Battery Energy Availability and Consumption during Vehicle Charging across Ambient Temperatures and Battery Temperature

2013 DOE Hydrogen Program and Vehicle Technologies Annual Merit Review

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Sponsored by Lee Slezak

U.S. Department of Energy

Energy Efficiency and Renewable Energy

Bringing you a prosperous future where energy is clean, abundant, reliable, and affordable

Project ID # VSS110

Overview

- **Timeline**

  2013 Recharge Testing/Analysis Tasks

  - Chevrolet Volt Testing – Complete
  - Nissan Leaf Testing - Complete
  - Toyota Prius PHV Testing - Complete
  - Ford Focus BEV Testing – On-going
    - In-depth benchmarking 2014 AOP task
  - Final reporting – On-going

- **Budget**
  - FY 2013 $200k

- **DOE VSSST barriers addressed**

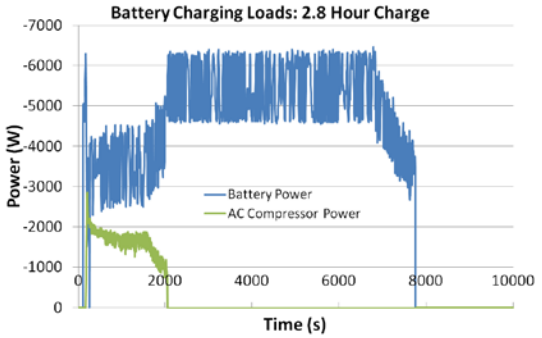
  Constant advances in technology
  - **F:** Constant advances in technology
  - **D:** Lack of standardized test protocols
  - **E:** Computational models, design and simulation methodologies (Data availability)

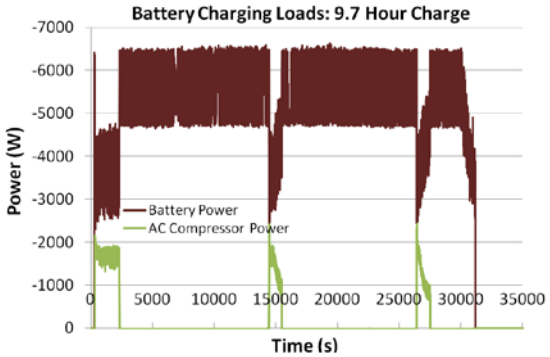
- **Partners**
  - DOE and other National Laboratories
  - Vehicle OEMs, and Suppliers
  - Standards development working groups

Relevance: Thermal Management During Recharge

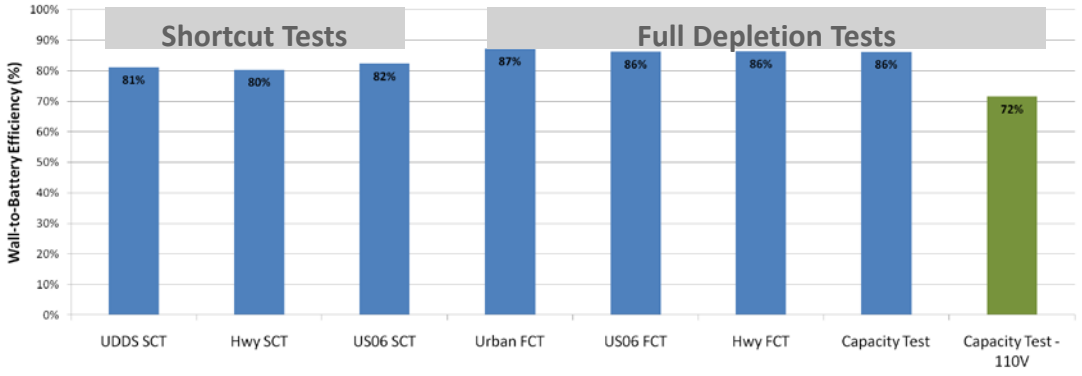
- **Previous vehicle testing has shown battery cooling system operation during recharge can have an appreciable impact:**
  - AC wall power remains the same during charge, but battery recharge in-flow can be reduced during cooling/heating
  - Efficiency and charge time will vary depending on battery state
- Complex battery heating/cooling systems more prevalent
  - Many PHEVs and BEVs have separate battery thermal management
- Stand-by loads for cooling/heating may be significant
  - Limited information for measuring and evaluating these impacts
- In a V2G scenario, available power may be reduced
  - Unanticipated reduction in loading capability/functionality

