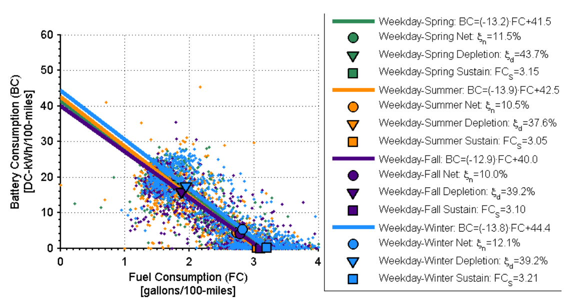

Figure 84: Fleet-Aggregated, Highway SEC Lines by Weekday and Seasons

The weekday highway SEC lines share slopes with less deviation across seasons as observed in the city weekday set (Figure 83). This is confirmed by comparing the slopes and intercepts listed in the legend. Highway events demonstrate between 12.9 and 13.9 DC-kWh/gallon in the fall and summer respectively. The all-electric extrapolation is observed between 40.0 and 44.4 DC-kWh/100-miles in the fall and winter, respectively. The charge-sustaining fuel consumption is reported between 3.05 gallons/100-miles (32.8 mpg), and 3.21 gallons/100-miles (31.2 mpg).

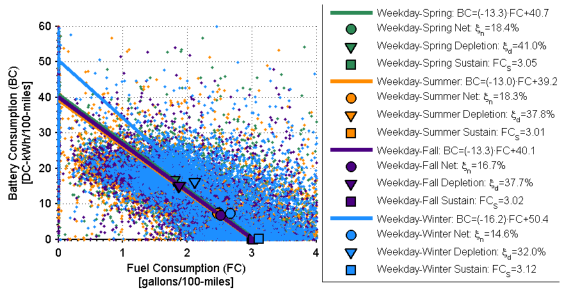

Figure 85: Fleet-Aggregated, Combined SEC Lines by Weekday and Seasons

The combined winter results are observed to be attenuated compared to the city winter results. This is due to the distance weighted averaging of highway results. Energy trade-off results are observed between 13.0 and 13.3 DC-kWh/gallon for spring through fall. The winter energy trade-off is elevated to 15.2 DC-kWh/ gallon. CS fuel consumption is rated between 3.02 and 3.12 gallons/100-miles - 33.1 and 32.1 mpg, respectively.

Stable Energy Consumption Parameters by Route-Type, Weekday, Weekend, and Season

A summary of the SEC line analysis is presented by comparing parameters across the operations classes. Results for trip-type, time-of-week, and season are plotted together for the total distance accumulated and for each of the SEC line parameters discussed. The distance accumulated is discussed first to indicate the relative weight under which the result should be considered. The energy trade-off results are shown first, followed by the charge-sustaining fuel consumption and charge-depleting, electric-only, battery energy consumption results. The results are concluded by discussing the charge-depleting and net electric degrees.

The energy trade-off demonstrates values between 12 and 20 DC-kWh/gallon (Figure 86).

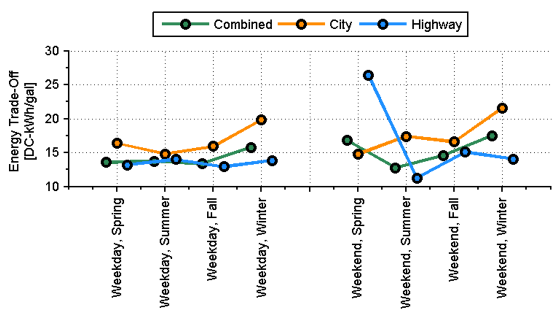

Figure 86: Energy Trade-Off by Route-Type, Time-of-Week, and Season

Highway energy trade-off is relatively stable for weekday-highway events. Weekday city events demonstrate elevated energy trade-off indicating colder weather conditions increase the amount of battery energy required to displace a gallon of fuel. The weekend results demonstrate elevated noise compared to the weekday results. However the trend observed in the weekday city driving persists with elevated energy trade-off observed in weekend winter conditions. The weekend-spring highway operation reported elevated energy trade-off but is in disagreement with the weekday spring result which has greater amount of miles weighting its value. The noise observed in the weekend results is likely due to the relatively low sample size and will require further investigation to properly address.

The importance of the energy trade-off is the insight it provides into the cost trade-off for the vehicle between charge-depleting and charge sustaining operation. The DC-kWh figure can be adjusted by the average charge-efficiency to approximate the AC-kWh/gallon energy trade-off. Note that both AC-kWh and gallons are both standard billing units for the respective energy sources. As will be sown later, the charge efficiency averages near 80%. Assuming 13 DC-kWh/gallon, 80% charge efficiency, \$0.10/AC-kWh, and \$4.00/gallon, the energy cost trade-off would report slightly over 59% cost savings or \$0.41 of electricity for each \$1.00 of fuel consumed. Under these assumptions, roughly 16.3 AC-kWh consumed displaces one gallon of fuel used in vehicle operating in charge-sustaining mode.

The charge-sustaining fuel economy is evaluated in the same fashion with time-of-week, season, and trip-type reported. The fuel economy is observed to be relatively stable within a trip-type across time-of-week and season (Figure 87).

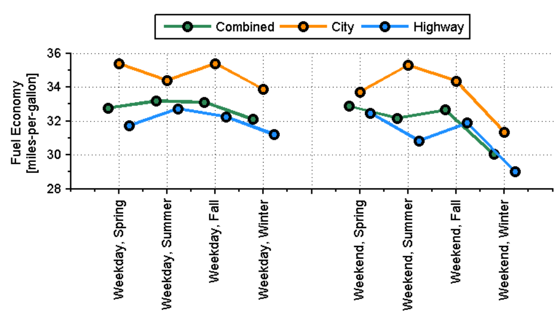

Figure 87: Charge-Sustaining Fuel Consumption by Route-Type, Time-of-Week, and Seasons

The charge-sustaining fuel economy ranges between 29 and 36 mpg. City driving demonstrates greater fuel economy than highway. Since the distance travelled is weighted slightly more in highway trip-types, the highway fuel economy will contribute more to the reported combined, charge-sustaining, fuel economy.

The projected, charge-depleting, electric-only, battery consumption is reported by trip-type, time-of-week, and season. Weekday, highway trip-types demonstrate relatively stable battery consumption across seasons reporting between 40 and 43 DC-kWh/100-miles (Figure 88).

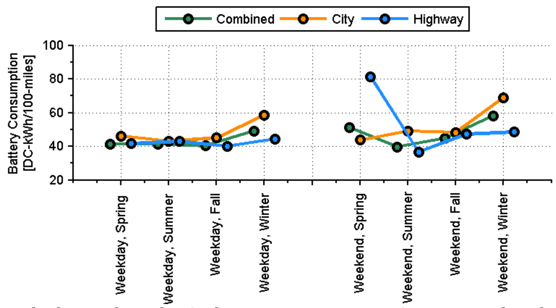

Figure 88: Extrapolated, Charge-Depleting, Electric-Only Battery Energy Consumption by Route-Type, Time-of-Week, and Seasons

The weekday-winter highway results demonstrate a very slight increase compared to the other seasons at 43 DC-kWh/100-miles, but the observation may not be significant. Near 61 DC-kWh/100-miles, city weekday-winter battery consumption is greatly elevated compared to all other results.

As with energy trade-off, the weekend results show elevated noise while reiterating the city-winter observation of elevated battery energy needed to displace fuel. The weekend-spring highway battery consumption also reports elevated battery energy consumption but is in disagreement with the much heavier distanced-weighted weekday result.

One important way the electric only battery consumption estimate can be used is in the comparison between a fully electric version of the vehicle to the charge-sustaining and conventional versions of the vehicle. The energy trade-off comparing the charge-sustaining charge-management mode has already been discussed. The conventional Ford Escape FWD vehicle can be compared by assuming comparability to EPA fuel economy estimates.

