Performance Evaluation of Lower-Energy Energy Storage Alternatives for Full-Hybrid Vehicles

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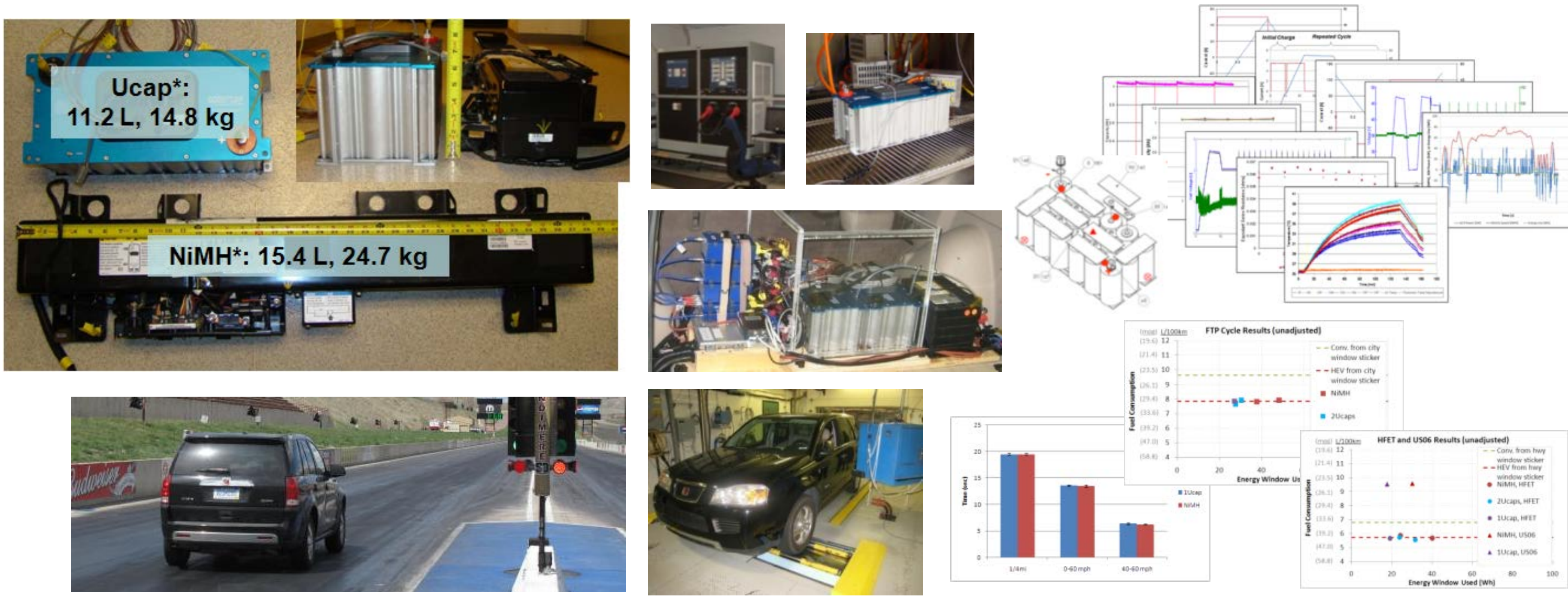
NREL is a national laboratory of the U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy, operated by the Alliance for Sustainable Energy, LLC.

Motivation

- Hybrid electric vehicles (HEVs) are effective at reducing per-vehicle fuel use
- Incremental cost remains a barrier to wider market penetration
  - Energy storage system (ESS) arguably the largest contributor
- ESS cost reductions/performance improvements → improved vehicle-level cost vs. benefit
  - Increase market demand and aggregate fuel savings
- LEESS considerations
  - Technical evaluation—can it do the job? ← **Project Focus**
  - Potential for lower cost with less energy?
  - Potential benefits from alternative technology?
    - Better life, better cold temperature performance

Related Background Work: NREL Evaluation for GM of Replacing NiMH Batteries with Ultracapacitors in the 42-V Saturn Vue BAS HEV

- Motivation: Ucap potential for superior cycle life, cold temperature performance, and long-term cost reductions
- Bench tested Ucaps and retrofitted vehicle to operate in 3 configurations



Photos by Jeff Gonder and Jason Lustbader, NREL

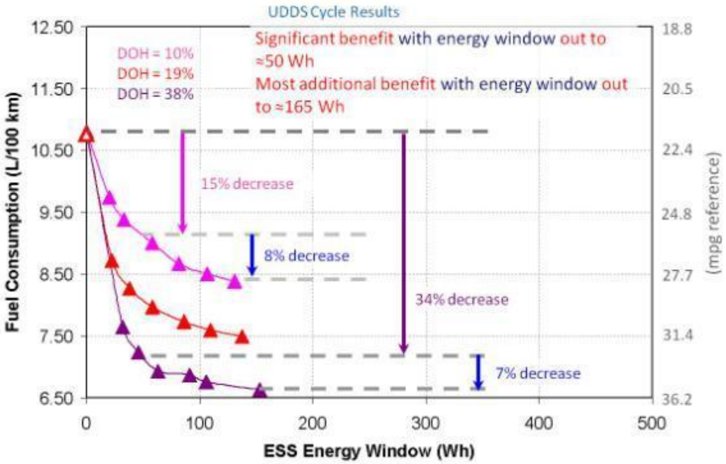
Findings: 42V HEV with ultracapacitors performed at least as well as the stock configuration with a NiMH battery

BAS = belt alternator starter ("mild" HEV)

Additional Background: NREL Analysis for USABC of Full-HEV Fuel Savings Sensitivity to Energy Storage Size

- NREL performed simulations and analyzed test data in conjunction with an EES TT Workgroup
  - Re-evaluating ESS targets established in the late 1990s / early 2000s

- Results suggested power-assist HEVs can still achieve high fuel savings with lower energy and potentially lower-cost ESS – see:
  - Gonder, J.; Pesaran, A.; Howell, D.; Tataria, H. "Lower-Energy Requirements for Power-Assist HEV Energy Storage Systems—Analysis and Rationale." *Proceedings of the 27th International Battery Seminar and Exhibit*; Mar 15-18, 2010, Fort Lauderdale, FL. http://www.nrel.gov/docs/fy10osti/47682.pdf



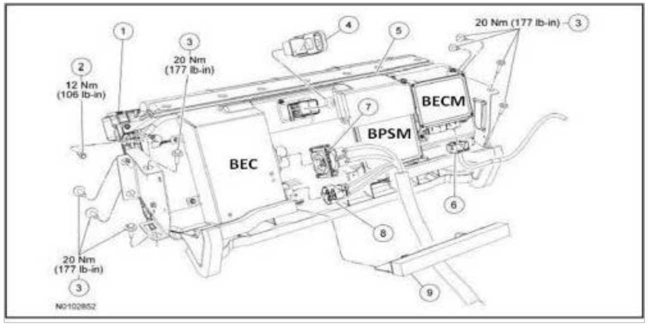
- USABC established targets and began supporting device developers
  - See: http://www.uscar.org/guest/article_view.php?articles_id=87
  - Open to any ESS technology (very high power batteries, electrochemical double-layer capacitors, or asymmetric supercapacitors)

USABC = United States Advanced Battery Consortium
EES TT = The FreedomCAR/USDRIVE Electrochemical Energy Storage Technical Team

Current Project:
Hardware Evaluation of Potential Full-HEV LEESS Devices

- Set up a reusable vehicle test platform using a 2012 Ford Fusion Hybrid
    - Cooperative research and development agreement (CRADA) with Ford to facilitate
- Second set of production Ford control modules to interface with LEESS cells
    - Custom state estimator sends instantaneous state of charge (SOC) and power capability information to vehicle controller
- Maintain stock operating capability (using production NiMH cells)
    - Able to switch between operation using the stock battery and using the LEESS device under test
    - Provides back-to-back performance comparison

Photos by John Ireland, NREL



Fusion test platform and traction battery with Bussed Electrical Center (BEC), Battery Pack Sensor Module (BPSM), and Battery Energy Control Module (BECM)

Bench Testing of First LEESS under Evaluation

- JSR Micro provided LIC modules
  - Asymmetric storage device with battery and ultracapacitor-type characteristics
  - 3.8 V max/cell, and doubled volumetric capacitance due to lithium doping

