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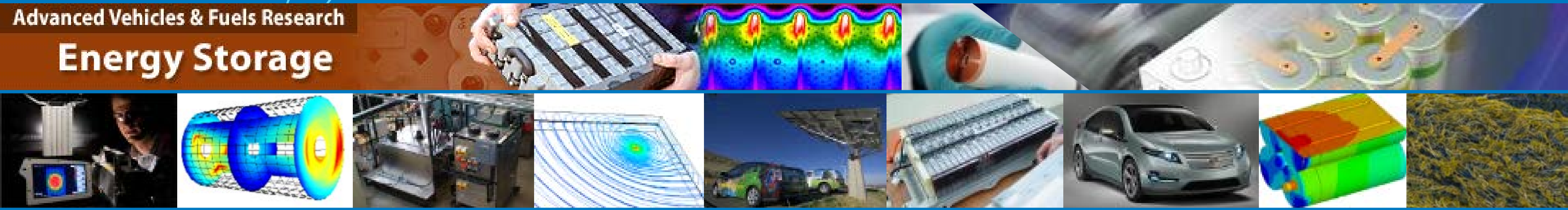
Testing Low-Energy, High-Power Energy Storage Alternatives in a Full-Hybrid Vehicle



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Presenter: Ahmad Pesaran
Authors: Jon Cosgrove and Jeff Gonder
National Renewable Energy Laboratory

Supported by: DOE Vehicle Technologies Office

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Overview

- **Background – HEVs and their Batteries**
  - Moderate-energy, high-power
- **Analysis – HEV Fuel Economy vs. Battery Size**
- **Hybrids with Low Energy Ultracapacitors (NREL's Experience)**
- **Interest in Lower-energy Energy Storage System (LEESS)**
  - Low-energy, very high-power
- **Developing an HEV Test Bed for Evaluating LEESS**
- **Testing Lithium-ion Capacitor (LIC) as a LEESS**
- **Test Results with LIC in the HEV Test Platform**
  - In-vehicle comparison with stock nickel-metal hydride (NiMH)
- **Summary and Future Work for LEESS HEV Test Platform**