The EPA reports the 2008 FWD Escape city/combined/highway at 20/22/26 mpg respectively. The EPA reports the 2009 FWD Escape city/combined/highway at 20/23/28 mpg respectively (FuelEconomy.gov, 2012). For simplicity, 25 mpg is assumed as an estimate for the conventional Ford Escape - or 4.0 gallons/100-miles. Assuming 40 DC-kWh/100-miles for the fully electric Ford Escape, the energy trade-off between the electric and conventional Escape would be 10 DC-kWh/100-miles. Assuming 80% charge efficiency results in 12.5 AC-kWh needed to displace a gallon of fuel. Applying the fuel cost assumption from prior, the energy cost trade-off would be $0.31 of electricity for every $1.00 spent on fuel – or 69% fuel cost reduction. Note that the EPA estimates indicate less than 25 mpg as a combined fuel economy. This observation indicates greater fuel costs savings could be achieved.

The energy trade-off, fuel consumption, and battery energy consumption provide information about the vehicle's overall energy consumption and the trade-off between the two energy sources. The electric degree provides another perspective on the vehicle's ability to use electricity by reporting the fraction of the energy sourced from the battery.

The depletion electric degree measures the vehicle's ability to use electricity while the vehicle is known to prioritize battery depletion (Figure 89).

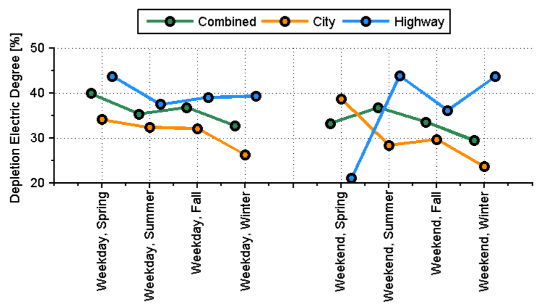

Figure 89: Depletion Electric Degree by Route-Types, Time-of-Week, and Seasons

While depleting the vehicle demonstrates between 25% and 45% electric degree. Weekday events suggest highway operation provides elevated electric degree compared to city operation. The weekend-spring results conflict with this observation, but as mentioned previously, the weekend-spring highway results demonstrated low distance weighting and is likely subject to greater noise. In both weekday and weekend operating cases the electric degree is observed to decrease in the winter for city operation compared to warmer months.

The net electric degree combines the depletion electric degree with the operator's charging habits. As a result, the net electric degree will always be less than the depletion electric degree since the vehicle's utility factor cannot be greater than 1 (Figure 90).

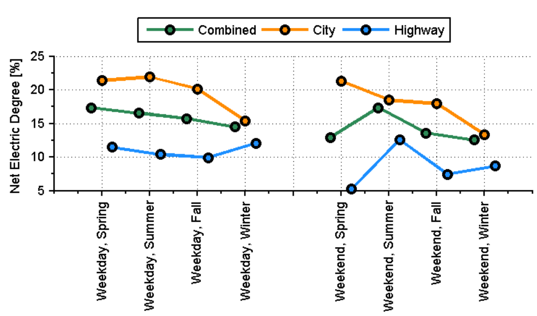

Figure 90: Net Electric Degree by Route-Type, Time-of-Week and Seasons

The net electric degrees are observed between 6 and 25%. City net electric degree is observed greater than highway net electric degree for both weekday and weekend events. The highway events appear relatively stable for weekday events with a slight depression during warmer seasons of the year. The weekday city net electric degree peaks in the summer at 25% and falls to near 15% by the winter. A similar feature is observed in weekend city net-electric degree.

CHARGE OPERATIONS ANALYSIS

Charge data is evaluated by the fleet aggregated charge event efficiency and load shapes.

CHARGE EVENT EFFICIENCY

In this section we explore the charger efficiency with respect to charge energy consumed and battery initial state-of-charge. The net energy efficiency is defined by the fraction of energy delivered to the battery relative to the grid energy consumed.

The grid energy consumed was used to weight the histogram for the charge event net efficiency observed for the fleet (Figure 91).

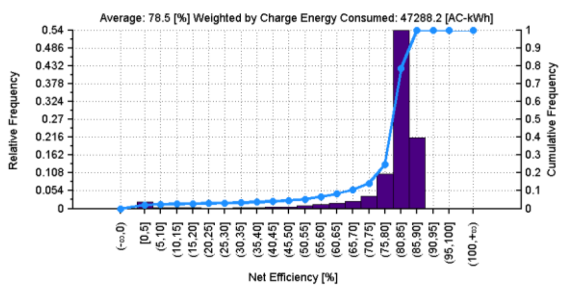

Figure 91: Fleet Aggregated, Charge Event Net Efficiency Histogram Weighted by Charge Energy Consumed

The maximum fraction is observed in the 80 to 85% net efficiency bin with 54% of charge energy consumed. The median values falls at 82% net efficiency. Note the small fraction (~2.5%) of charge energy consumed was allocated to 0-5% net efficiency. This biases the energy consumed weighted average net efficiency toward 78.5%. The maximum, average net efficiency was observed near 86%. To further explore the charging operations and their impact on observed charger efficiency, the charge energy consumed was used to weight the histogram for charge energy consumed (Figure 92).

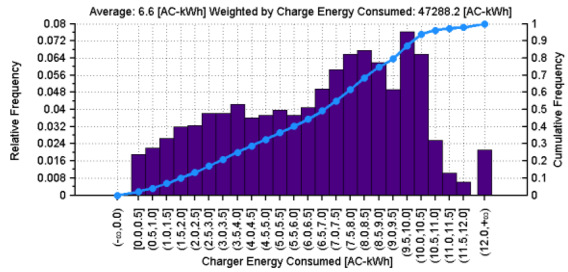

Figure 92: Fleet Aggregated, Charge Event, Charge Energy Consumed Histogram Weighted by Charge Energy Consumed

The maximum fraction is observed between 9.5 to 10 AC-kWh and accounts for 7.6% of charge energy consumed. The histogram reports 2% of charge energy can be attributed to events with 0.5 AC-kWh consumed or less. Over 2% of events are observed to consume greater than 12 AC-kWh. The median value is reported near 6.8 AC-kWh and the average is reported at 6.6 AC-kWh.

The charge energy consumed was also used to weight the initial battery state-of-charge histogram (Figure 93).

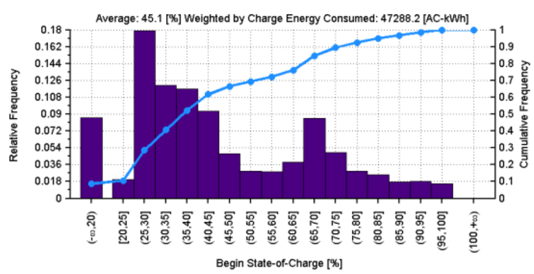

Figure 93: Fleet Aggregated, Charge Event, Initial State-of-Charge Histogram Weighted by Charge Energy Consumed

The histogram reports roughly 9% of charge energy consumed can be attributed to events with initial battery state of charge at less than 20%. The maximum fraction of battery energy consumed falls into an initial battery state-of-charge between 25 and 30%. Just less than 1.8% of battery energy consumed is attributed to charge events starting with 95 to 100% battery state-of-charge.

A 2D histogram for initial battery state of charge versus battery energy consumed was used to explore fleet charging operations further. The histograms were evaluated by weighting the frequency by event count and charge energy consumed.

The event count 2D histogram indicates a high frequency of events initiating at battery state-of-charge above 90% and charge energy consumed less than or equal to 0.5 AC-kWh (Figure 94).