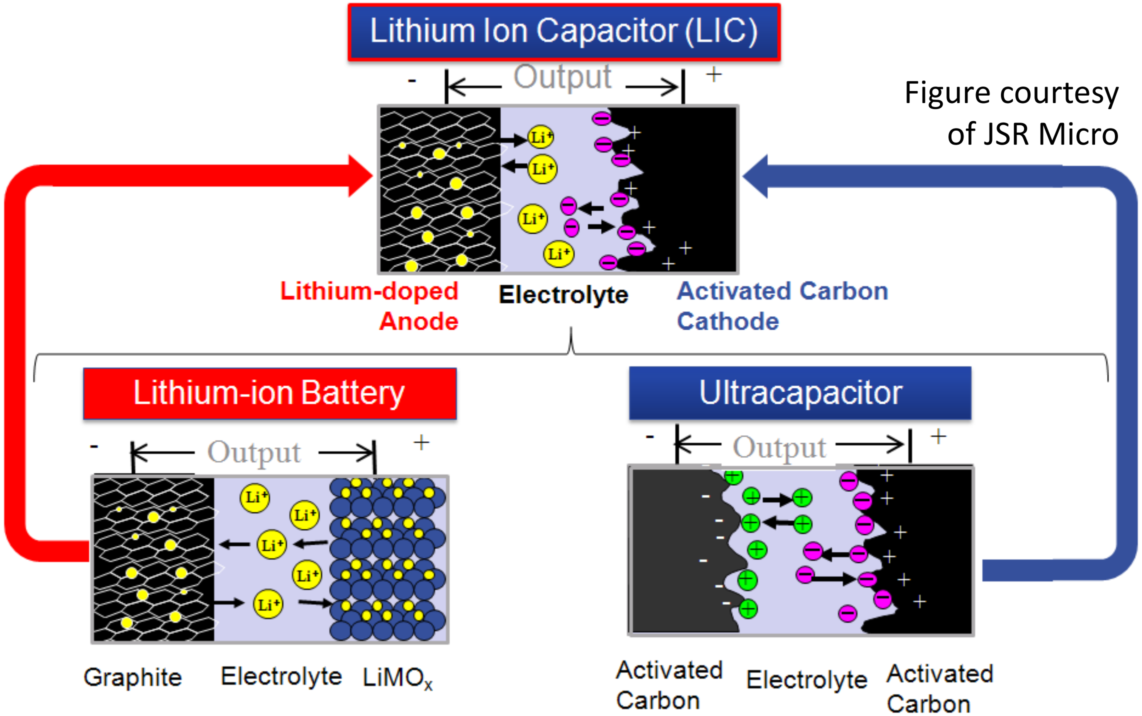


Figure courtesy of JSR Micro

- Conversion pack sizing

	# of Cells	Nominal Voltage	Total Energy (Wh)
Stock Sanyo NiMH*	204	275	1,370
8 JSR 192 F LIC Modules	96	300	260**

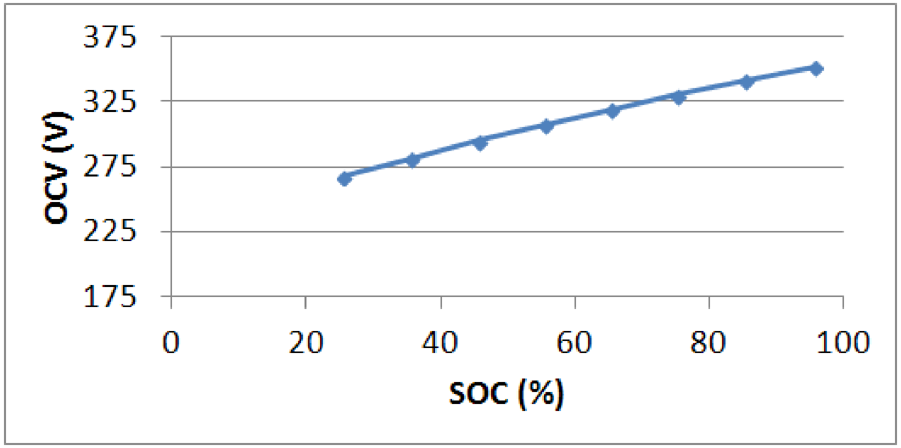
*Based on fact sheet published by Idaho National Laboratory (INL): http://www1.eere.energy.gov/vehiclesandfuels/avta/pdfs/hev/batteryfusion4699.pdf
**Assuming 175 V – 350 V maximum in-vehicle operating window

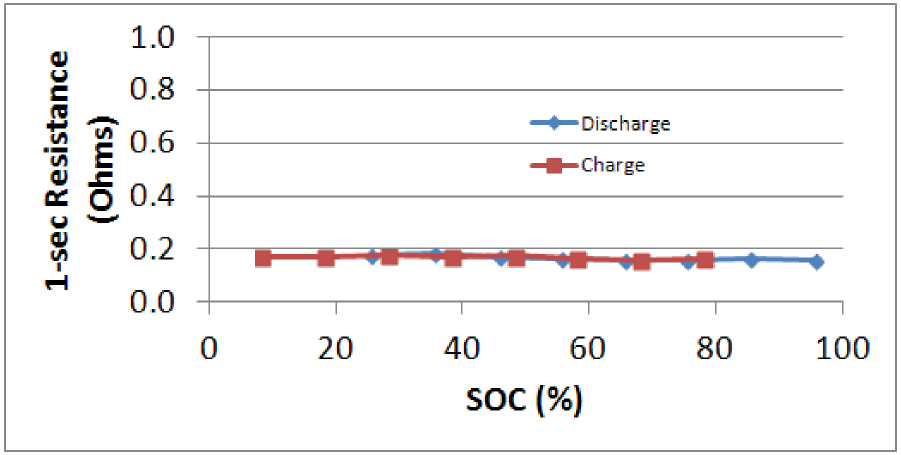
JSR LIC Pack Characterization

- Bench cycling at multiple temperatures
  - Static capacity test
  - Hybrid pulse power characterization (HPPC)
  - US06 drive profile
- Impedance 2–3x less than NiMH*