Background – HEVs and their Batteries

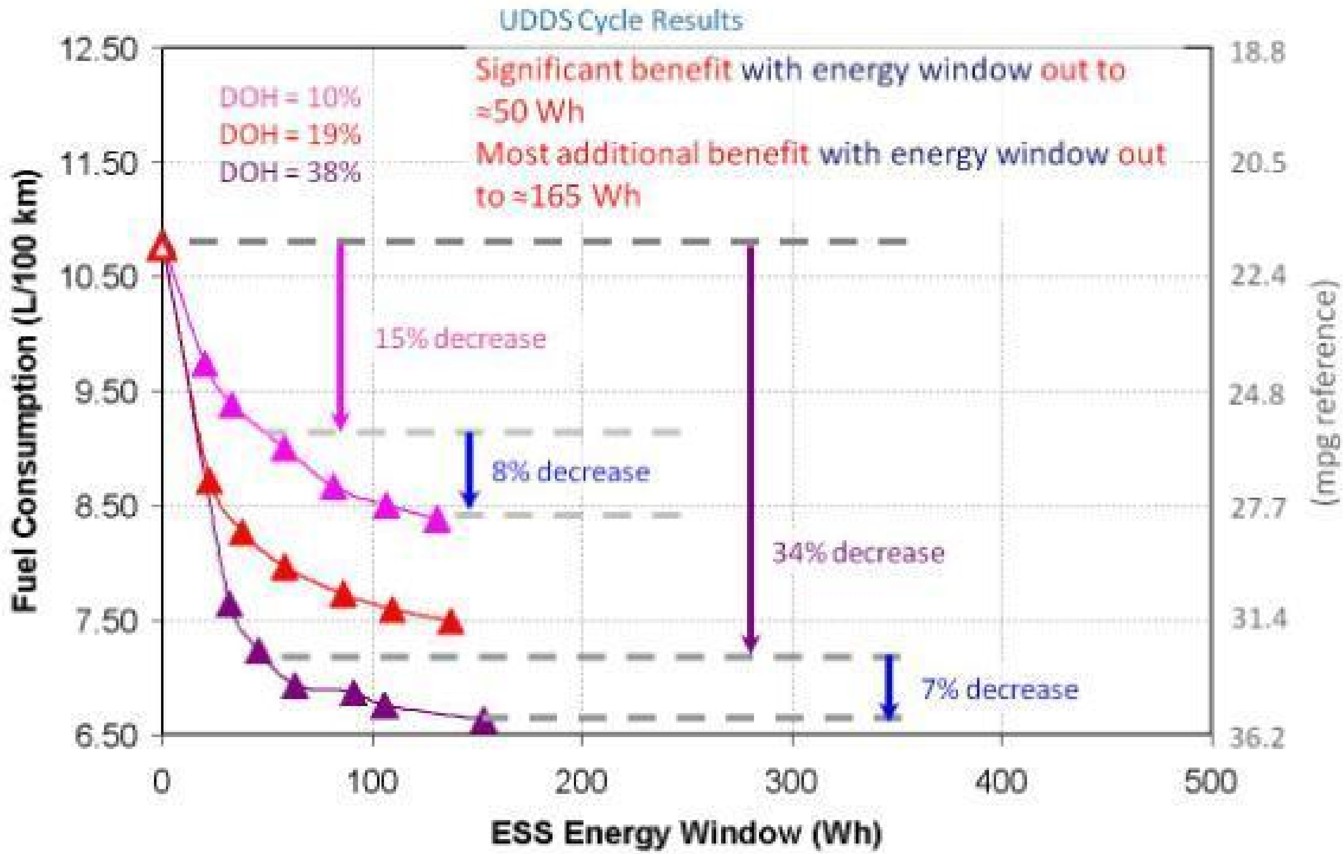
- **Hybrid electric vehicles (HEVs) are effective at reducing per-vehicle fuel use**
  - 30-50% higher fuel economy than comparable conventional vehicle
- **United States Advanced Battery Consortium (USABC) battery targets for mid-size vehicle:**
  - 300 Wh available energy and 25 kW power
  - 300,000 shallow (25 Wh) cycles and 15 years life
  - $20/kW
- **Many HEV models in the market; some very successful**
- **NiMH technology has been a good fit from many perspectives; some OEMs are moving toward Li-ion technology**
- **Most USABC targets (energy, power, cycle, and calendar life) have been achieved with a relatively oversized battery, but not cost**
- **Incremental cost of HEVs remains a barrier to wider market penetration**
  - Energy storage system (ESS) is arguably the largest contributor

Increasing Market Share of HEVs

- **ESS cost reductions and performance improvements lead to improved vehicle-level cost vs. benefit**
  - Increase market demand and aggregate fuel savings
  - NiMH performance and cost may be leveling off??
  - Room for Li-ion improvements, but there is concern about safety
- **How can the cost of ESS for full HEVs be further reduced?**
  - Increase volume production
  - Use less expensive materials
  - Potential benefits from alternative technology?
    - Better life, better cold temperature performance
    - Cheaper materials
  - Re-evaluate energy and power requirements

Analysis: HEV Fuel Savings Sensitivity to Energy Storage Size

- **In 2010, NREL performed simulations and analyzed test data in support of USABC**

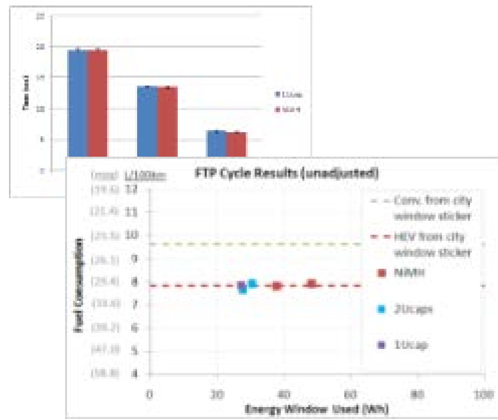


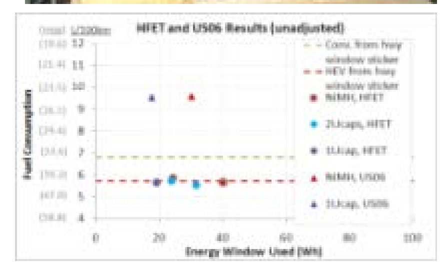
- **Results suggested power-assist HEVs can still achieve high fuel savings with lower energy (less than 150 Wh) and potentially lower-cost ESS**

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

NREL Evaluation of Hybrid with Low-energy Ultracapacitors (2010-2011)