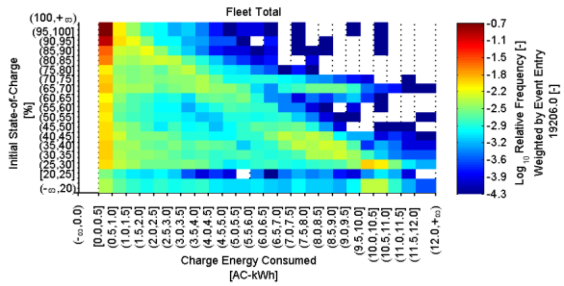

Figure 94: Fleet Aggregated, Charge Event, Operation, Event Entry Weighted, Frequency by Initial Battery State-of-Charge and Charge Energy Consumed

The color map is scaled from -0.7 to -4.3 and represents the $\log_{10}$ of the event entry weighted frequency. Note that the frequency between warm and cool colors is orders of magnitude apart. The map is read such that only yellow through red regions mark the most important regions. Blank, or white, regions were not populated by data.

The dark red region in Figure 94 indicates -0.7 which is used to calculate the fraction of events in that region by $10^{-0.7}$=0.1995. Thus 19.95% of events are indicated at low energy consumed and near full initial battery state-of-charge. This observation suggests that the charger is being reset while the battery is full. This charger reset phenomena flags additional charge events in the data record that are dominated by high initial state-of-charge and low charge energy consumed.

The fraction of charge energy consumed provides another insight into charging operations (Figure 95).

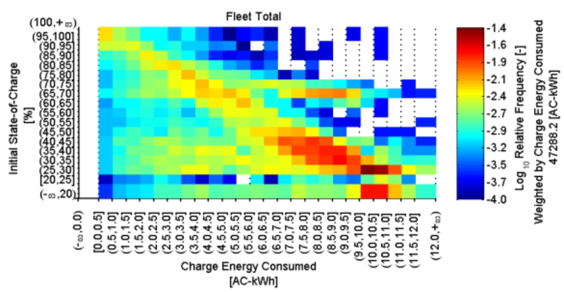

Figure 95: Fleet Aggregated, Charge Event, Operation, Charge Energy Consumed Weighted, Frequency by Initial Battery State-of-Charge and Charge Energy Consumed

As with the event weighted histogram, the charge energy consumed frequency is scaled by $\log_{10}$. Warm colors are orders of magnitude more frequent than cool colors. Note that the dark red region, representing -1.4, indicates a charge energy consumed frequency around 3.98% while -4.0 relates to 0.01%.

A broad region appears from 100% initial state of charge and near zero-energy consumed toward 20% initial state of charge and around 11 AC-kWh consumed. Charge energy allocated below this region represents incomplete charges. Charge energy allocated above the region represents complete charge with more energy than normal consumed. The high frequency region observed above the main trend line is likely due to the two battery systems employed in the aggregated fleet results.

The average efficiency for the initial state-of-charge and battery energy consumed domain was explored by calculating the energy consumed weighted average. The average was calculated for the same set of bins used to explore the event and charge energy weighted initial state-of-charge and charge energy consumed 2D histograms (Figure 96).

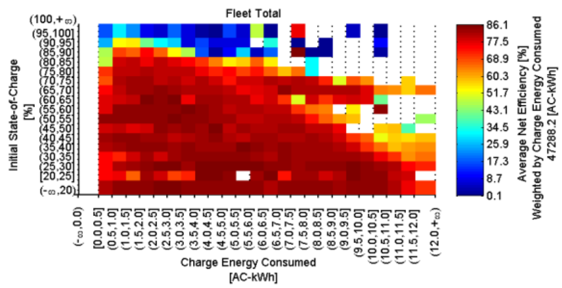

Figure 96: Fleet Aggregated, Energy Consumed Weighted, Average Net-Efficiency Versus Initial State of Charge and Battery Energy Consumed

The map suggests extremely low efficiency above the full charge region and helps explain the 0-5% efficiency region observed in the energy weighted distribution of net charge efficiency. The maximum average net efficiency was observed at 86.1%.

LOAD SHAPES

Load shapes for the aggregated fleet were evaluated by time-of-week and season. The load shapes were calculated by averaging observed charging at 1 minute intervals across local time of day (EPRI, 2011). Filters were put in place to ignore days demonstrating no drive or plug-in activity. The results allow a discussion regarding the average daily energy demanded per vehicle and the average charge power demand variation across local time-of-day, time-of-week, and season given the vehicle is either driven or plugged-in during the day.

The daily average energy demonstrated by the fleet varies between 4.8 and 6.6 AC-kWh per vehicle (Table 1).

Table 1 – Daily Average Energy Consumption per Vehicle by Time-of-Week and Season

Filter	Average Charge Energy per Vehicle-Day [AC-kWh/vehicle-day]
Total	6.2
Weekday	6.4
Weekend	5.3
Weekday, Spring	6.6
Weekday, Summer	6.1
Weekday, Fall	6.5
Weekday, Winter	6.1
Weekend, Spring	5.2
Weekend, Summer	5.5
Weekend, Fall	5.6
Weekend, Winter	4.8

The average for all data reported 6.2 AC-kWh/day/vehicle. Weekend average energy appears slightly attenuated compared to weekday average energy per vehicle-day. Within the weekday season set, spring demonstrates the greatest daily average energy consumption followed by fall. Winter and summer weekday charging appears equal on an energy basis.

Information regarding potential grid impacts is provided by the average power per vehicle load shapes. The weekday versus weekend load shapes show significant difference in wave-form (Figure 97).

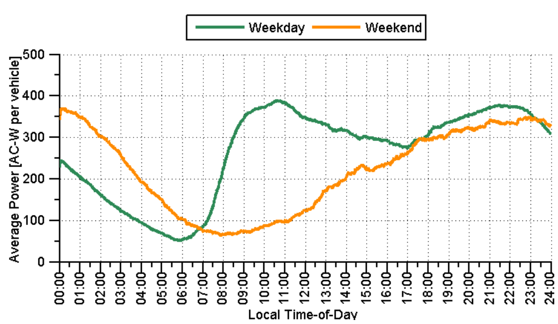

Figure 97: Fleet Aggregated Load Shapes for Weekday and Weekend

The weekend maximum power is observed near midnight at 360 AC-W per vehicle. The weekday load shape demonstrates two peak power domains near 10:00 and 22:00 just under 400 AC-W per vehicle. The variation in load shapes for weekday and weekend was also explored across seasons. The variation in weekdays across season is observed with slight variations in magnitude but with the general characteristics observed in weekday events (Figure 98).

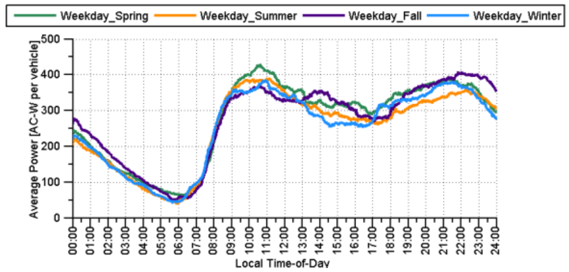

Figure 98: Fleet Aggregated Load Shapes for Weekdays Across Seasons

Across seasons, the weekday load shapes show minimums in the neighborhood of 50W with two peaks occurring around 10:00 and 22:00.

Some minor variation across seasons is also observed. Fall and spring weekdays around 10:00 demonstrate near 50W/vehicle difference relative to the 380W observed for fall, the spring represents a 13% greater power draw compared to fall observations near 10:00. The magnitude of difference is observed throughout the day between different seasons with local convergence near noon. No single season dominates the maximum or minimum power domains across the vehicle day.

As with the weekday results, weekend results across season demonstrate the general characteristics of the weekend load shape with variation in the waveform's magnitude (Figure 99).

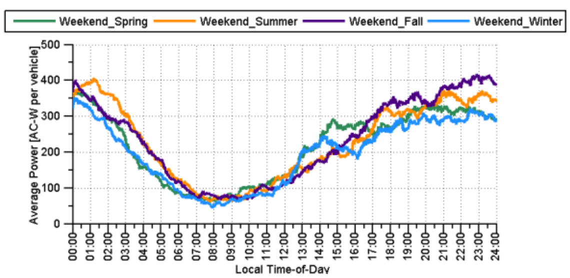

Figure 99: Fleet Aggregated Load Shapes for Weekends Across Seasons

The weekend spring results are observed slightly greater in magnitude in the early morning hours before eventually converging with the other seasons around 08:00. No single season dominates the load shapes across the vehicle day.