Photo by John Ireland, NREL

25°C, 8-Module HPPC Results

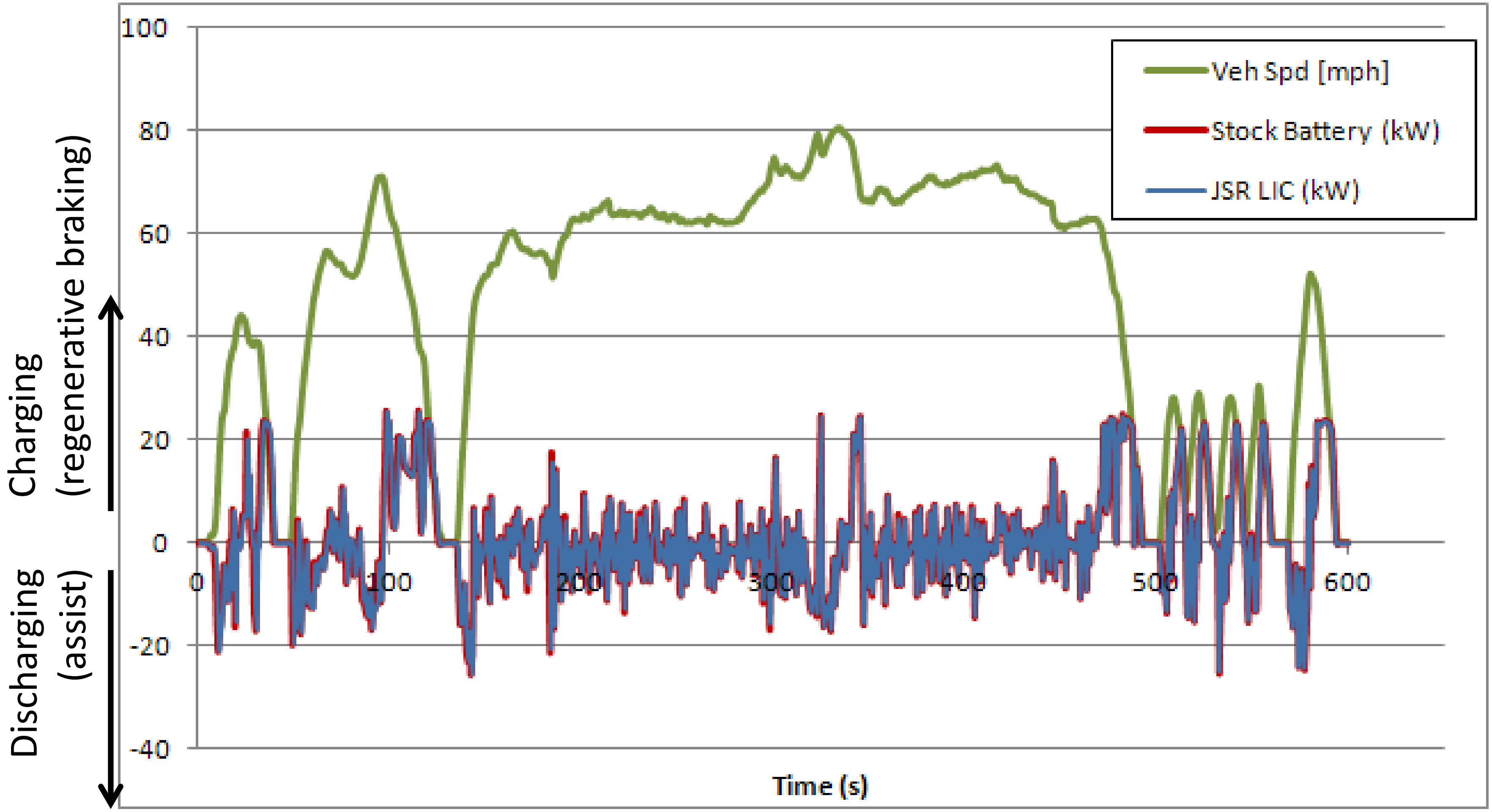




*Based on calculations from INL fact sheet

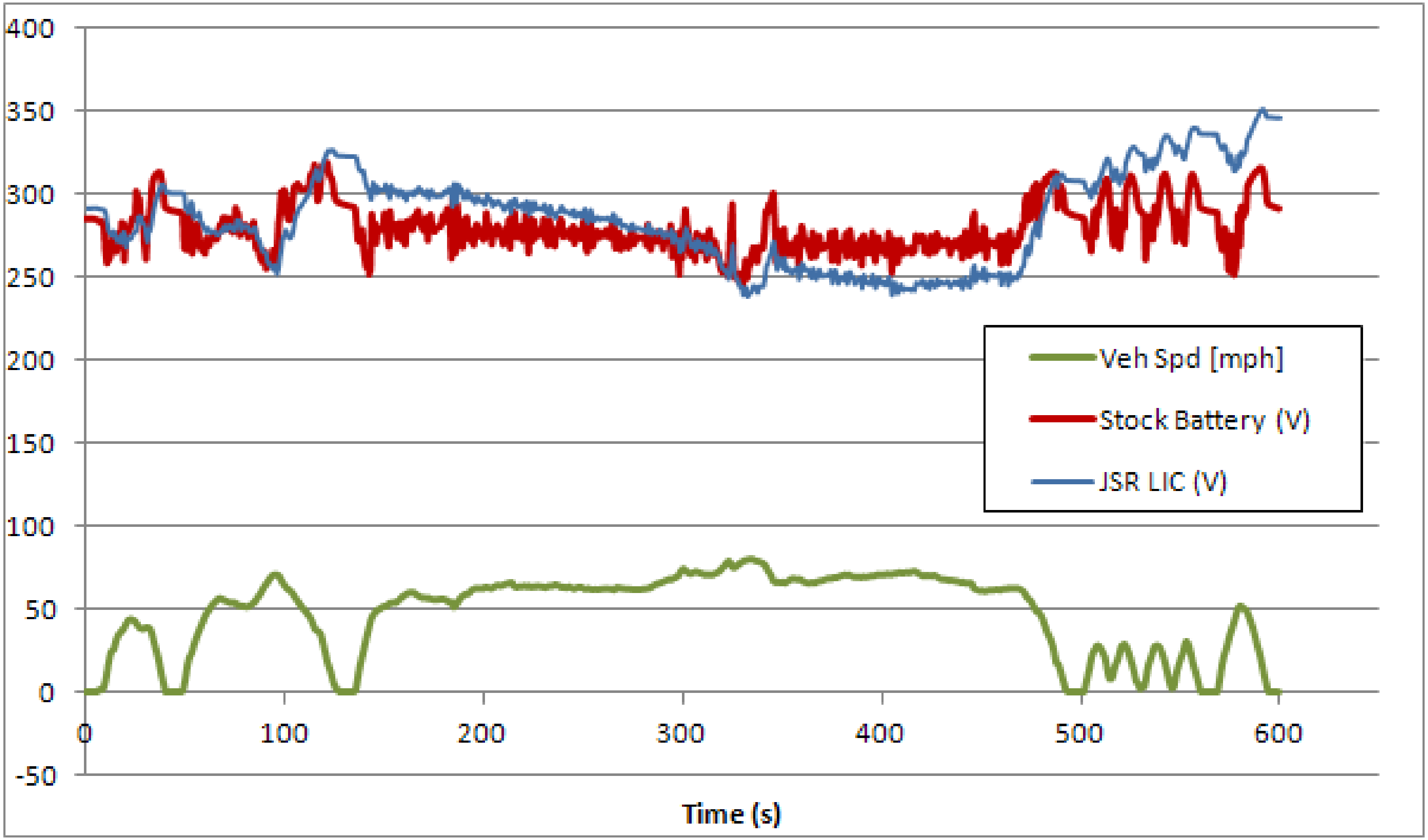
OCV = open circuit voltage

US06 Stock Vehicle (NiMH) & LEESS (JSR LIC) Lab Comparison



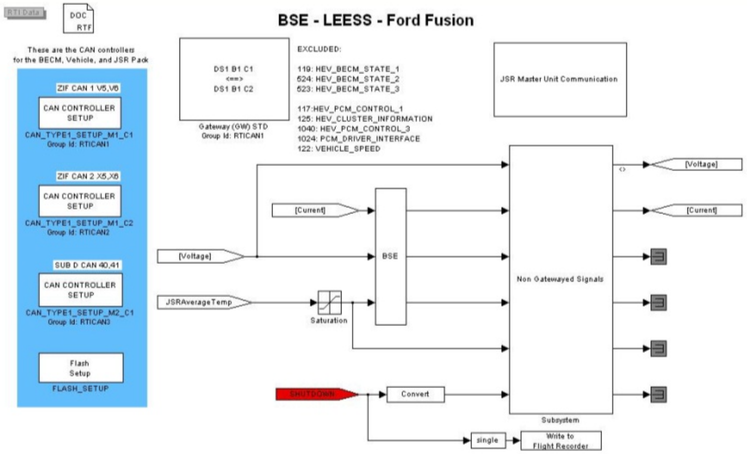
Stock battery data courtesy of Argonne National Laboratory (ANL) chassis dynamometer testing
US06 = aggressive drive cycle with high speeds and accelerations

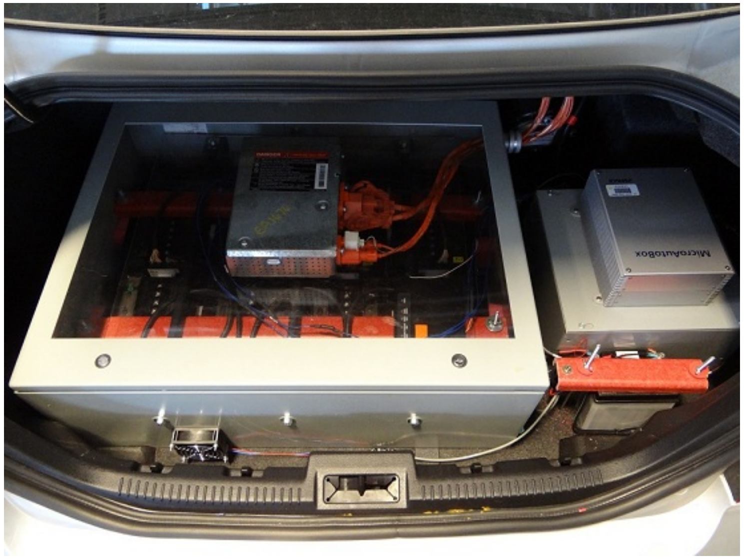
US06 Profile Comparison: Stock Battery (in vehicle) vs. JSR Micro LIC (in lab)



LEESS Control and Vehicle Interface: MABx, LIC State Estimation, and Vehicle Communication

- Controls for LIC state estimation, safety, etc. implemented via rapid control prototyping with dSpace MicroAutoBox (MABx)
- Adaptive state estimation model used to monitor LEESS pack state and estimate power capabilities
- State estimation and power capabilities were validated against bench test data from LIC modules undergoing US06 and HPPC cycles
- MABx interfaces with LEESS modules and with the Ford hybrid controller over the vehicle controller area network (CAN) bus





Simulink state estimation model (above), and LEESS installation in the trunk space showing the JSR LICs and MABx
(Photo by Jon Cosgrove, NREL)

In-Vehicle Comparison: 0–60 mph Accelerations*
Stock Battery (NiMH) & LEESS (JSR LIC)