- **Objective: verify fuel economy analysis for low-energy ESS**
- **Take advantage of Ucap potential for superior cycle life, cold temperature performance, and long-term cost reductions**
- **Modified a Saturn Vue mild hybrid for testing Ucaps and NiMH systems**





Photos by Jeff Gonder and Jason Lustbader, NREL

Findings: HEV with ultracapacitors performed in acceleration and FE at least as well as the original HEV configuration with NiMH battery

BAS = belt alternator starter ("mild" HEV)

Vehicle: 42-V Saturn Vue BAS HEV

Interest in Lower-energy Energy Storage System (LEESS)

- **USABC asked NREL to performed further analysis to re-evaluate the energy storage targets for power assist HEVs**
- **NREL analysis showed that significant fuel economy improvements could be achieved with a low-energy, very high power ESS**
- **USABC established targets for LEESS in 2010**
  - 26 Wh available energy
  - 55 kW – 2s discharge

USABC

UNITED STATES ADVANCED BATTERY CONSORTIUM LLC

USABC Goals for HIGH POWER, LOWER ENERGY- ENERGY STORAGE SYSTEM (LEESS) FOR POWER ASSIST HYBRID ELECTRIC VEHICLE (PAHEV) APPLICATIONS

USABC Requirements at End of Life for LEESS PA HEV

End of Life Characteristics	Unit	PA (Lower Energy)	
2s / 10s Discharge Pulse Power	kW	55	20
2s / 10s Regen Pulse Power	kW	40	30
Discharge Requirement Energy	Wh	56	
Regen Requirement Energy	Wh	83	
Maximum current	A	300	
Energy over which both requirements are met	Wh	26	
Energy window for vehicle use	Wh	165	
Energy Efficiency	%	95	
Cycle-life	Cycles	300,000 (HEV)	
Cold-Cranking Power at -30°C (after 30 day stand at 30 °C)	kW	5	
Calendar Life	Years	15	
Maximum System Weight	kg	20	
Maximum System Volume	Liter	16	
Maximum Operating Voltage	Vdc	≤400	
Minimum Operating Voltage	Vdc	≥0.55 V_{max}	
Unassisted Operating Temperature Range	°C	-30 to +52	
30° -52°	%	100	
0°	%	50	
-10°	%	30	
-20°	%	15	
-30°	%	10	
Survival Temperature Range	°C	-46 to +66	
Selling Price/System @ 100k/yr)	$	400	

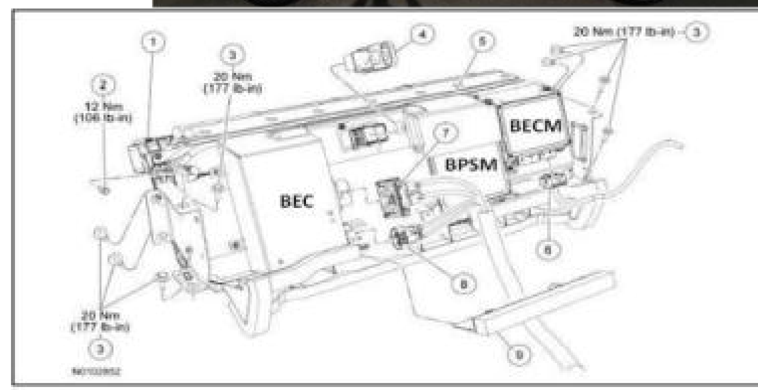
Interest in Lower-energy Energy Storage System (LEESS)

- **USABC issued a Request for Proposal Information (RFPI) to support LEESS development in 2010**
  - 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 funded two battery firms for developing LEESS in 2011:**
  - A123 Systems (high power iron phosphate/graphite batteries)
  - Maxwell Technologies (lithium-ion capacitor)
- **New LEESS technologies being developed or offered by others**
- **We felt there was a need to evaluate in-HEV performance of LEESS technologies**
- **NREL obtained support from the DOE Vehicle Technologies Office to evaluate various LEESS technologies in a power-assist HEV test bed**