Conclusions

Drive Operations Analysis

The drive operations were evaluated by analyzing the distance-weighted average energy consumption and factors influencing variations from the average observations.

Stable Energy Consumption

The distance-weighted average energy consumption was evaluated by employing a method of stable energy consumption lines. The lines were used to gain further information regarding the trade-off between fuel and battery energy consumption. The results were presented across trip-type, time-of-week, and season.

The energy trade-off results suggest that highway operation provides a stable environment for the electric drive system to displace fuel consumed. The city events show a high degree of variations, perhaps due the difference in driving behavior (start-stop, etc). City trip-types during winter seasons demonstrate attenuated capacity for the electric drive to displace fuel while in charge-depletion operation. Charge-sustaining fuel consumption was found between 32 and 36 mpg. Higher charge-sustaining fuel consumption is observed during warmer months, possibly due to the lack of electric air-conditioning in the analyzed vehicles. The vehicle is estimated to require 40 DC-kWh/100-miles to support pure electric drive operation. Typical operation demonstrates below 20 DC-kWh/100-miles with associated fuel consumption near 1.8 gallons/100-miles.

The electric degree was used to evaluate the fraction of fuel energy displaced by battery energy. Electric degree for charge-depleting charge-management operation indicates the average electric degree while charge depleting. The aggregated fleet demonstrated depleting electric degrees between 25 and 45% depending on the season. Warmer seasons reported greater electric degree. Winter operation indicates lower electric degrees.

Charge Operations Analysis

The charge event efficiency and load shapes were evaluated for the aggregated fleet.

Charge Efficiency

The charge event efficiency was investigated by evaluating the fraction of battery energy delivered to charger energy consumed or net-efficiency. The net-efficiency sensitivity was explored relative to initial battery state of charge and charger energy consumed. Typical efficiencies were observed greater than

77.5%. The maximum average charge event was observed near 86% with average and median charge efficiency indicated near 78.5% and 82% respectively.

Load Shapes

The charge load shapes provide insight into averaged power profiles across vehicle-days. The results provide insight into daily average energy consumption and average power demanded per vehicle across time-of-week and seasons. The daily average energy demonstrated by the fleet varies between 4.8 and 6.6 AC-kWh per vehicle. Average power per vehicle was observed to vary between weekday and weekend events with weekday events demonstrating two peaks at 10:00 and 22:00 just under 400 AC-W per vehicle. The weekday power consumption was observed relatively flat between the peaks with magnitudes between 250 and 350 AC-W/vehicle across seasons. Weekend events demonstrated a single peak power occurring later in the evening and early morning. The peak is observed near 400 AC-W per vehicle. The minimum weekend power is observed near 08:00 at just above 50 AC-W per vehicle across seasons.

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Appendix – Ford: Smart & Connected Research

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Introduction

In addition to the original project, it was decided to add a workstream that would be targeted at demonstrating the benefit of using advanced information systems in an intelligent PHEV system. By adding computational capabilities, access to external data sources and cloud connectivity, is it possible to maximize the benefits from PHEVs both considering fuel economy and the electric vehicle driving experience?

To start the foray into the area of this research, Ford equipped one of its existing prototype vehicles from the fleet with a research platform that allowed us to prototype and investigate potential benefit features, to understand the real-world implications, and get end-user feedback. In addition to the Escape PHEV vehicle, a commercial C-Max Energi and a Fusion Energi was also used.

The Rapid Prototyping Platform (V2C)

As the traditional way of developing functionality for vehicles is optimized to deliver features which are known and decided on in advance, we needed a way of performing rapid prototyping ideas for features in our PHEVs. As the focus included both changes to the powertrain and to user interfaces, we came up with a hybrid solution, depicted in Figure 100. Initially, a MicroAutoBox was mounted in the trunk and connected to the vehicle CAN networks. This allowed us to run and test Simulink-based controls algorithms. As soon as those algorithms were stable, we were able to convert them into powertrain code and run them in a development Powertrain Control Module (PCM) with debugging capabilities that replaced the existing standard module in the vehicle. This module is responsible for the energy management of the vehicle, and our modified code allowed us detailed control over the decision on when and where to use the electric motor and/or the gas engine.

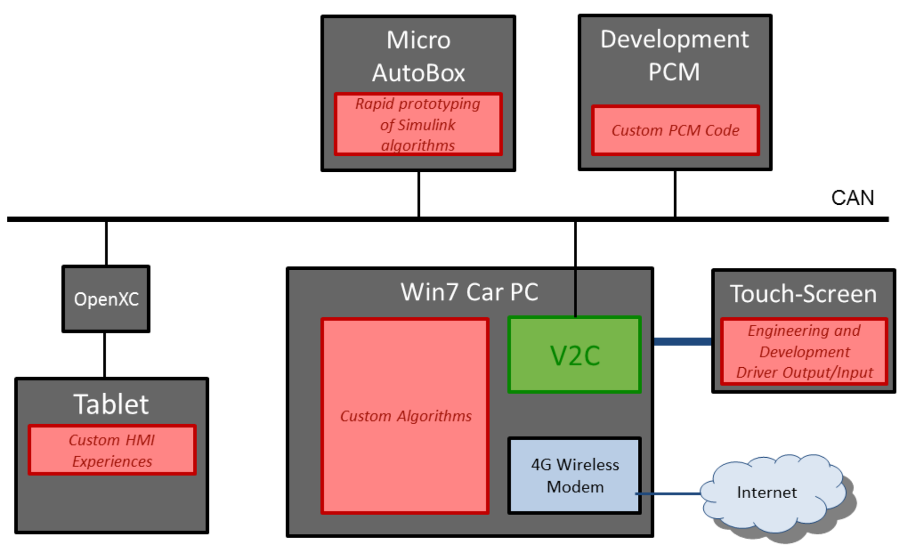


Figure 100 - The Rapid Prototyping environment

To implement high-level controls we then installed a CarPC in the trunk of the car – a ruggedized Windows 7 based PC which was connected to the Internet/cloud using a 4G LTE connection, with the vehicles all CAN networks and also included a GPS for location determination. The CarPC was hooked up to a touch-screen installed in the front of the car, next to the existing infotainment system.

We then built a software prototyping framework named Vehicle2Cloud (V2C) which abstracted away the lower level implementations of the included connectivity technologies and allowed us to quickly create high-level custom algorithms that could communicate both with the vehicle and the cloud.

The V2C framework was built on Windows .NET using a Client/Server application structure allowing concurrent access to the vehicle for multiple features at once. It also included libraries for common tasks related to location such as a data model for GPS and location information and algorithms for GeoFencing (detecting when the vehicle is at or near specific locations). Finally, V2C provided access to highly detailed map data with extensive map attributes through a connection to the ADASRP Map Research environment by Nokia/Here and an up-to-date ADAS compatible high definition map database.

The final portion of the rapid prototyping solution was a modified version of Ford's OpenXC car connectivity solution[1] allowing us to interact with the vehicle from a standard Android tablet, especially before the CarPC/V2C system was fully developed or in place.

Figure 101 - Installation of the rapid prototyping system in the vehicle.

With this setup we were able to research both drivability and fuel economy ideas in several areas, as described below.

[1] http://openxcplatform.com/

Research Areas

Research Area 1 – Low-level Driver Control

The first area investigated was allowing the driver to manually change the operating mode of the vehicle (electric/hybrid/gas propulsion). We constructed a GUI showing relevant information about the state of the vehicle and availability of battery energy, and which allowed the driver to select operating mode with the push of a button. The initial version of this system is depicted in Figure 102.