Long vs. Short Recharge





Recharge Time Impacts Wall-to-Battery Efficiency

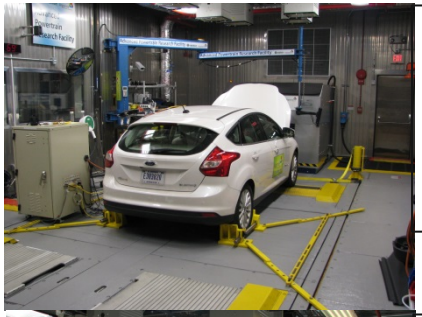


Approach/Strategy: PHEV/BEV Evaluation of Vehicles

A range of PHEV and EV test vehicles were evaluated…

- Available PHEV/BEVs for testing
- Range of operating styles
- Range of charger capabilities
- Range of battery thermal management capabilities

List of technologies assessed is by no means exhaustive, but provides some insights across a fairly wide range of possibilities



Ford Focus (BEV)
- 110 kW Battery power
- ~6.6 kW Charging power
- Liquid cooled/heated battery

Chevrolet Volt (PHEV)
- 111 kW Battery power
- ~3.3 kW Charging power
- Liquid cooled/heated battery

Nissan Leaf (BEV)
- 90 kW Battery power
- ~3.3 kW Charging power
- Minimal battery cooling

Toyota Prius (PHEV)
- 37 kW Battery power
- ~2.6 kW Charging power
- Air cooled battery pack

Approach/Strategy: Instrumentation and Testing

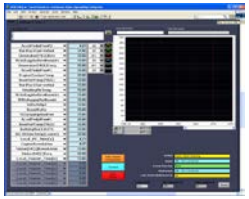
Assessing charging loads across a range of hot/cold battery and ambient conditions requires careful test sequencing and instrumentation

Testing considerations include:

- Ambient recharge temperature
  - Thermal management during long charges
- Vehicle soak time and temperature
  - Large battery thermal capacity
  - Observed cooling over multiple cold days
- Battery usage prior to charging
  - How much battery cooling prior to charging
- Vehicle HVAC settings
  - Hot/Cold runs done with/without HVAC to assess battery specific demands before charge

Highlighted Instrumentation:

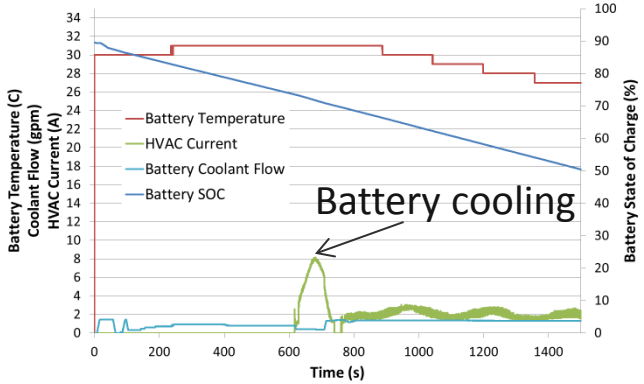
- Battery current loop – Required to measure actual battery current
- OCR Battery Measurement – PEV batteries difficult to directly instrument
- HVAC Instrumentation – Loads during charging
  (can be tricky with complex thermal/HVAC systems)