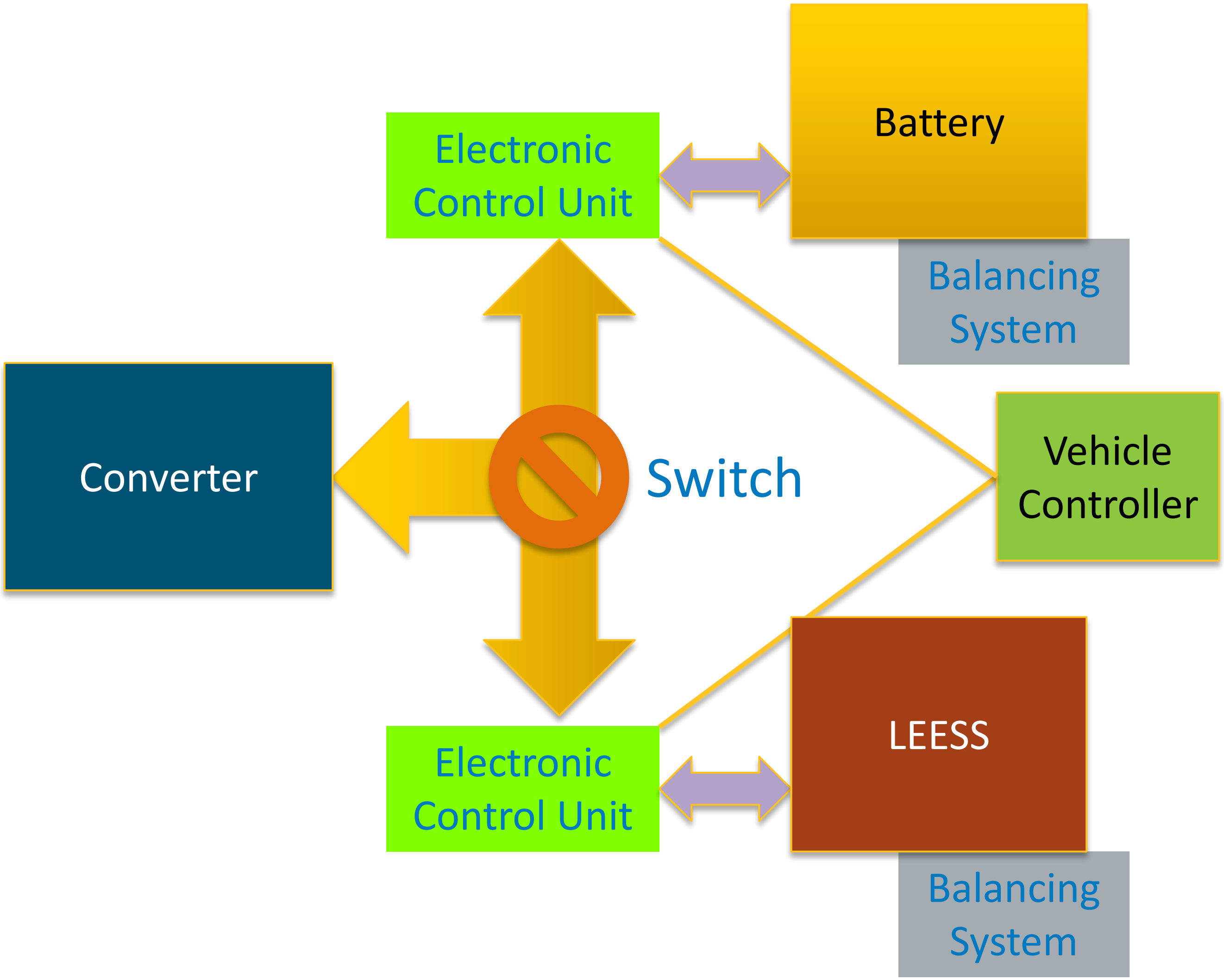
Developing an HEV Test Bed for Evaluating LEESS