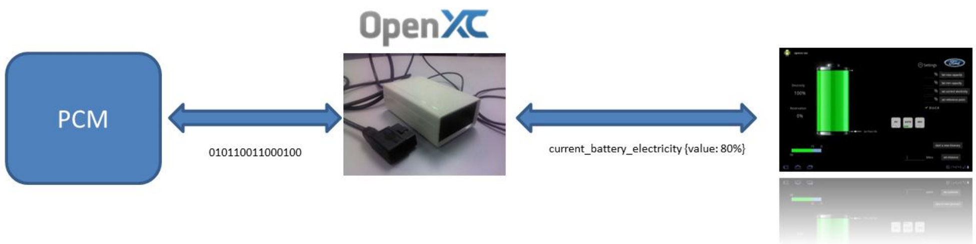


Figure 102 - The OpenXC based EV Choice System

The responses were overwhelmingly positive and the drivers appreciated to be able to better control where to spend their electric energy even though they were aware of the possible fuel economy implications if they did not end up using all the available electricity. We gave the choice between *EV* (only electricity), *Auto* (default) and *HEV* (saving electricity for later). Examples of the buttons are shown in Figure 103.

Figure 103 - EV Choice Buttons

In parallel, a variant of this feature has been introduced in our production PHEVs (the CMAX Energi and Fusion Energi vehicles) although the implementation varies slightly from the research prototype and happened independently. The production implementation labels the modes as *EV Auto* (default), *EV Now* (drive only on electricity) and *EV Later* (save the electricity for later). See Figure 104 for the actual button and cluster screen as used in the CMAX Energi.

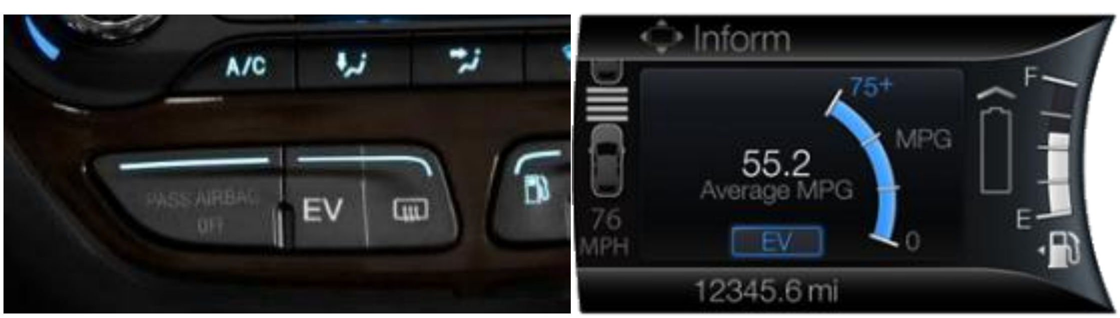


Figure 104 - Production implementation of EV selection features in a CMAX Energi

Research Area 2 – High-level Driver Control

Although the low-level driver control offered a compelling way for the drivers to control their energy use, it required frequent manual interaction while driving. So, our second research area was to see if we could introduce a high-level control where the driver would tell his/her intention to the system and the actual driving control would be handled automatically. For this we turned to an idea that was invented by our team a few years earlier – GreenZone. GreenZone allows the user of a PHEV to define specific areas that he/she wants to drive electrically inside of, and the vehicle will then automatically switch modes while driving.

We implemented a cloud-based website where drivers could log on using a regular PC or tablet, and define geographical zones in. A screenshot of the website is available in Figure 105. The vehicle would then, when started, connect to the cloud and download the zones associated with the current driver.

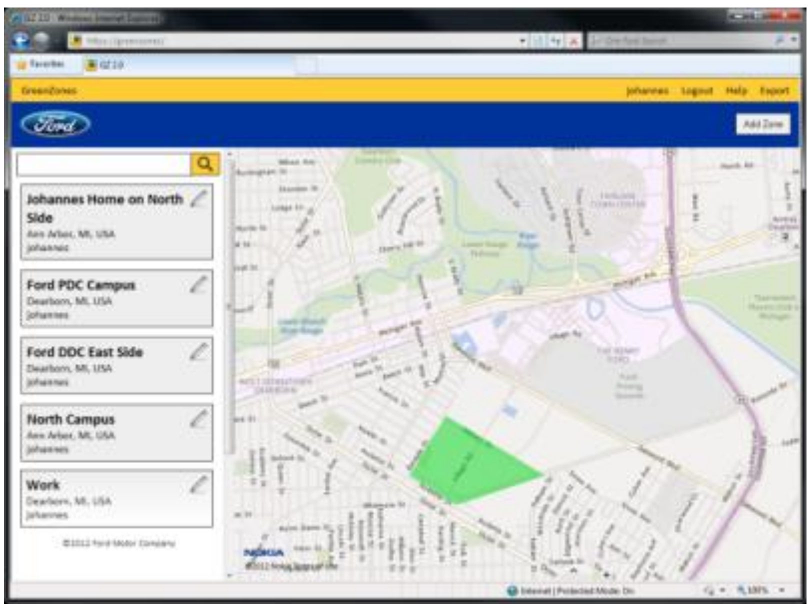


Figure 105 - GreenZone Prototype Website

When the driver entered a destination into the navigation system, the GreenZone feature would figure out which portion of the upcoming route would be inside any zone and estimate how much energy would be used for each portion of the route. It would then reserve the total energy needed for electric driving in zones from being used in the beginning of the trip, and release each zone's energy reservation upon entry. Furthermore, it would also change the operating modes (as mentioned in the previous research area above) accordingly. This is illustrated in Figure 106 where the vehicle is traveling the westbound route from Dearborn to Ann Arbor. There are two zones defined – one in Dearborn and one in Ann Arbor. The route color shows that the initial portion of the route will be driven in automatic mode, which defaults to electric (as there is plenty of electricity available in the battery), but that the vehicle will switch to reserved/hybrid mode (red color) after a third of the route when the remaining available electricity needs to be saved for the final zone. Then, when entering the last zone around the end destination, the energy is released and the vehicle will drive in pure electric mode again.

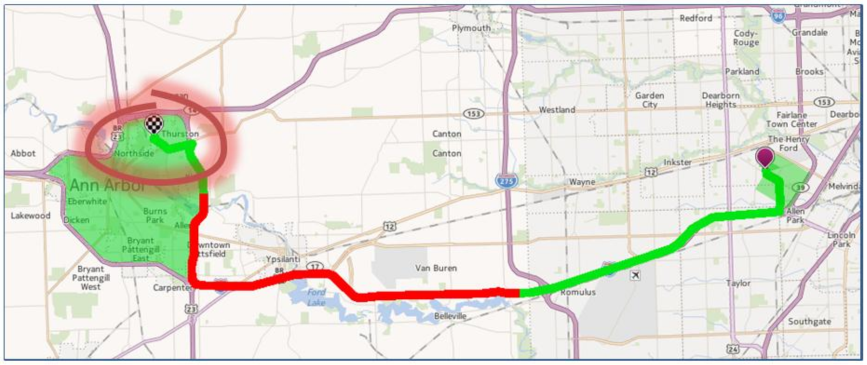


Figure 106 - GreenZone Route Overview Example

Due to limitations of the electric motor used, the prototype vehicle could not be forced to drive solely using electricity – a hard very acceleration would still cause the engine to come on to deliver the power the driver needed and expected. However, the system was implemented, worked well and was well received. Figure 107 shows the drive of Figure 106 without the GreenZone system active. The top red line represents the actual energy available in the battery (the blue line at 32% represents the minimum level our prototype vehicle allowed the battery to discharge to) and the bottom red line shows the RPM when the engine was on. The grey line shows the speed profile measured in MPH. Note how the vehicle drives almost in pure EV mode in the city of Dearborn, but not in the city of Ann Arbor as there is no surplus energy left.