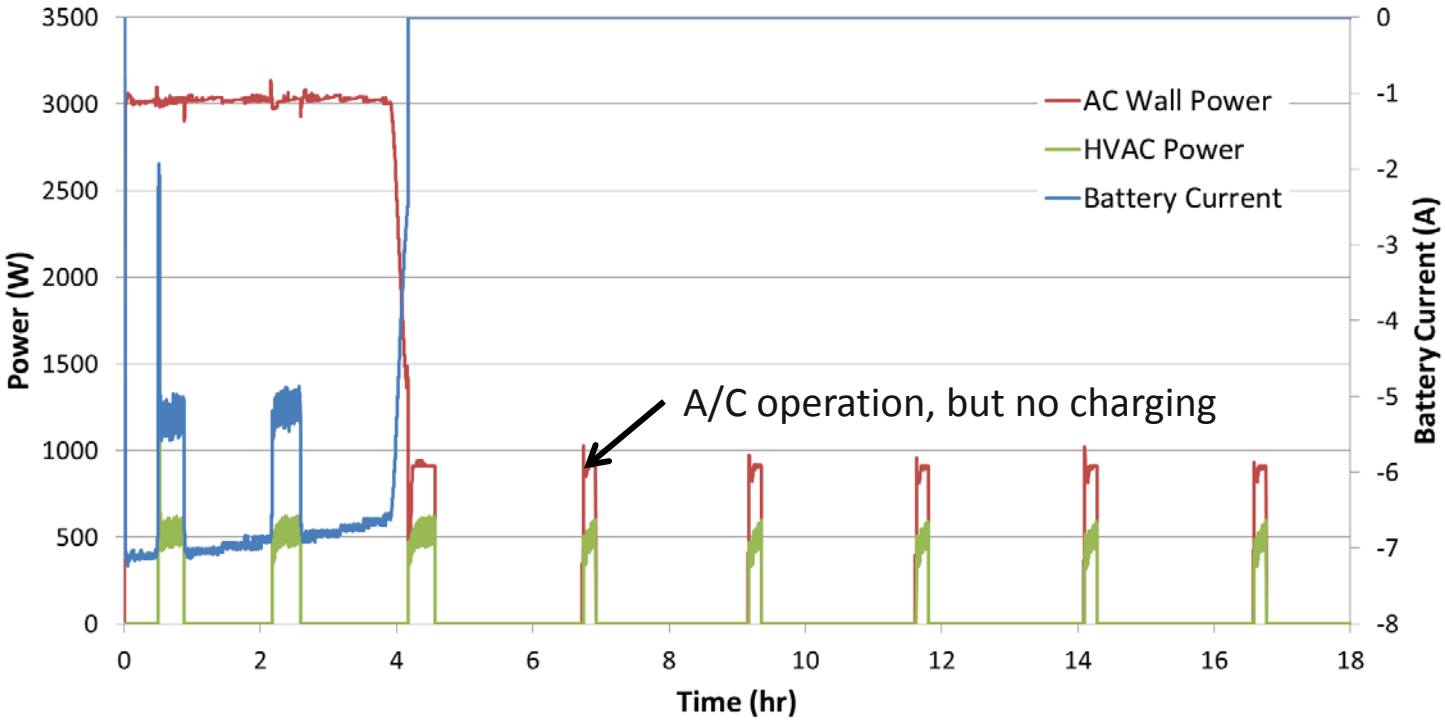
Accomplishments: Highlighted Battery Cooling Results

- **Chevrolet Volt shows two cooling operations during recharge under hot conditions…**
  - Cooling during battery charging (~500W DC load)
  - Cooling during stand-by (~1000W AC Load)
- **Other observations**
  - Cooling system activates at roughly 31C
  - Only hot soaked battery showed cooling during charge
  - Cooling during driving much more aggressive…