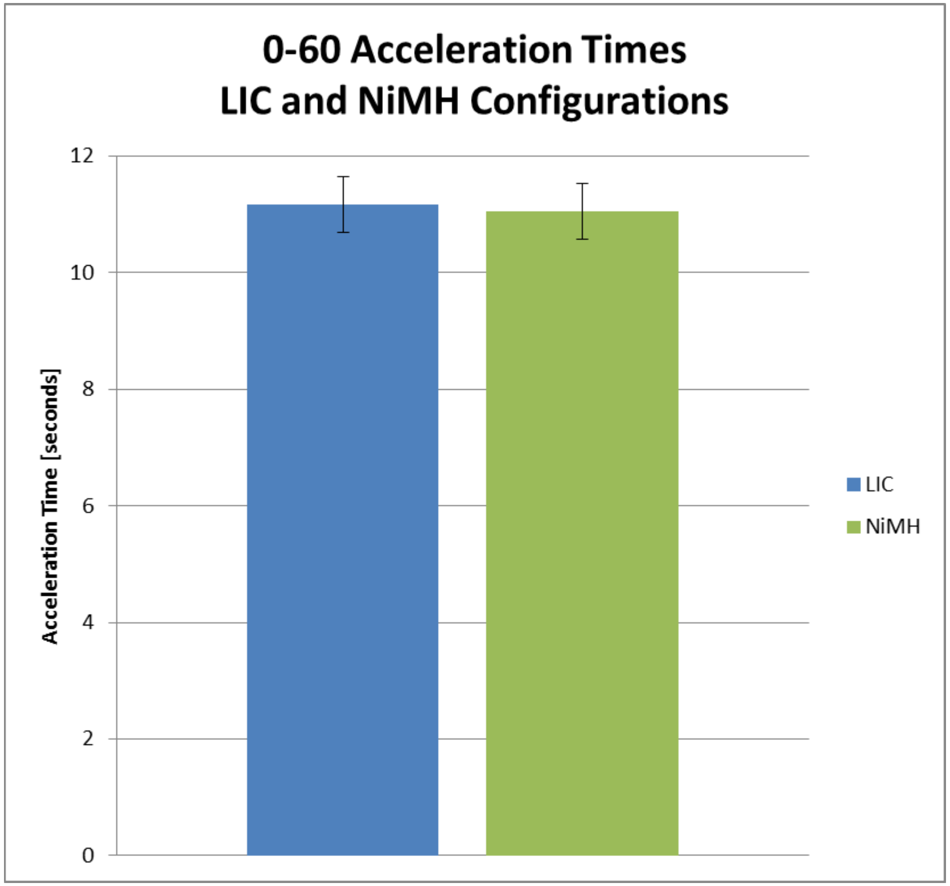


Photo by Petr Sindler, NREL

No significant difference found between acceleration times while in NiMH configuration vs. LEESS configuration

* Run with extra mass of both ESSs and at high altitude

In-Vehicle Comparison: Dynamometer Testing

Test Schedule

- Performed standard drive cycles with vehicle in NiMH and LEESS configurations
  - Test cycles included:
    - FTP/UDDS
    - HWFET
    - US06
    - Cold (20°F) FTP
  - Vehicle CAN traffic recorded using the MABx

FTP/UDDS = Federal Test Procedure/Urban Dynamometer Driving Schedule (city testing)
HWFET = Highway Fuel Economy Test

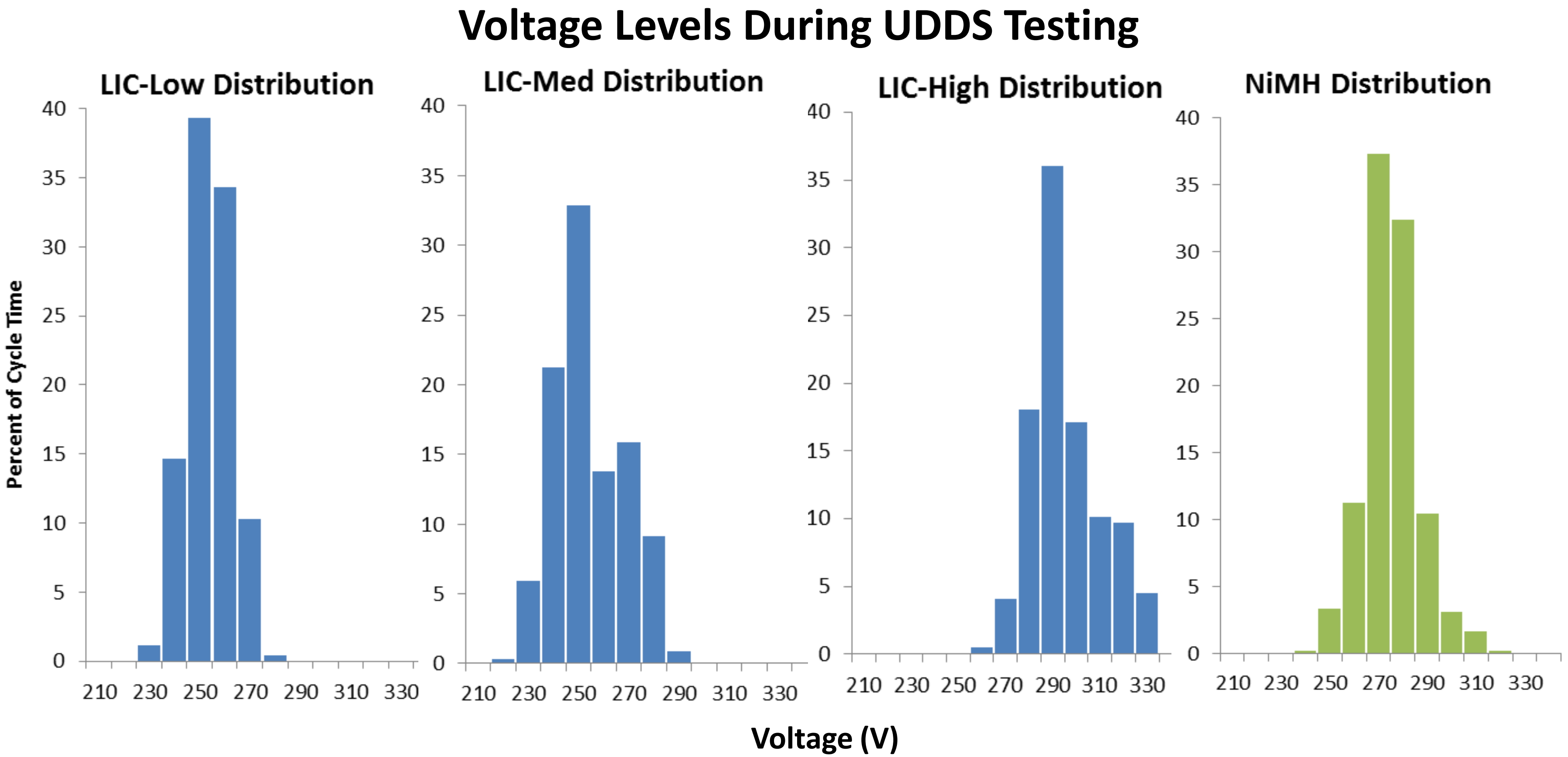
Dynamometer Facility

- Testing details
  - CAN fuel rate calibrated to bag measurements for comparisons

Photo by Jon Cosgrove, NREL

In-Vehicle Comparison: Dynamometer Testing Production NiMH vs. 3 LIC configurations

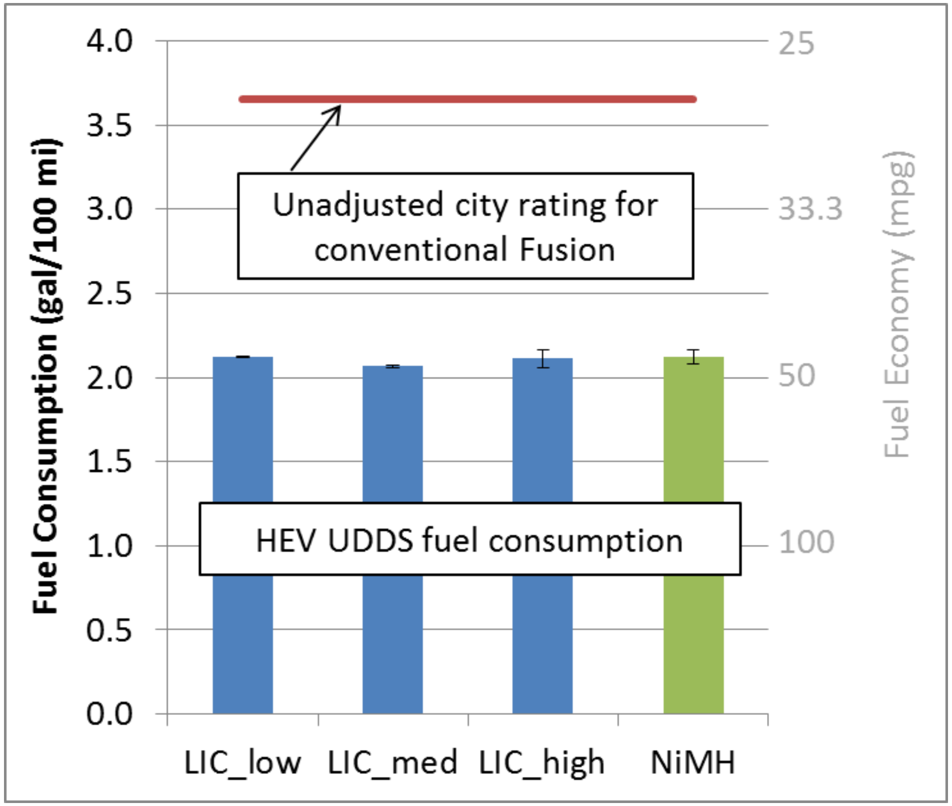
- Evaluated several LIC scenarios in addition to the production configuration
  - LIC-High: Energy constrained only by vehicle and device voltage limits
  - LIC-Med: Artificially reduced upper voltage limit to constrain energy
  - LIC-Low: Further reduced upper voltage limit for most constrained evaluation