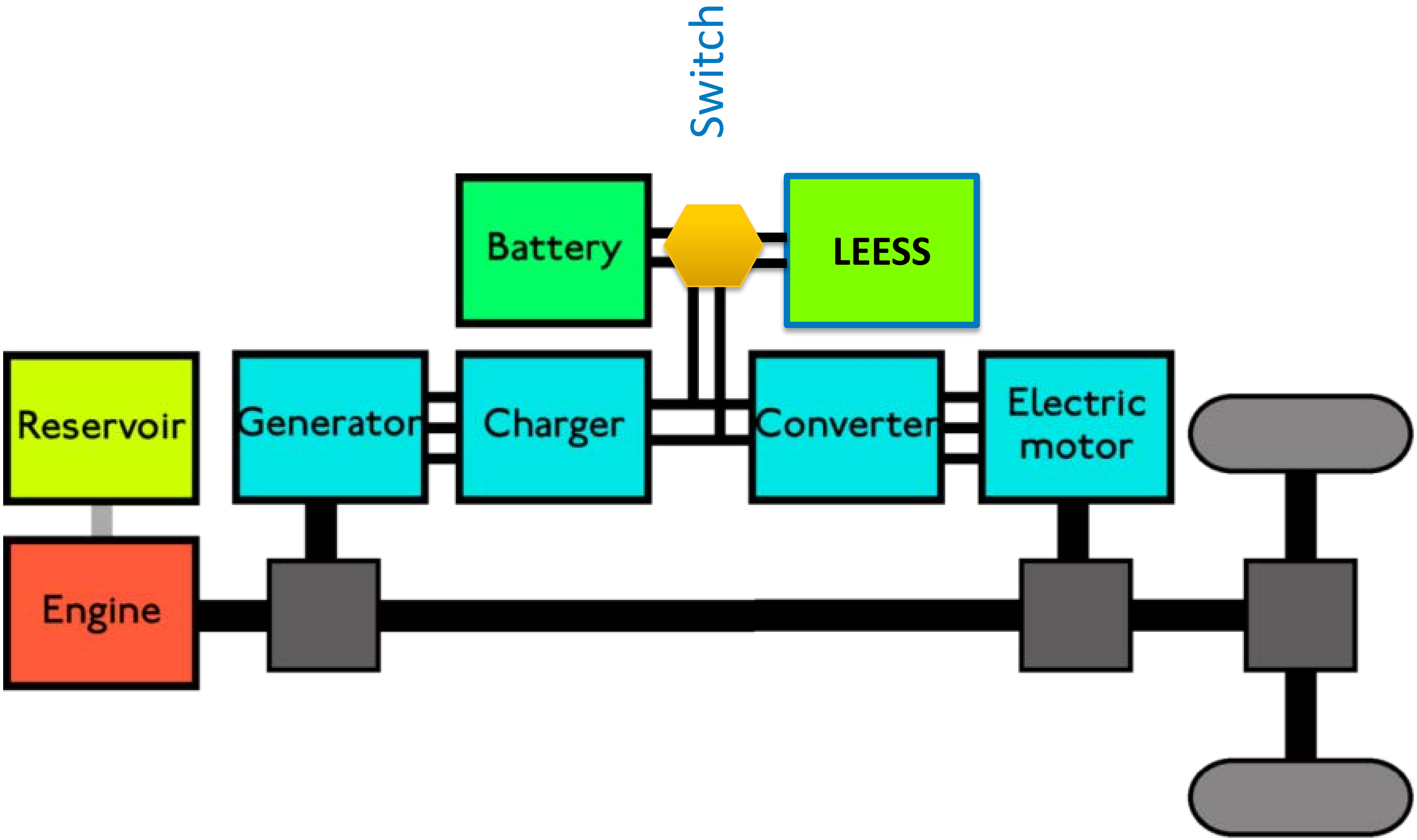
- **Set up reusable vehicle test bed using 2012 Ford Fusion Hybrid**
  - Entered into Cooperative Research and Development Agreement (CRADA) with Ford to facilitate modifications
- **Use voltage and volume of stock NiMH battery system for sizing of LEESS to be placed in trunk of the vehicle**
- **Install second set of production Ford control modules to interface with LEESS**
  - Custom state estimator sends instantaneous state of charge (SOC) and power capability information to vehicle controller
- **Maintain stock operating capability (using production NiMH system)**
  - Able to switch between operation using stock battery and using LEESS under test
  - Provides back-to-back performance comparison