Chevrolet Volt:
Hot ambient steady-state operation



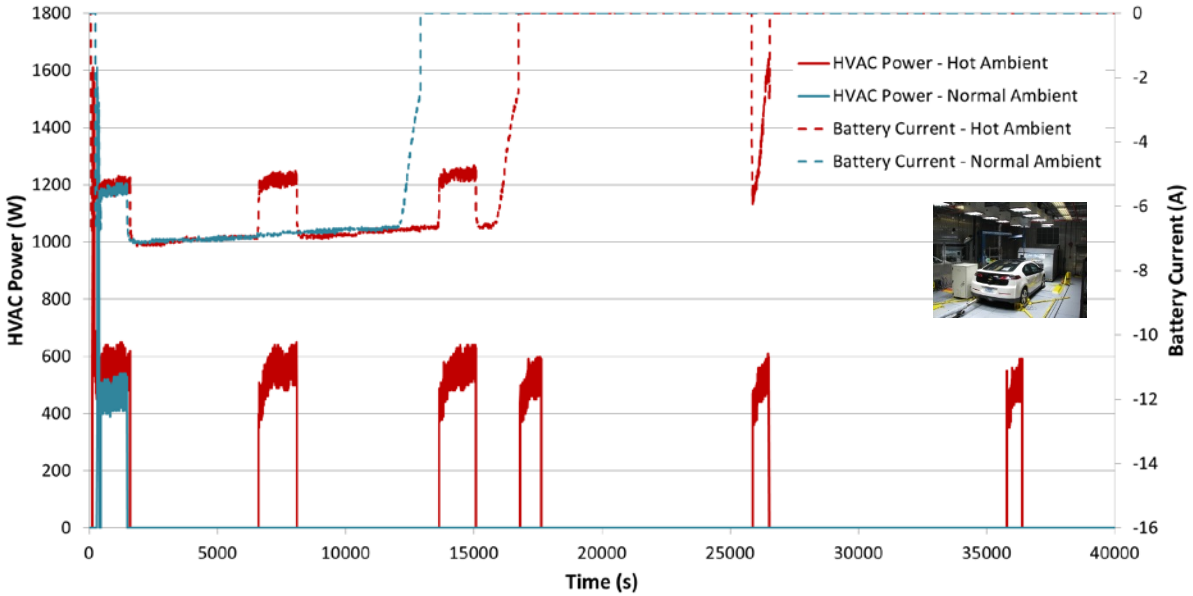
Chevrolet Volt: Hot ambient recharge following hot charge depletion



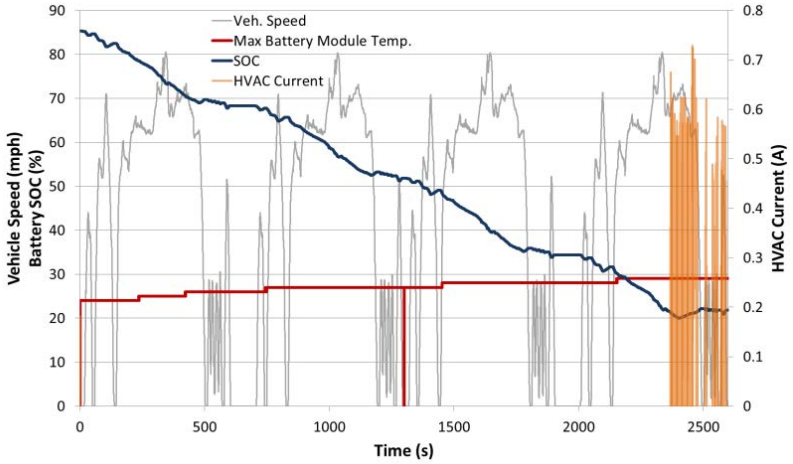
Accomplishments: Highlighted Battery Cooling Results

- **Stand-by cooling only observed during hot ambient charging**
- **Initial thermal state impacts battery cooling behavior**
  - Cooling system often only activates once CS operation achieved for normal operation
  - Hot soaked battery requires cooling before CS despite less aggressive cycle