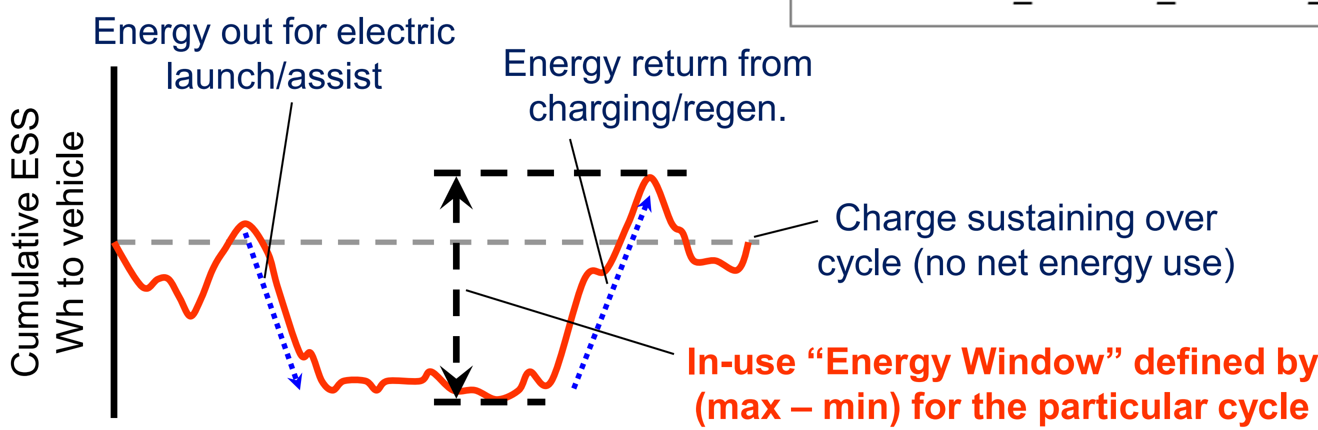


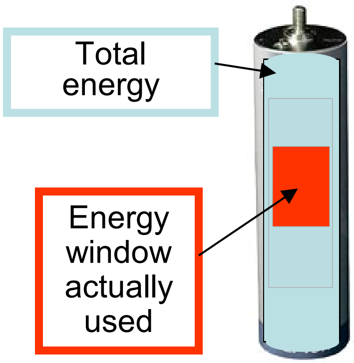
In-Vehicle Dynamometer Testing: Fuel and Energy Use Comparisons

- Small fuel use differences between the HEV configurations—all show significant savings compared to the non-hybrid vehicle

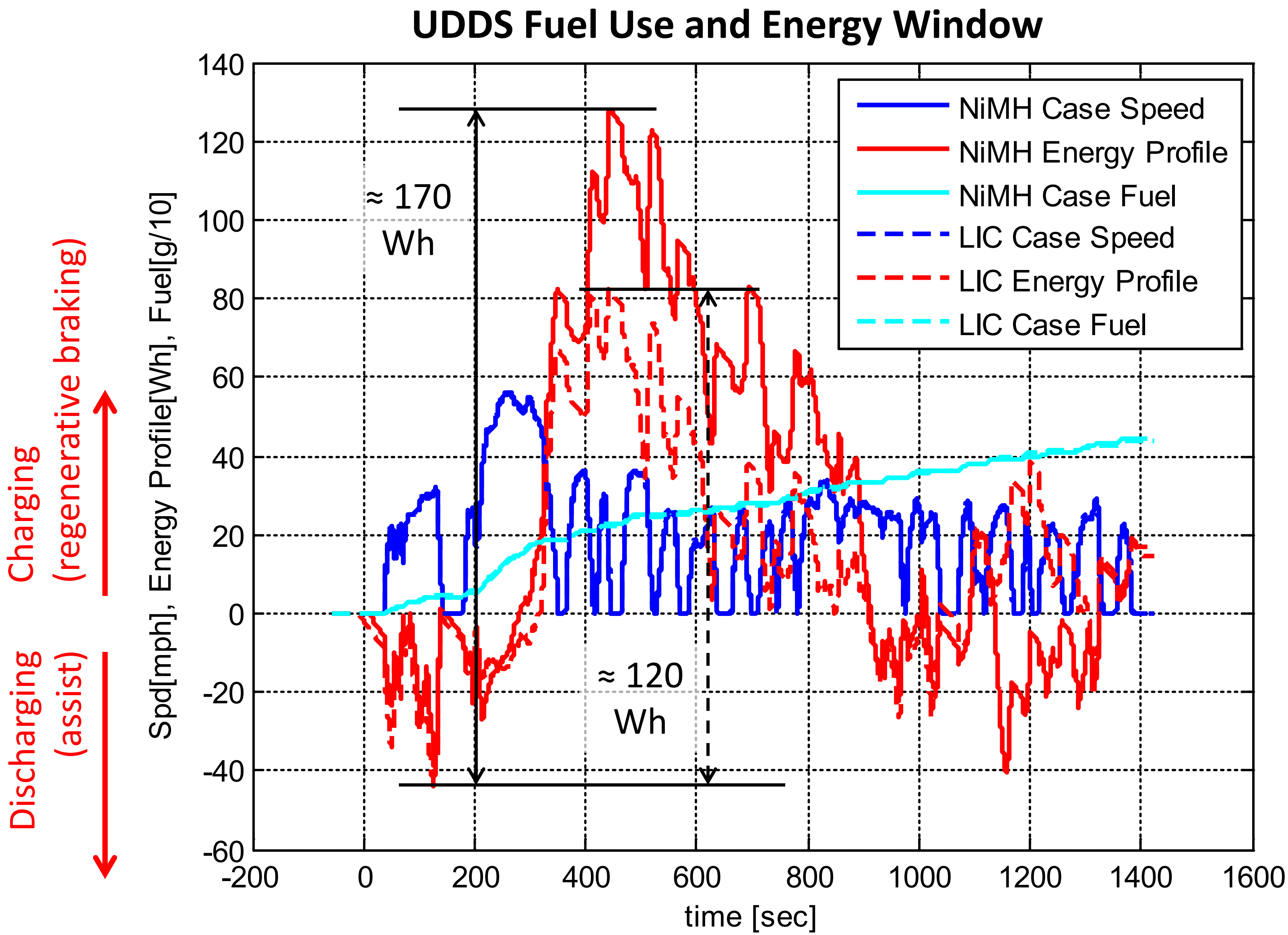
- Also measure energy window used by each ESS configuration for each cycle