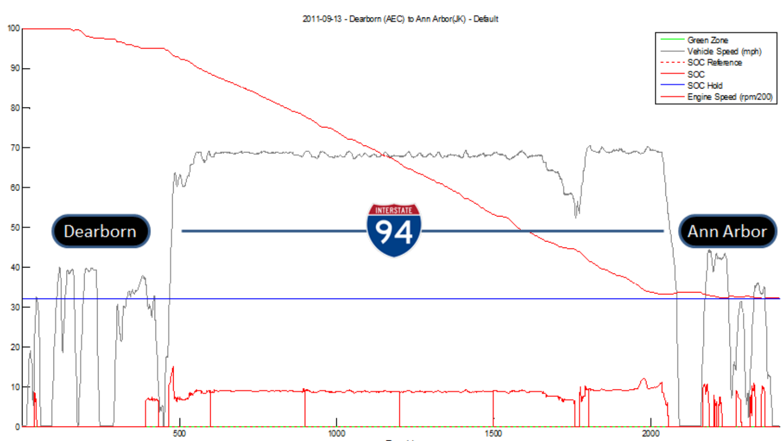


Figure 107 - Default driving scenario

In contrast, Figure 108 shows the same route with the GreenZone feature activated. The zones are overlaid on the graph and we can see how the vehicle adds an energy reservation to the battery to start with (blue line is at 38% instead of 32% until the last zones is reached. You can also clearly see how the last portion of driving happens without the use of the engine since we now have an adequate amount of electricity available for this last portion.

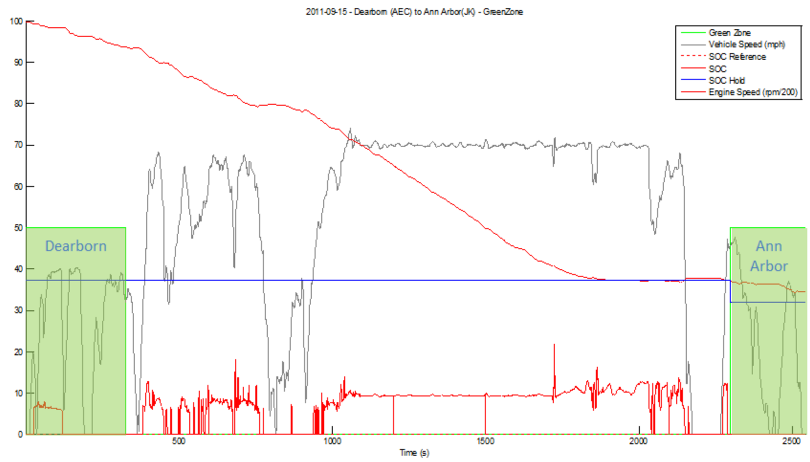


Figure 108 - GreenZone Driving Scenario

The system was implemented both in the Prototype Escape PHEV and in modified versions of both our production PHEV vehicles using the V2C prototyping framework. While the system works great for the ideal case, there is still work left to be done, especially around robustness, failure modes, and energy estimation. The system continues to be an internal research topic.

Research Area 3 – Fully Automated Controls

While research area 1 and 2 investigated different ways for the driver to be in control over the EV driving experience, research area 3 investigates if it is possible to deliver more “EV” miles automatically without any interaction at all required from the driver. One such feature is **RoadType SOC Reservation** which reserves part of the battery capacity while driving on highways, and releasing it when exiting the highway, enabling more EV driving on local routes directly after each highway trip segment, when the driver will notice the quietness of the electrical drivetrain the most. Figure 109 shows an overview graph of the system in action on a trip consisting of a highway section surrounded by two local sections.

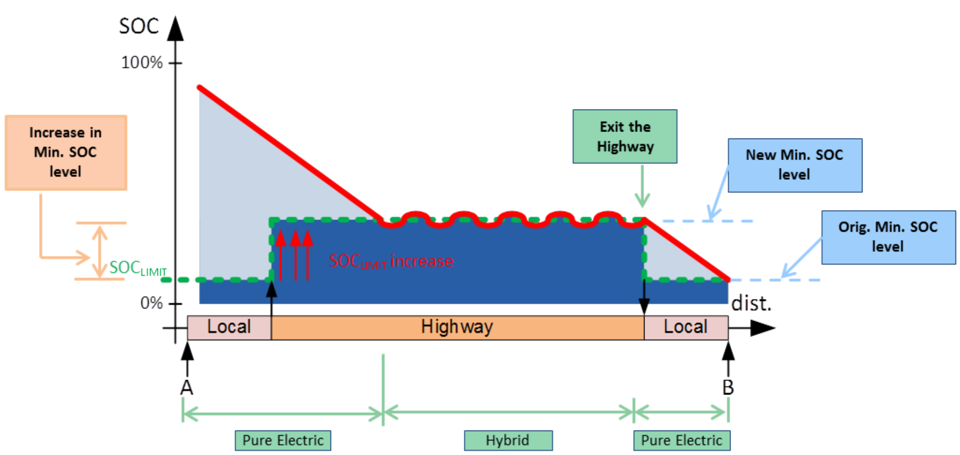
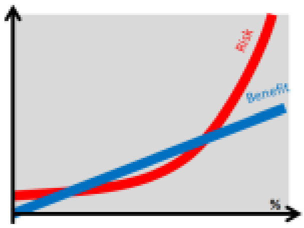


Figure 109 - RoadType SOC Reservation overview



While the ideal case would be to reserve enough energy for the whole final local section to be driven completely in electric mode, this is only possible if the full route is known in advance, otherwise we always risk saving too much energy, ending up not using it all and possibly running the gas engine more than would have been needed. So, in reality this feature will only be able to give a slightly increased electric driving experience.

There are two major questions that need to be answered for this feature to be successful. The first is “how much energy to reserve”. Since this is a route-agnostic feature, we want the system to reserve enough energy to make a noticeable difference for the driver (“benefit”) while at the same time not reserving too much so that there will be extra surplus electric energy left in the battery at the end of the trip (“risk”).

The second question is “what is a ‘highway’” – or in this case, how to determine at which roads to reserve energy on and which to release the reserved energy on. One possible distinction is roads where the driver won’t notice if the engine is running or not, however that varies between different vehicles and drivers.

The initial implementation of this feature used average vehicle speed as a means of determining if the car was on a “highway” or not since that allowed a quick prototype implementation to start with. However, initial user feedback shows that the decision cannot be made on vehicle speed alone and probably needs to consider map features or other factors as well.

It is worth mentioning that Ford’s Fusion and C-Max Hybrid vehicles include a feature named “EV+” exploring a similar concept where the vehicle will detect when it is close to a common destination and allow the hybrid battery to deplete slightly more than normal – increasing the electric drivability towards the end of the trip. This is possible since the vehicle will need to run the engine to heat up the catalyst at the beginning of next trip anyway, and the extra discharge can be recouped at that point. This feature is available also in the Energi (PHEV) vehicles, but is only available when the plug-in battery is depleted (i.e. system operating in hybrid mode). So if the vehicle is always charged, then the Energi vehicles will never enter EV+. The most frequent destinations will still be learned though.

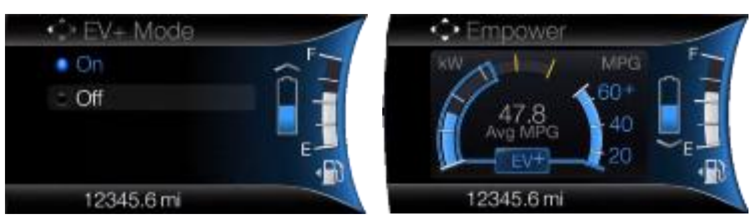
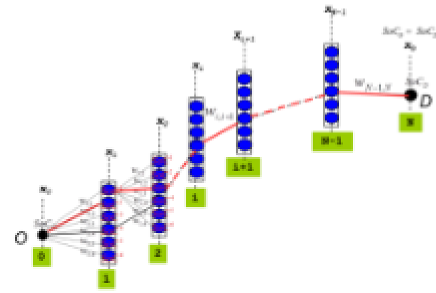


Figure 110 - EV+ in the Fusion Hybrid

Research Area 4 – Under-the-hood Optimizations

The fourth research area contained features that would improve the vehicle's performance without changing the driving behavior. Below are two examples of features – *Path Forecasting* and *Battery Cloud Calculations*.