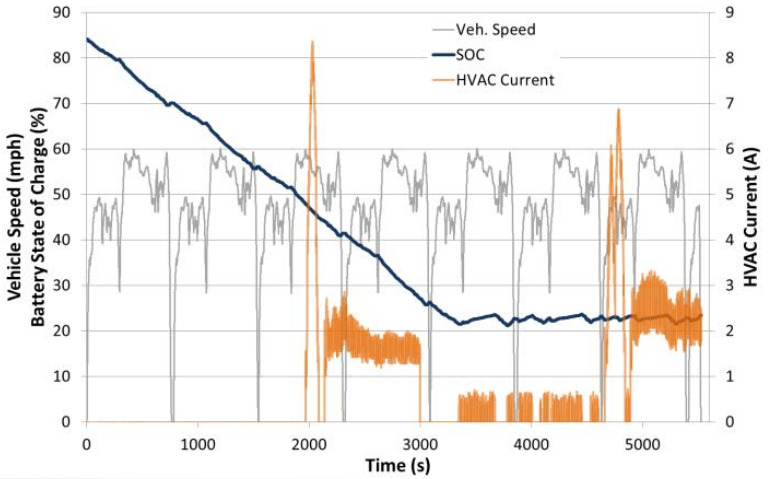
Chevrolet Volt: Hot Battery Recharge in Hot (35C) and Normal (25C) Ambient Conditions



Chevrolet Volt: Aggressive (US06) operation at normal conditions



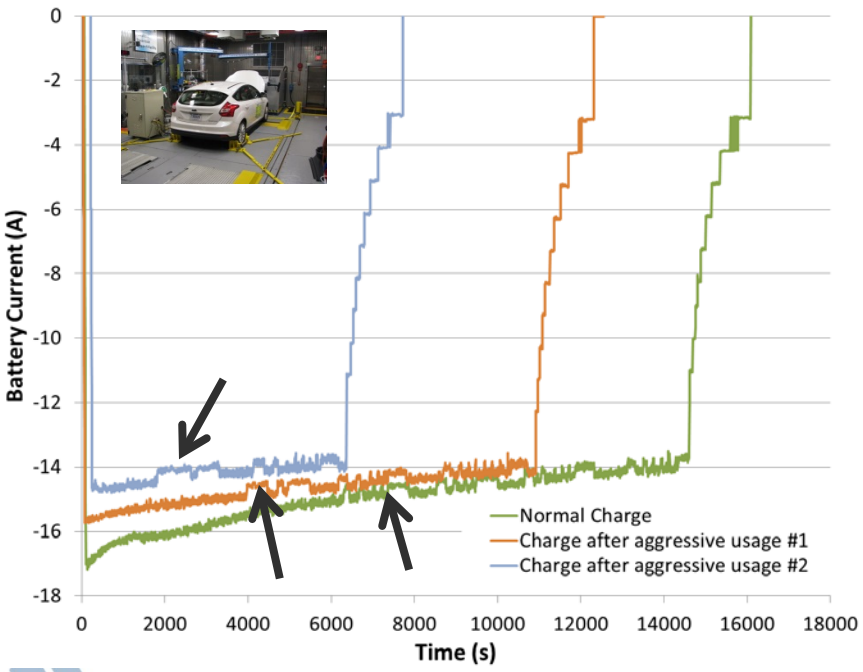
Chevrolet Volt: Hwy operation under hot conditions



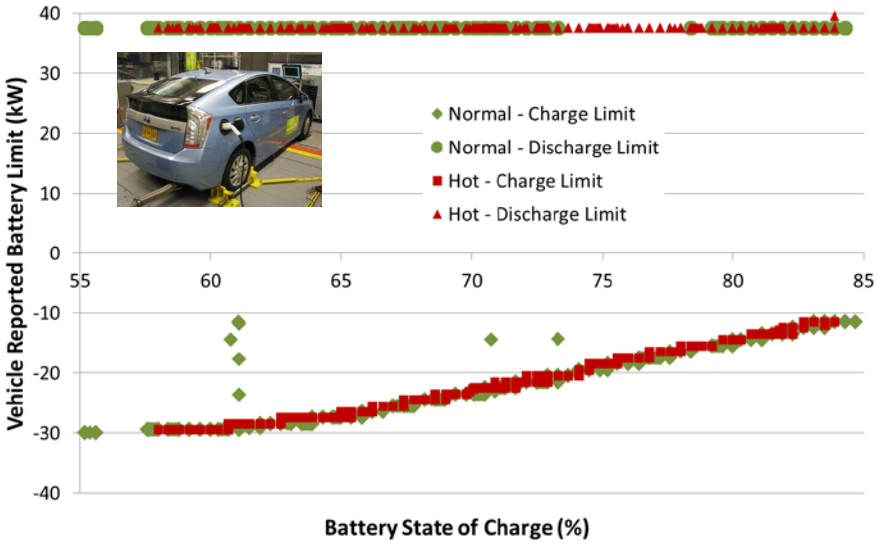
Accomplishments: Highlighted Battery Cooling Results