Photos by John Ireland, NREL



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

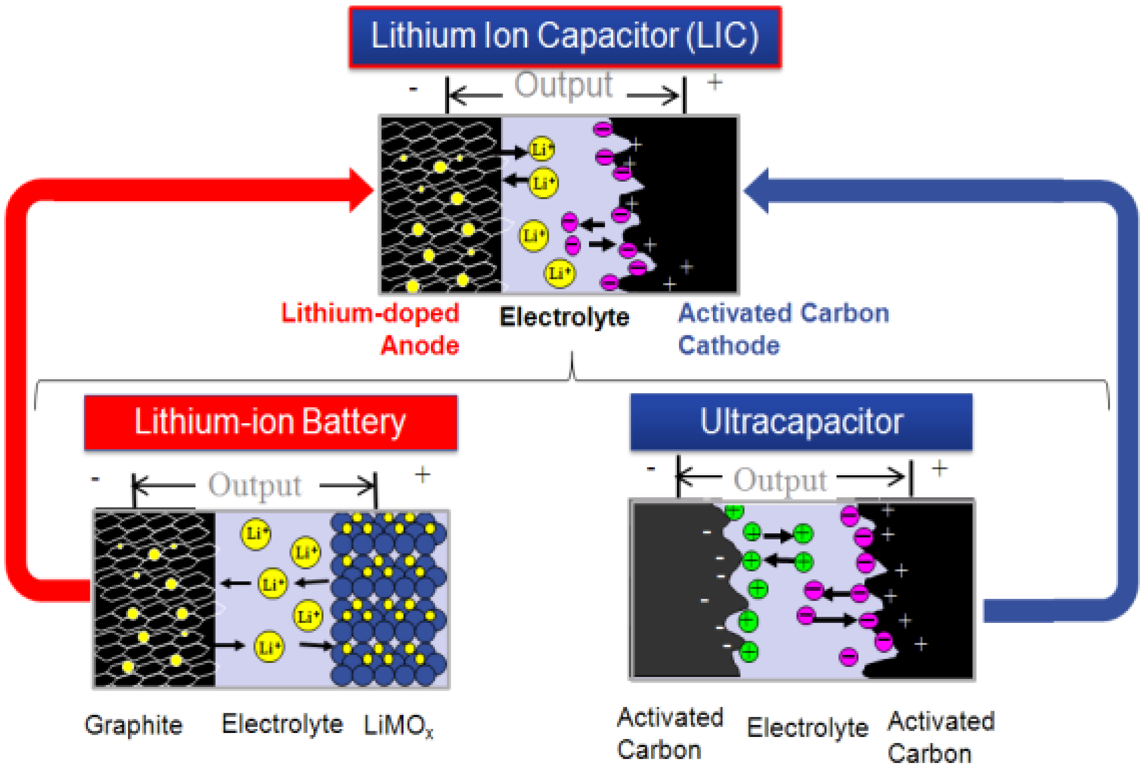

Battery
Electronic Control Unit
Balancing System
Converter
Switch
Vehicle Controller
LEESS
Electronic Control Unit
Balancing System



Switch
Battery
LEESS
Reservoir
Generator
Charger
Converter
Electric motor
Engine

Evaluating the First LEESS Technology in HEV Test Bed

- **Lithium-ion capacitor (LIC) technology**
  - Lithiated graphite as anode and activated carbon as cathode with li-ion electrolyte
  - Asymmetric storage device with battery and ultracapacitor-type characteristics
  - 3.8 V max/cell, and doubled volumetric capacitance due to lithium doping
- **JSR Micro provided LIC modules**



Sizing of Stock Battery and LEESS LIC for HEV Test Bed

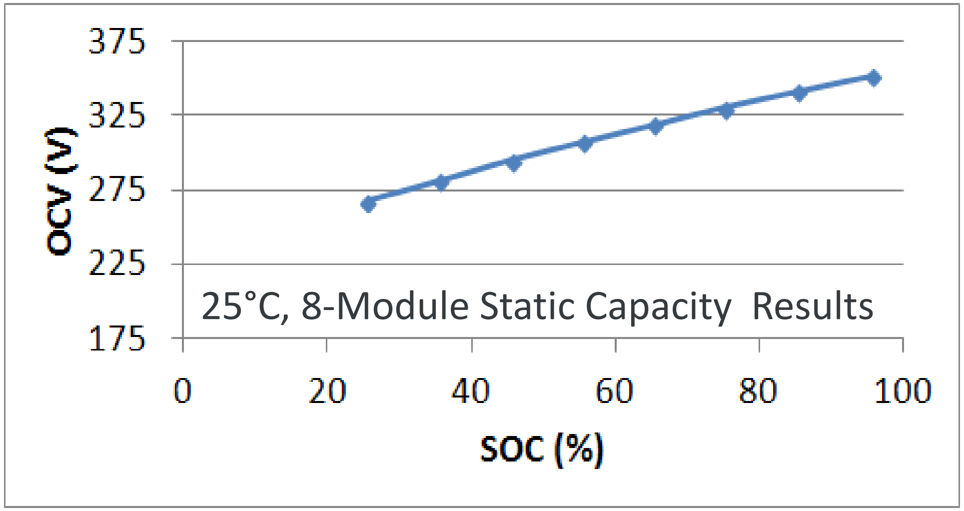
	# of Cells	Nominal Voltage	Total Energy (Wh)
Stock Sanyo NiMH*	204	275	1,370
8 JSR 192 F LIC Modules	96	300	260**
6 JSR 192 F LIC Modules	72	225	180**