Path Forecasting



The idea with Path Forecasting is that if the complete future route is known, we could in advance determine exactly when or where to use electricity in order to utilize it optimally. This is done by using a Supervisory Receding Horizon Controller to maximize the fuel economy by scheduling an optimal battery State of Charge (SoC) usage profile ("path") along the intended route based on speed and road grade prediction ("forecasting"). This is an example on how we use *preview information* of a full route to improve Fuel Economy. As will be discussed below, this requires both prediction of how the route will be driven (speed profile prediction) as well as access to detailed geographical data of the route.

The initial desktop simulation results are promising, but due to the huge amount of states, the current prediction models are too complex and inexact to give robust results in short enough time to be useful for a real-world implementation.

Cloud Based Battery Calculations

The second example of an under-the-hood optimization is using the cloud to improve battery calculations. In reality it is impossible to know exactly how much energy is available in a battery. The most common way to estimate this is based on measuring parameters such as voltage and resistance and then using a physical model to calculate the energy. This research idea was to replace the simple model that today's vehicles are limited to by using off-board computation capability in the cloud in order to improve the accuracy of the calculation. By leveraging a scalable high-capacity computation resource (a cloud based fast server) it is possible to either increase the multiplicity of the calculations from a pack-level calculation down to a cell-level or even sub-cell level, or to increase the complexity of the models from simple equivalent circuit models to more advanced electrochemical models, as shown in Figure 111.

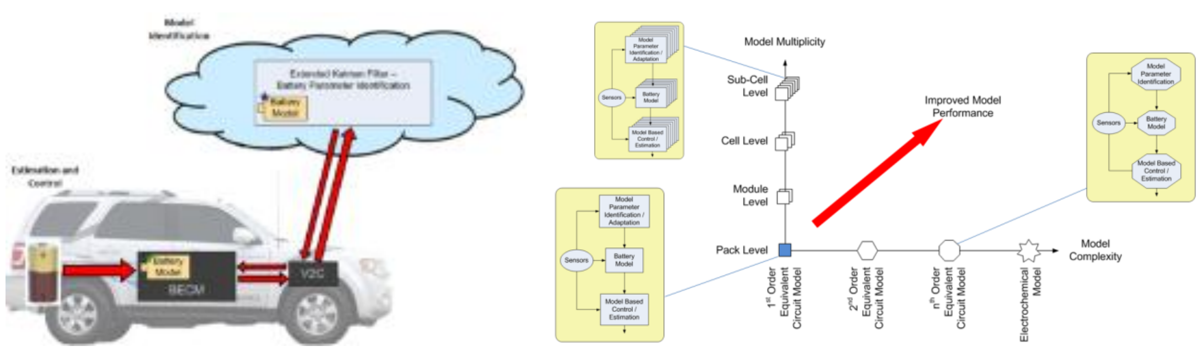


Figure 111 – (a) Cloud-based Parameter Calculation System overview
(b) Battery Parameter Calculation Improvement opportunities

While it is impossible to know how much better results the improved calculations yields since the actual true value is unknown, Figure 112 shows how the theoretical improvement in accuracy from going from the current pack-level estimate to a more detailed cell level estimate.

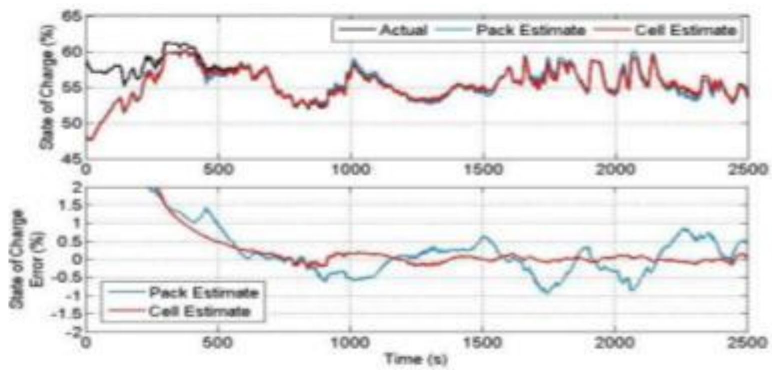


Figure 112 – Cloud-based Battery Calculations using a 60 seconds update rate

The main problem with cloud calculations is that since the transmission of data to and from the vehicle is not perfect and will happen in cycles, there will be performance issues when the update rate is decreased as the last “precise” estimation received in the vehicle “get too old”. The vehicle will need to perform a local adjustment of the last received value between the cloud calculations. Figure 113 shows the effect of a too slow update rate and Figure 114 shows how, when a local adjustment is made, we can still get results that are an improvement over the existing estimation.

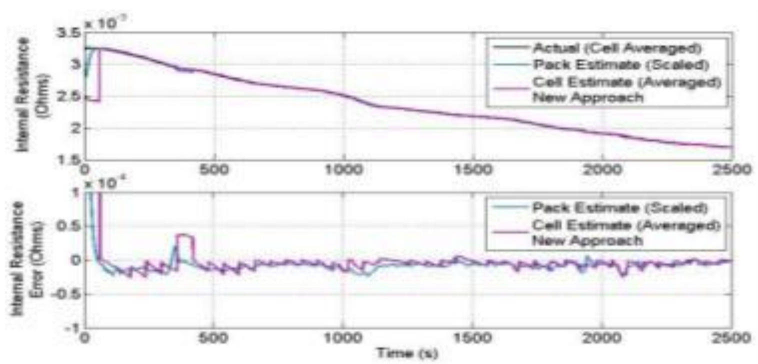


Figure 113 - Cloud-based Battery Calculations using a 5 minutes update rate

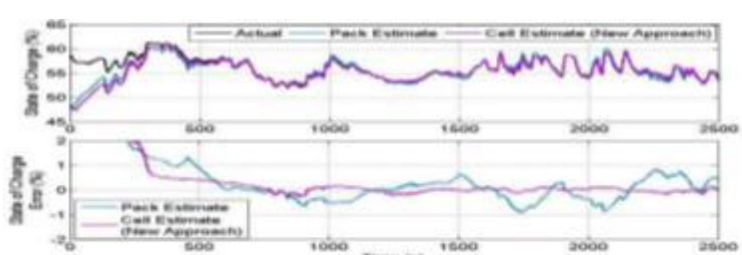


Figure 114 - Cloud-based Battery Calculations with a local adjustment

Research Area 5 – Supporting Algorithms

The last research area consists of algorithms and technologies needed to support the first four research areas. Trip Profiling is the art of understanding how and where the driver uses his car and being able to predict future usage. The first step is to **analyze** existing trips, e.g. to understand the relationship between the driving parameters and energy usage (energy analysis) or to be able to recognize common routes or destinations.

The next step is to perform **predictions** on how the upcoming trips is going to be undertaken – either predicting where the user will go (destination prediction), which way he will drive there (route prediction), how the route will be geographically (e.g. grade profile estimation) or how the driver will drive there (speed profile prediction and energy estimation).

We will give one example each from these two steps.

Analysis

In theory, the energy usage of a vehicle could be determined by a classical physical forces model. In reality, however, this model rarely gives reliable results as many of the external forces vary broadly, or are hard or impossible to estimate.

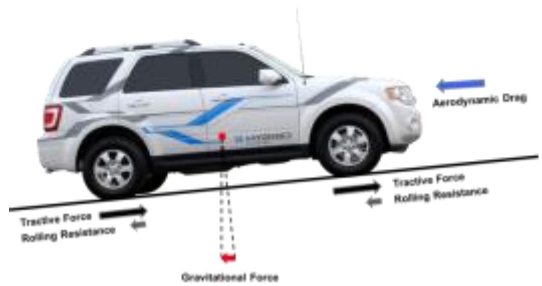


Figure 115 shows a 3-dimentional graph of the energy consumption along a regular commuting route. This route consists of mainly highway portions with a fixed speed limit. The portion to the right in the graph has a periodic variation mainly due to the geography of the highway that repeatedly goes under bridge crossings and therefore the speed varies as the car drives up and down small hills. The center section has much flatter geography but shows a more chaotic speed variance since is most often affected by traffic.