- **Other vehicles show a mix of behaviors regarding battery cooling during recharge**
  - Preliminary Focus BEV testing shows some cooling during charge at normal ambient
    - Much smaller loads, likely associated with fan/pump operation (highlighted in figure below)
    - Actuation varies by usage…more aggressive cycles see operation sooner
  - Prius PHEV shows no de-rating due to increased battery temperatures from hot soak
    - PHEVs in general are less sensitive due to engine capability to offset power requirements (depends on operation style)

Ford Focus BEV: Battery Recharge Current



Prius PHEV: Battery power limits vs. SOC for hot and normal soaked battery

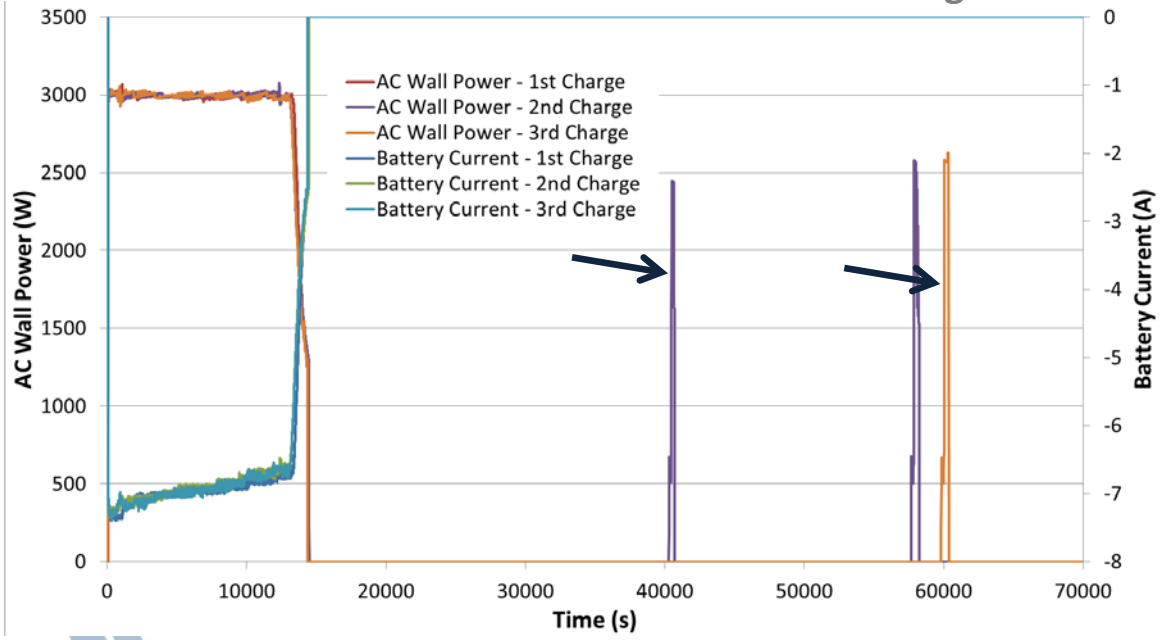


Accomplishments: Highlighted Battery Heating Analysis

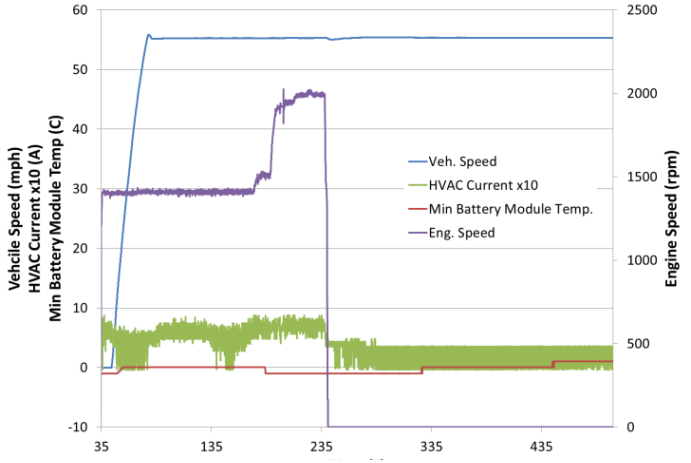
- **During cold ambient recharge (-7C) Volt shows stand-by heating loads (~2.5 kW wall power)**
  - Behavior differs depending on soak time…1st cold recharge shows no stand-by loads
  - Despite conditioning, vehicle still initially operates with engine on even with cabin HVAC system in-active

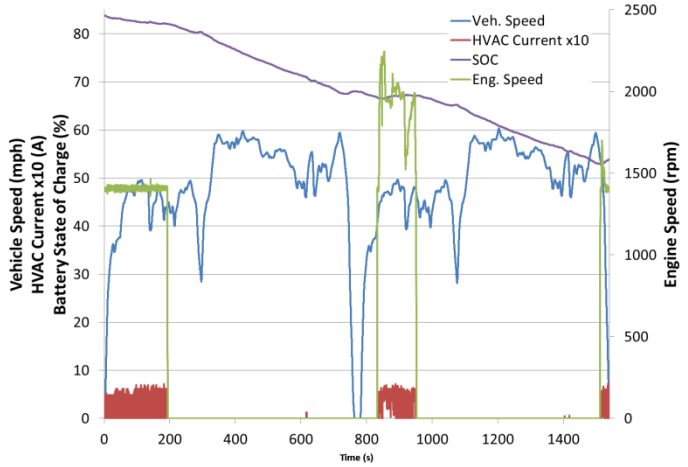
> EVs may require more thermal stabilization depending on soak time due to lack of engine power