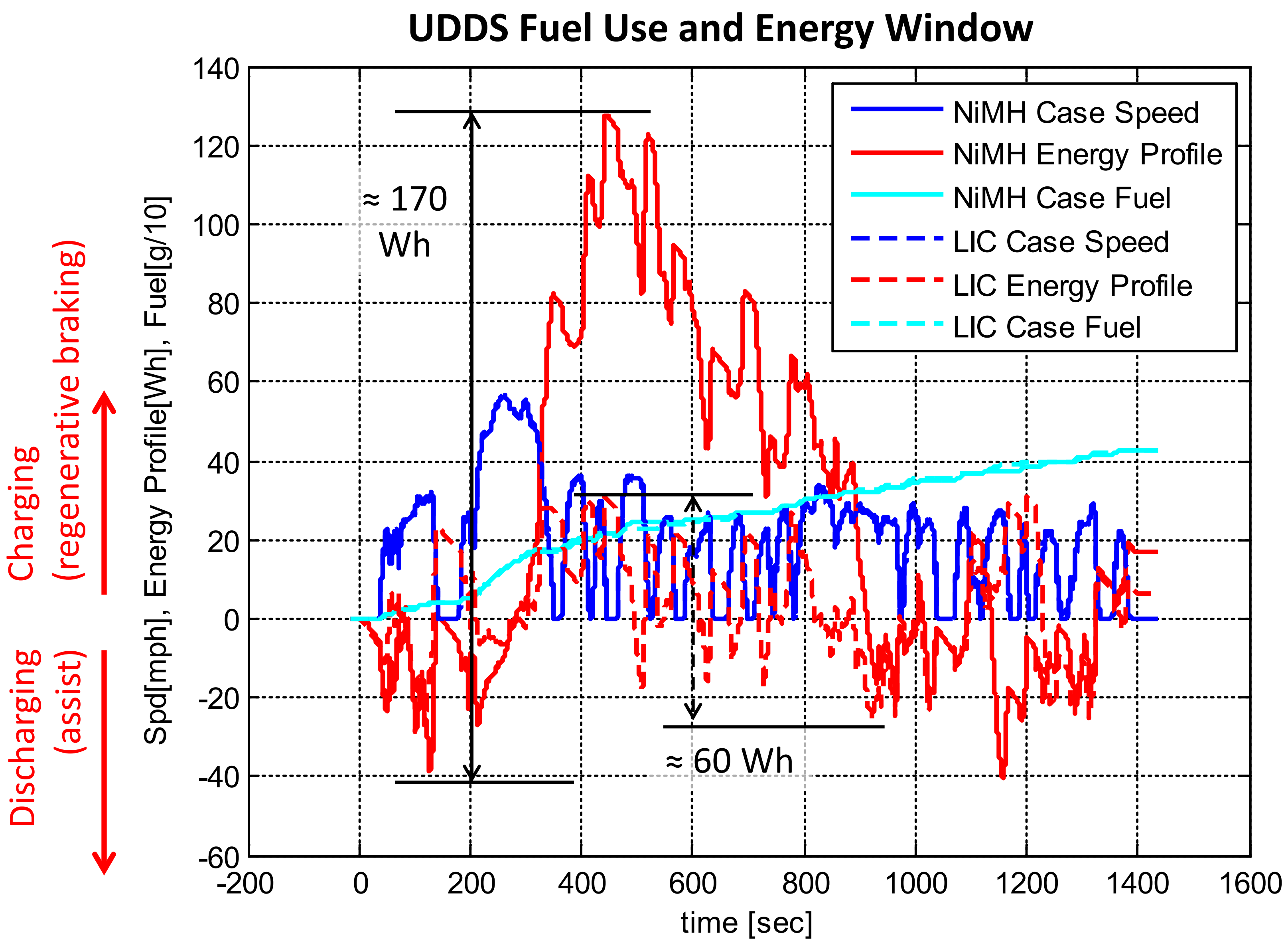




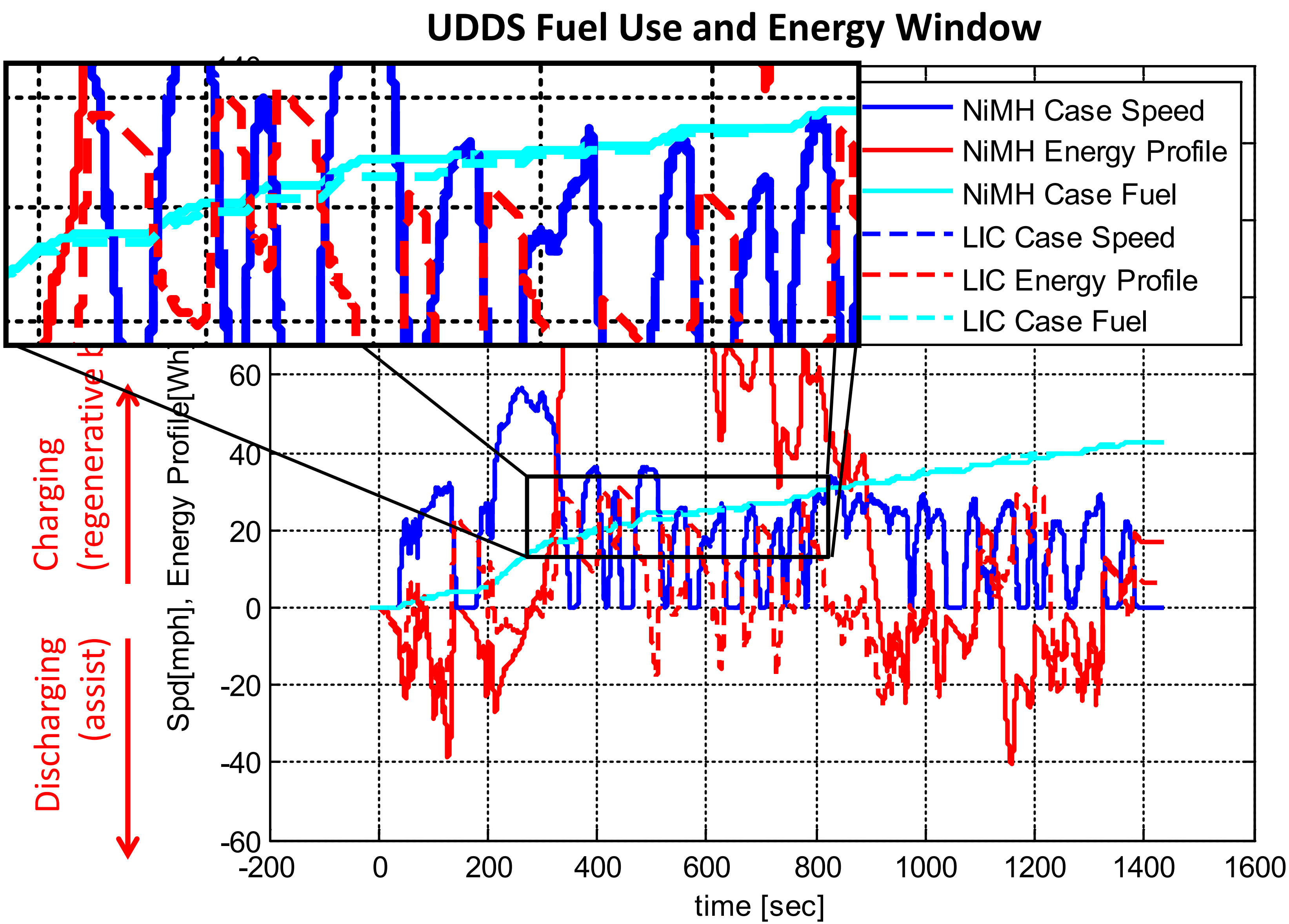
In-Vehicle Dynamometer Testing: Comparing NiMH and LIC-High Scenario



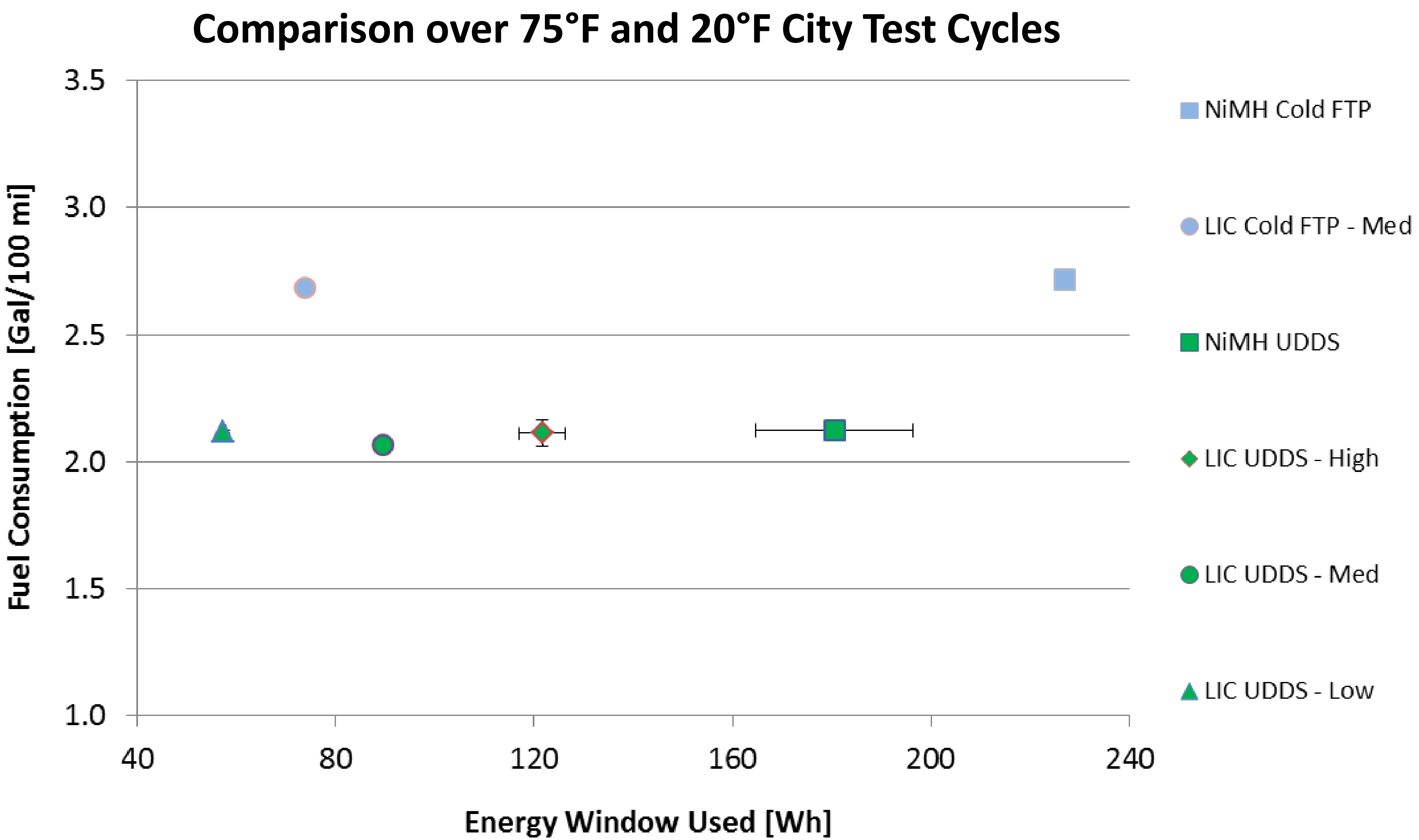
In-Vehicle Dynamometer Testing: Comparing NiMH and LIC-Low Scenario