*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

LEESS - LIC Pack Characterization: Energy & Power vs. SOC

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



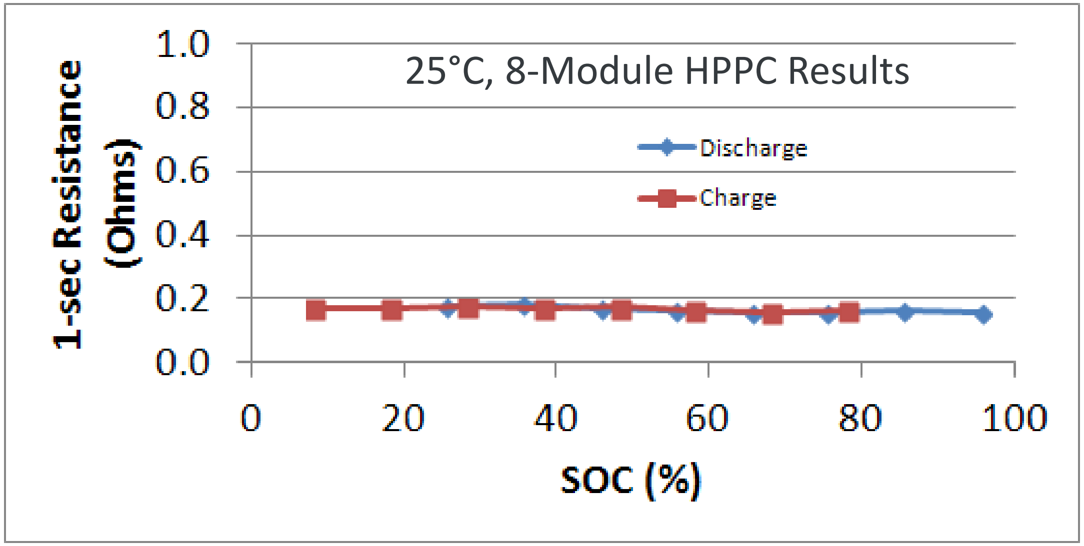
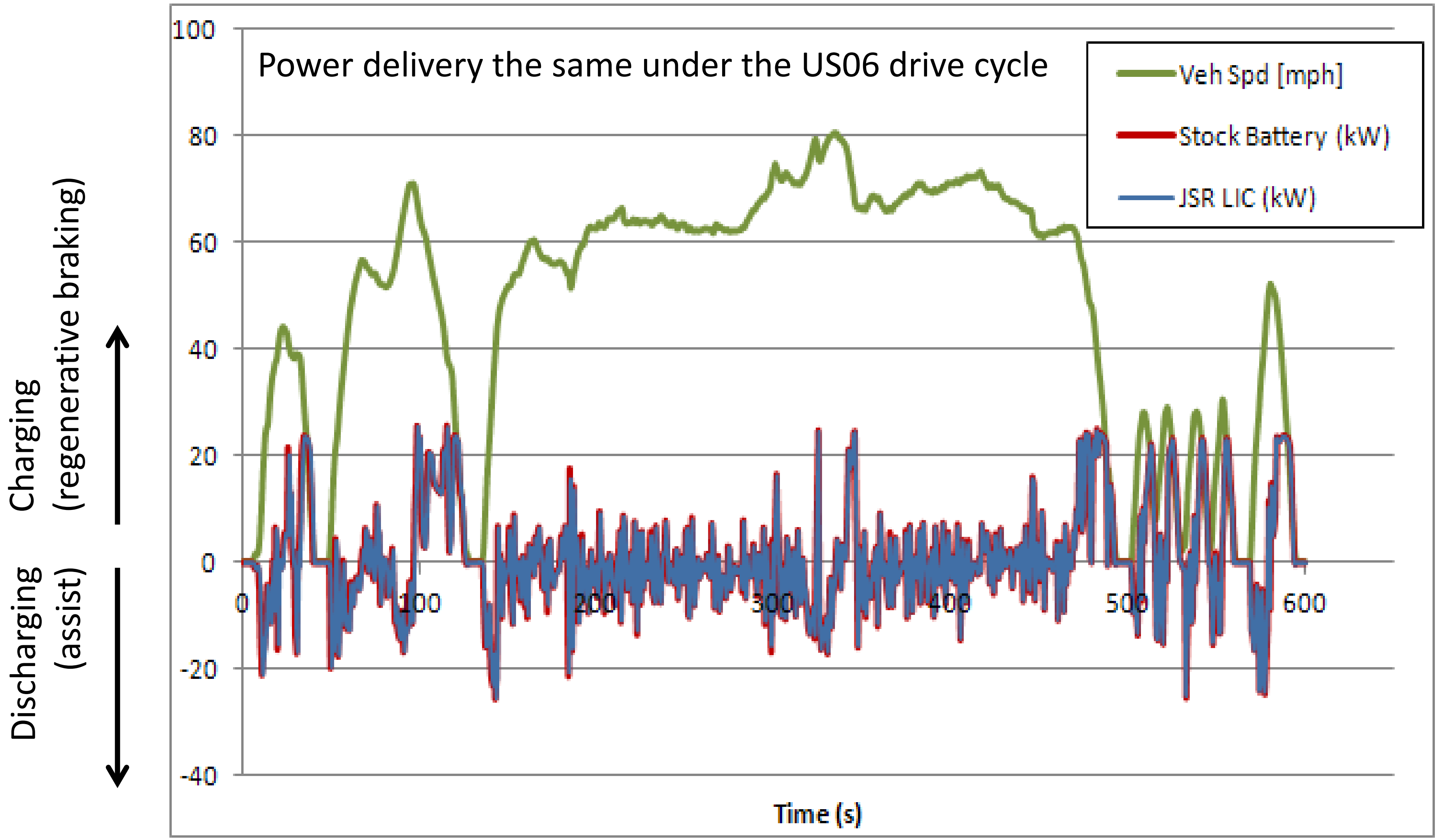