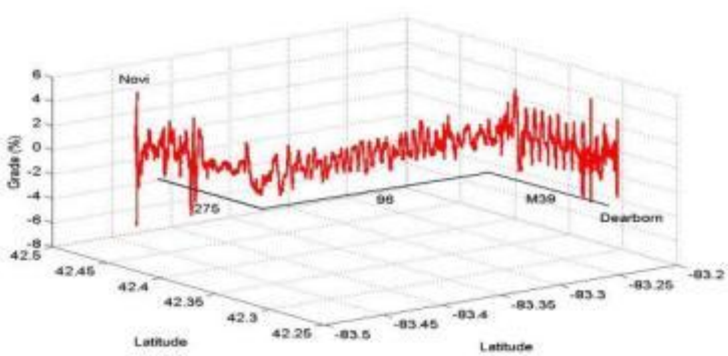


Figure 115 - Energy Consumption along a route

Figure 116 shows the cumulative energy consumption when this route is driven multiple times in as similar ways as possible. We clearly see that for this highly repeatable trip of less than 30 miles, the energy could vary with almost a factor of 2!

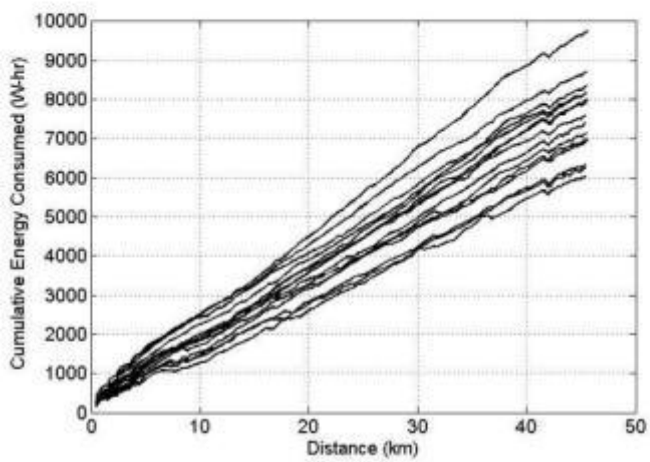
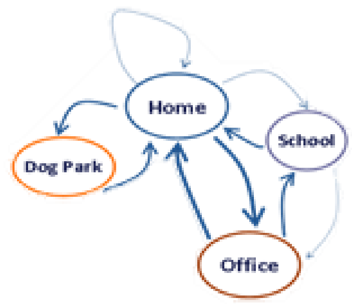


Figure 116 - Cumulative Energy Consumption along the same route

Prediction

To give a notion of how large and complex prediction is, we will consider possibly the simplest example – destination prediction – which tries to answer the question "where is the driver going". Although many vehicles have built-in navigation systems, very few people use them for every trip – drivers tend to only enter the destination when he/she is heading somewhere they are unfamiliar with. However, most people are quite predictable in their daily lives, with a fixed "work" and "home". It is therefore possible to predict the destination for a majority of the trips performed. But a prediction system is more than just the prediction itself. We can divide it into four different parts.



The first part is **clustering**. We collect the precise GPS *position* each time the vehicle is turned off. However, even though you park at the same parking spot, you will never be positioned at exactly the same spot every day – you will end up with a cluster of closely located positions. If you don't have a designated spot this cluster becomes larger to the extent that it can sometimes be hard to distinguish two clusters from each other. In Figure 117 we see an example of a user parking next to two different buildings. The clustering algorithm needs to be precise enough to clump related positions together into *locations* while being able to distinguish close locations from each other.

The second part is **relationing**. In the example below the two clusters are represented as a circle, or a center coordinate with a radius. While this is a perfectly fine definition for the vehicle itself, the coordinates means little for the driver, who might relate to his two parking locations as "Work" or "RIC" rather than [42.293174, -83.240465] and [42.293399, -83.239072]. We thus need a way to *relate* each location to a *name* or a *tag* that is meaningful for the driver. There are multiple ways of doing this – the two most popular are *reverse geocoding* and *POI approximation*. *Reverse geocoding* will return the closest street address to a specific location, but as few people think of their workspace by street address (or even know it), this is not always useful. *POI approximation* finds the closest point-of-interests in the vicinity, either a store or geographical feature, but this only works when you are able to park directly adjacent to your destination, or the destination is publically known. Backup alternatives could require asking the driver.

Figure 117 - Clustering and Relationing

The third component is the **prediction** itself. There are many different ways of performing prediction, using various algorithms and classification methods. Ford has previously, at the 2012 Google IO conference, shown how even a commercially available cloud-based prediction system can be used to predict destination.

The last component is the **presentation** of the results and getting verification from the driver. As the percentage of repeated trips increases over 90% (i.e. most trips are between known destinations), the accuracy of the prediction quickly rises to a level where we can start seeing acceptable results. Presenting a list of the top predicted candidate destinations from the driver increases the accuracy even more but must be made in such a way to not irritate or annoy the driver. Figure 118 shows typical prediction accuracies for a single driver when considering the top 1, 2 or 3 candidates for the result.

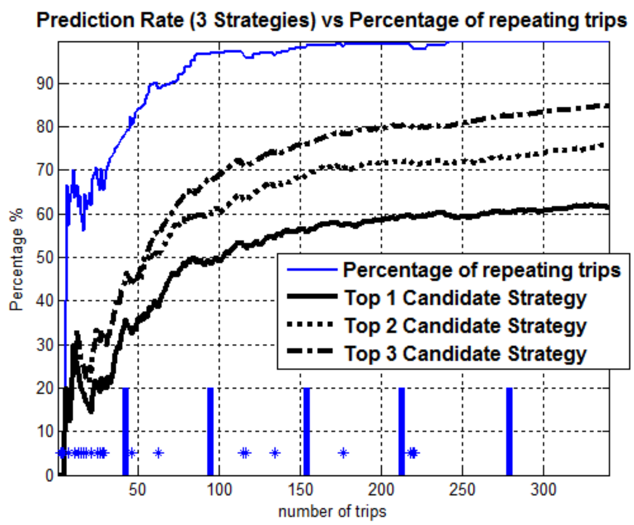


Figure 118 - Prediction Accuracy Example

Conclusions

The purpose of this workstream was to initiate research on demonstrating a benefit of using advanced information systems in an intelligent PHEV system. All the examples in the 4+1 research areas above show how adding external information, external computation capacity, or external inputs can improve either the drivability experience or potentially the fuel economy of Plug-in Hybrid Electric Vehicles.

Most of the features were implemented on the Escape PHEV prototype vehicle using a specially developed rapid prototyping environment, allowing us to better understand the improved driving experience or measure real-world fuel economy. We were also able to solicit comments from test-drives with invited drivers. The general feedback received was that almost all drivers enjoy smart PHEV features, and most of them like the ability to be in control over the driving experience. People see the electric driving mode of the PHEV as a unique and positive benefit and appreciate features that increase the amount of pure electric driving as long as it does not negatively affect fuel economy.

When it comes to potential fuel economy improvements; smart features are unlikely to improve the fuel economy label values. The current drive cycles used to determine these numbers only depend on a vehicle speed profile representing an average driver and trip, and do not contain any specific or personal data such as location information or road grade. The smart features investigated in this research focus on improvements based on individual driving characteristic or specific routes, and use this data to improve both drivability and fuel economy. By relying on personalized usage data, the features offer real value to customers, so we need to figure out how to capture this value in future regulations and interaction with drivers.

Finally, we have also shown that energy usage prediction is an integral component of any smart PHEV feature, but it is hard to get reliable predictions since there are many noise factors that affect the real-world energy usage of the vehicle. Any smart feature is therefore going to be managing a tradeoff between benefit and risk.