In-Vehicle Dynamometer Testing: Comparing NiMH and LIC-Low Scenario

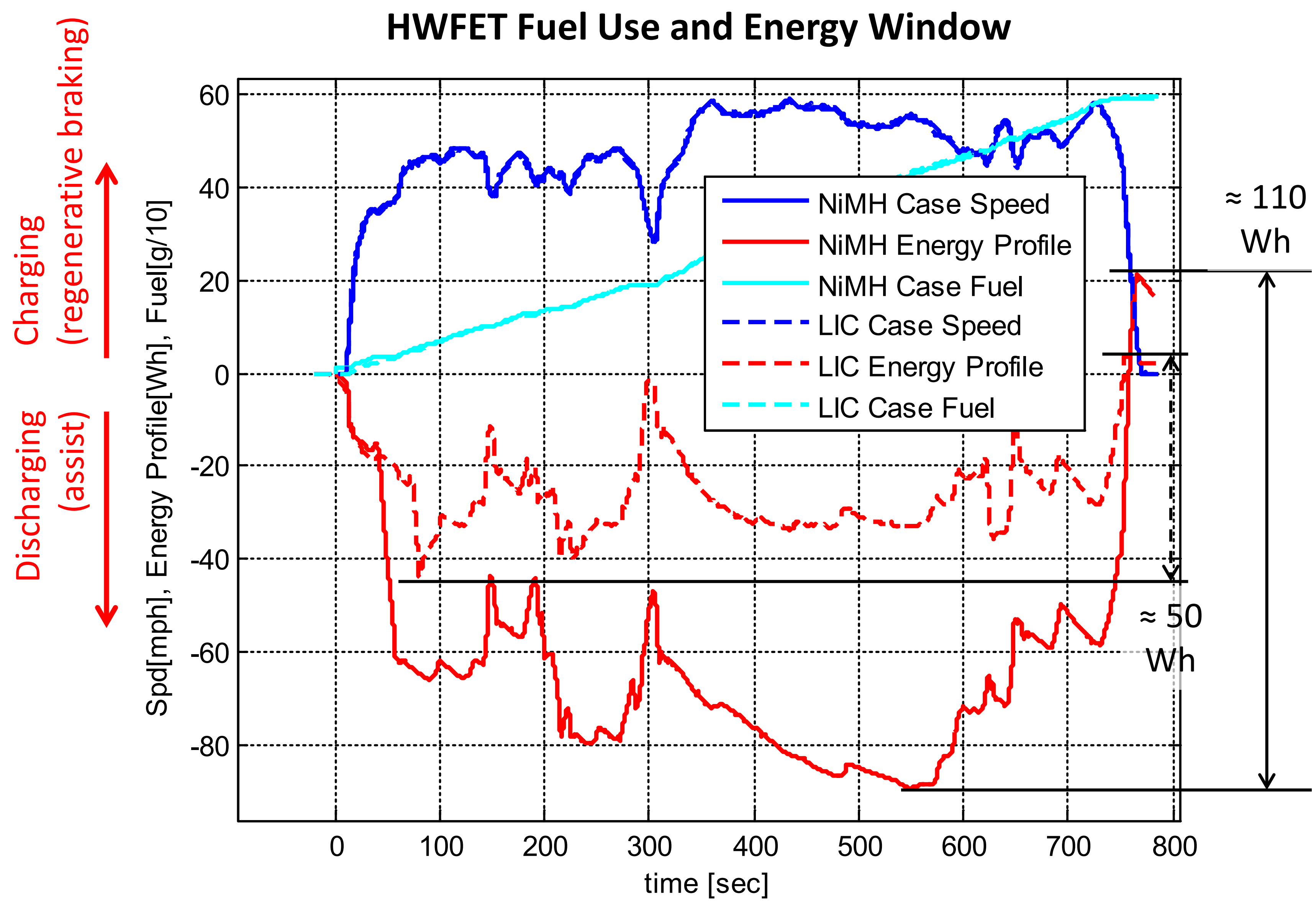


In-Vehicle Dynamometer Testing:
Fuel Use and Energy Window Observations



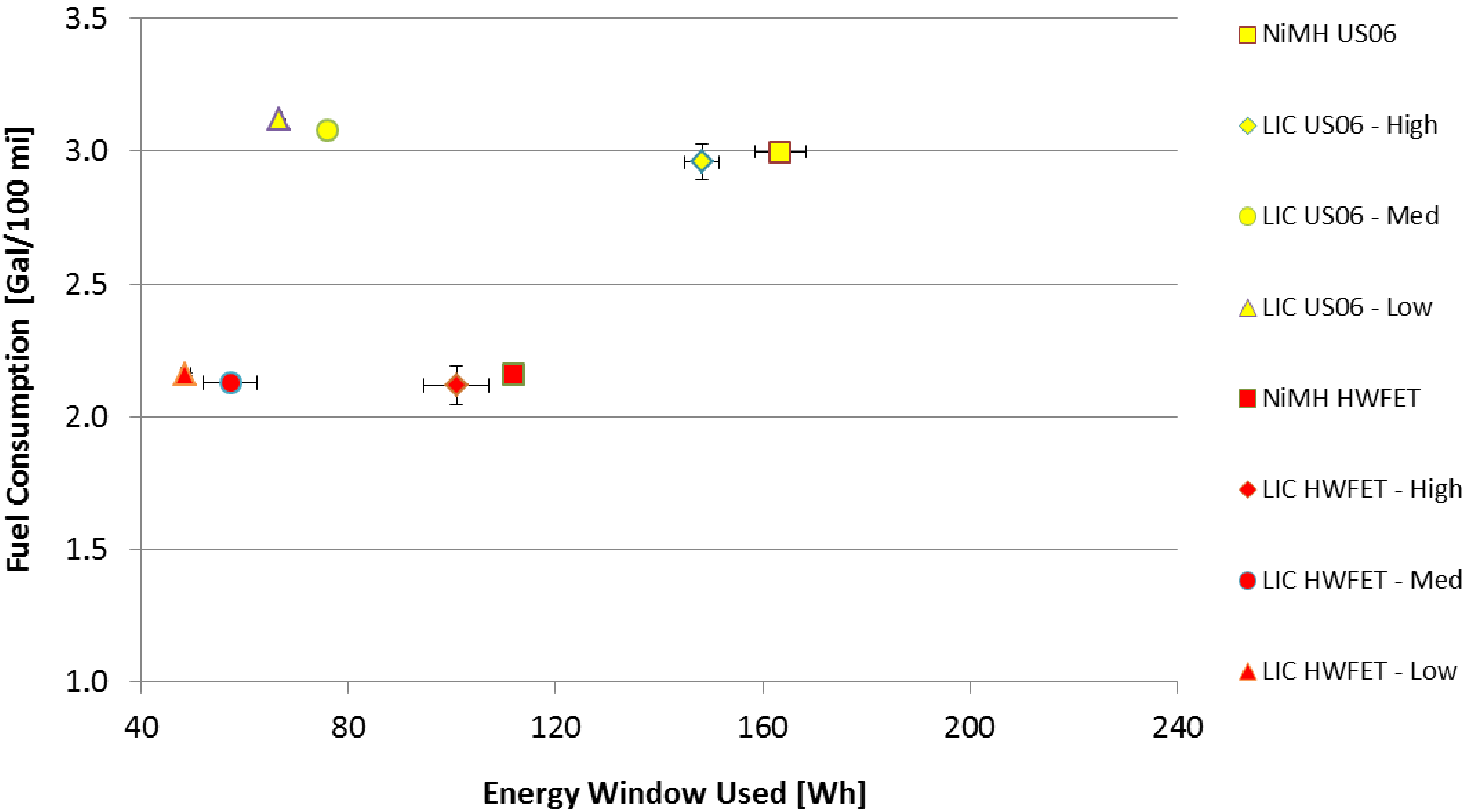
Negligible fuel consumption difference from significantly reduced energy window