Chevrolet Volt: Cold Ambient Charge



Chevrolet Volt: Cold soaked steady-state and Hwy operation without cabin HVAC



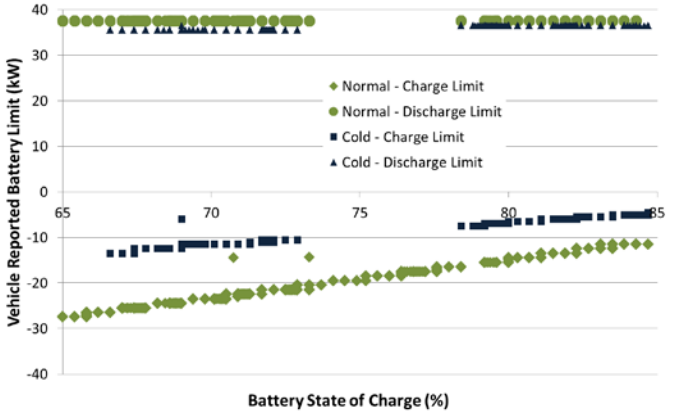


Accomplishments: Cold Battery Operational Analysis

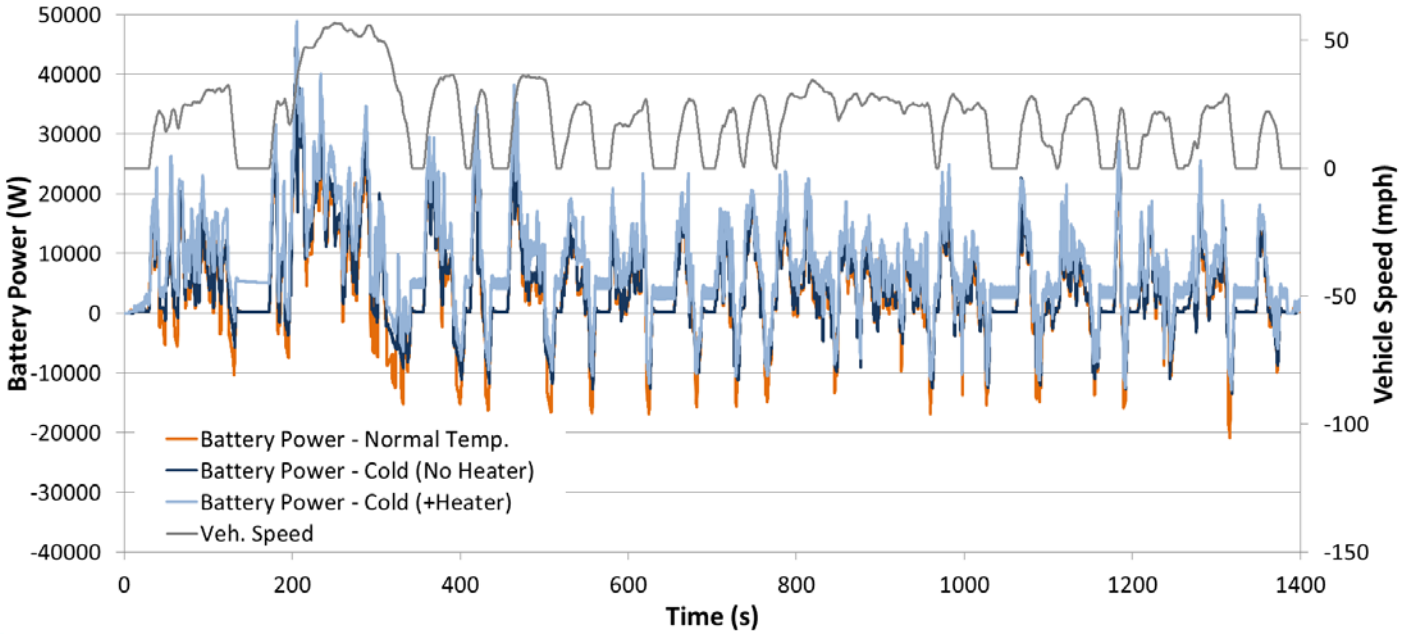
Other vehicles show reduced battery power during lower temperature testing…

- Suggests possibility for increased usage of thermal management systems
- Prius PHEV shows significantly reduced charge power and slightly reduced discharge power
- Nissan Leaf shows reduced regen. power following cold soak and recharge

Prius PHEV: Battery power limits vs. SOC for cold and normal soaked battery



Nissan Leaf UDDS Battery Usage for Normal and Cold Ambient Operation



Collaborations and Coordination with Other Institutions

J1711 HEV & PHEV test procedures
J1634 EV test procedures

SAE International

AVTA (Advanced Vehicle Testing activities)
- In-depth vehicle and component evaluation

INL Idaho National Laboratory · Argonne National Laboratory

Battery Energy Availability and Consumption

DOE technology evaluation
- DOE requests
- National Lab requests
- Overall energy analysis

NREL · ornl Oak Ridge National Laboratory · INL Idaho National Laboratory · Argonne National Laboratory

USDRIVE, tech teams and OEMs
- Shared data and analysis

USDRIVE Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability

Summary

Thermal management loads during recharge were assessed for recent battery electric and plug-in hybrid vehicles across a range of ambient and battery temperatures, findings include:

- Initial thermal state impacts battery cooling behavior
  - For PHEVs, CS operation is often reached before cooling is required when starting from normal (~25C) ambient temperature
- Chevrolet Volt shows two cooling operations when plugged-in under hot conditions
  - Cooling during battery charging (~500W DC load) and cooling during stand-by (~1000W AC)
- Stand-by cooling only observed during hot ambient charging

- While plugged-in, Volt shows intermittent stand-by heating
  - Occasional ~2.5 kW AC wall-load for heating while plugged-in and not charging
- Other vehicles show reduced battery power during lower temperature testing…
  - Suggests possibility for more prevalent thermal management during recharge in the future