In-Vehicle Dynamometer Testing: Comparing NiMH and LIC-Low Scenario



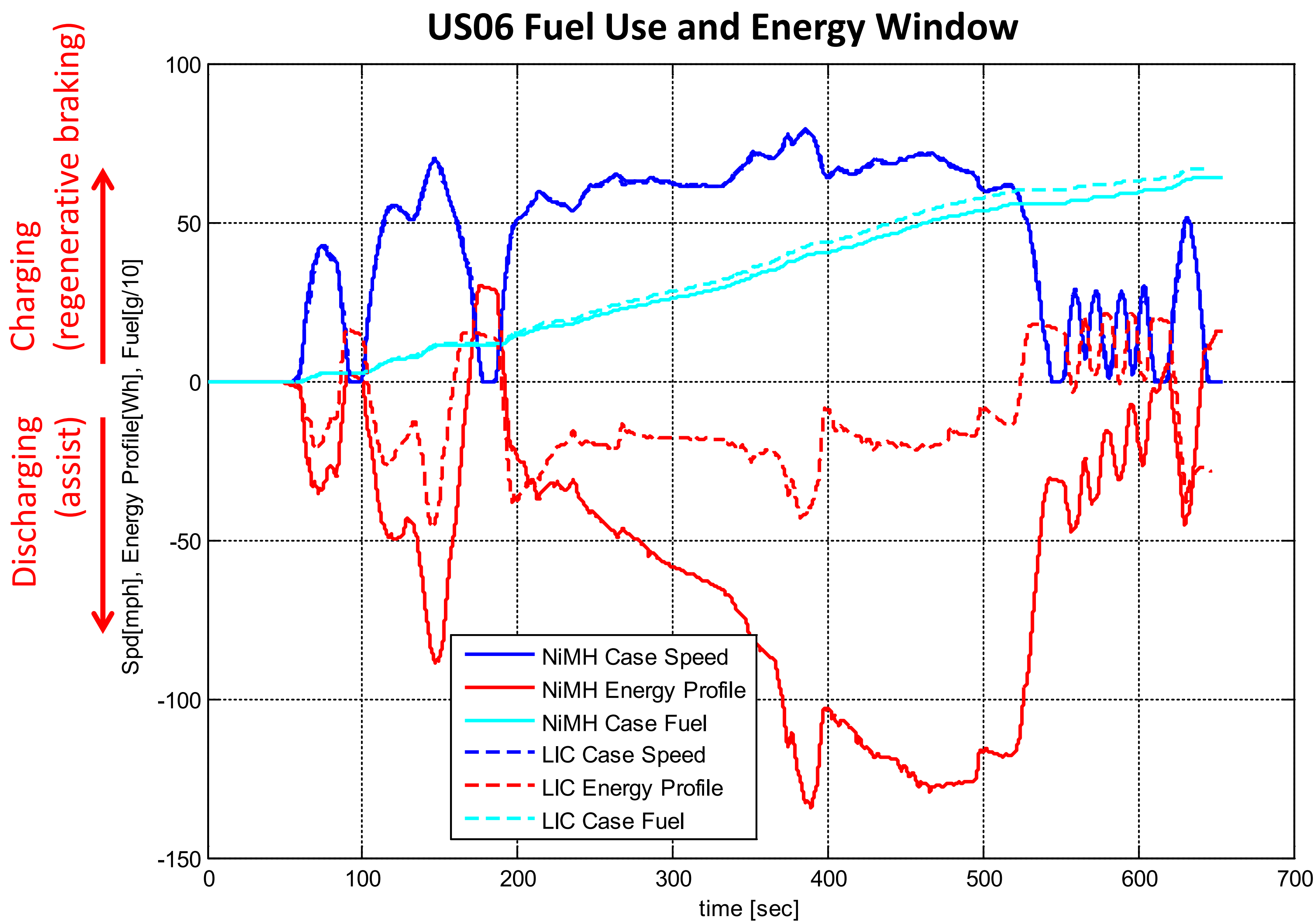
In-Vehicle Dynamometer Testing:
Fuel Use and Energy Window Observations

Comparison over Highway and High Speed/Acceleration Test Cycles



Small energy window provides level HWFET fuel consumption and slightly increased US06 fuel consumption

In-Vehicle Dynamometer Testing: Comparing NiMH and LIC-Low Scenario



In-Vehicle Dynamometer Testing:
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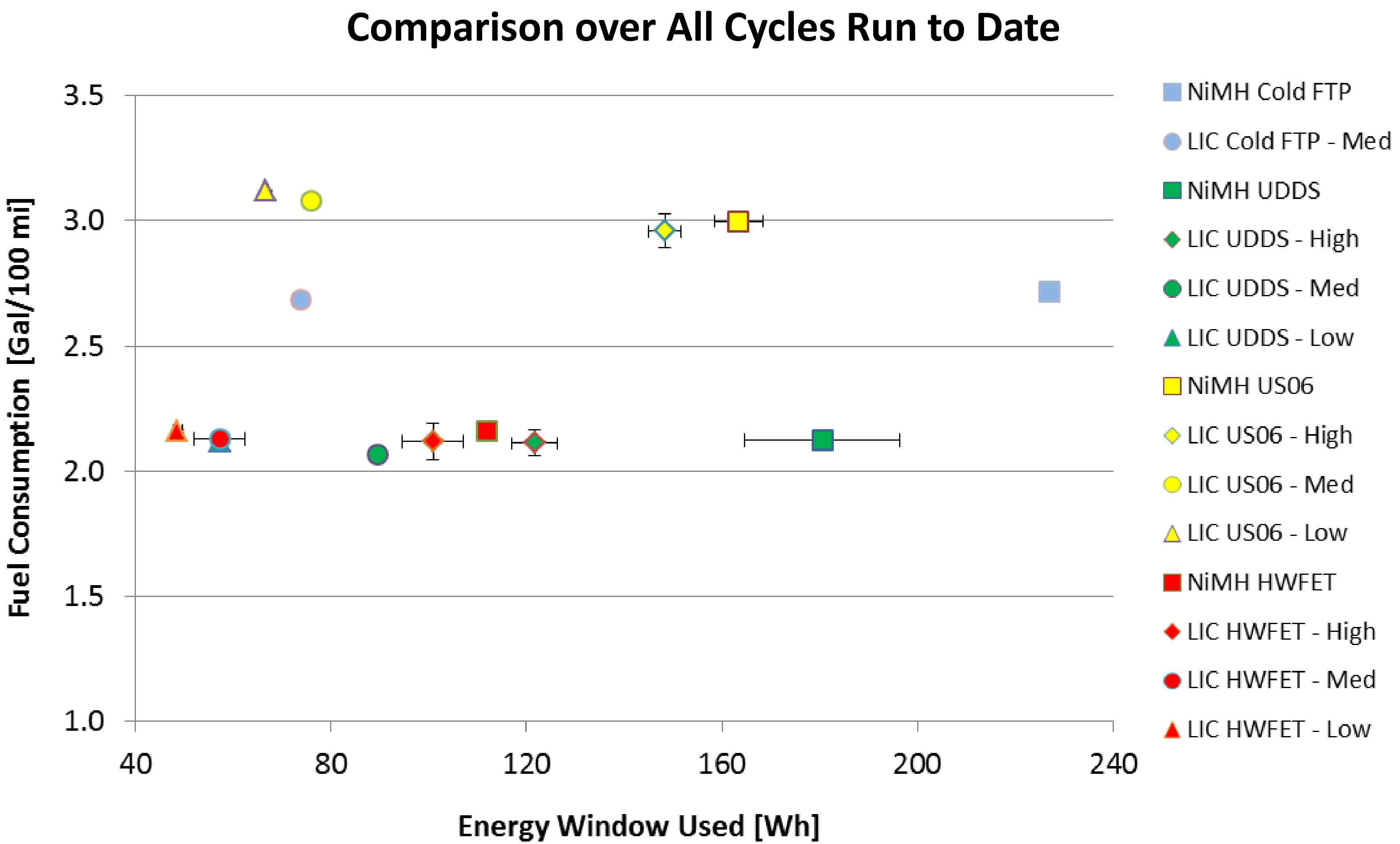

Significantly reduced energy window resulted in negligible fuel consumption difference on most cycles and small increase on US06 test

Summary

- HEVs are effective at reducing per-vehicle fuel use
- ESS cost reductions/performance improvements → improved vehicle-level cost vs. benefit
  - Increase market demand and aggregate fuel savings
- LEESS considerations
  - Technical evaluation
    - Road testing showed no differences in acceleration times
    - LIC configurations even with very small energy windows showed negligible fuel consumption difference to the production NiMH configuration for many cycles, and slight increases on the US06 cycle only
      - LIC calibration improvements may improve efficiency and drive quality
  - As long as engine can be started under worst-case conditions, considerable ESS downsizing may minimally impact fuel savings
    - Potential to achieve cost savings
    - Alternative technologies may allow downsizing while still satisfying life, power, and cold temperature performance requirements

Potential Next Steps

- Wrap up JSR LIC testing
  - 95°F SC03 for air conditioning comparison case
  - Very cold (e.g., -10°F ≈ -23°C) operation
- Bench testing followed by in-vehicle evaluation with additional LEESS devices
  - Next system will be ultracapacitor modules
- Consider possible changes if vehicle designed around a LEESS device – e.g., higher power motor
- Combine evaluation results with supplier cost estimates to refine business case assessment

Acknowledgments

- JSR Micro
  - Providing modules for evaluation
  - Related technical information and support
- Ford Motor Company
  - CRADA facilitating vehicle conversion
- U.S. Department of Energy
  - Cost-shared support between two Vehicle Technologies Office activities
    - Energy Storage (ES)
    - Vehicle Systems Simulation and Testing (VSST)
- USABC
  - Collaborated on precursor analysis to this effort and established LEESS performance targets for power-assist HEVs
- Maxwell Technologies
  - Providing double-layer capacitors as next system to test

Questions?

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