Photo by John Ireland, NREL

*Based on calculations from INL fact sheet
OCV = open circuit voltage

Benchtop Comparison Battery (NiMH) & LEESS (JSR LIC) under US06



Stock battery data courtesy of Argonne National Laboratory chassis dynamometer testing

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 interfacing with LEESS modules, vehicle controller area network (CAN) lines, and Ford engine control units (ECUs) to accomplish control**

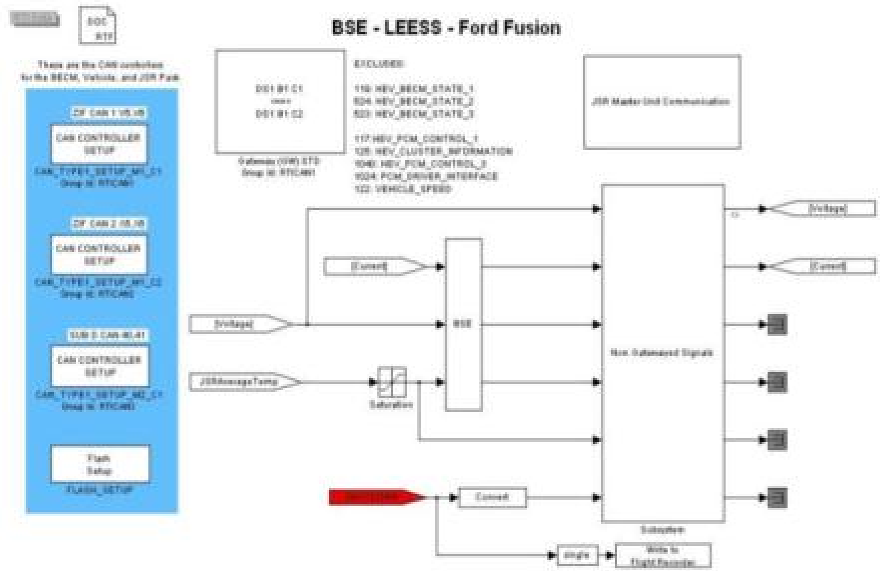
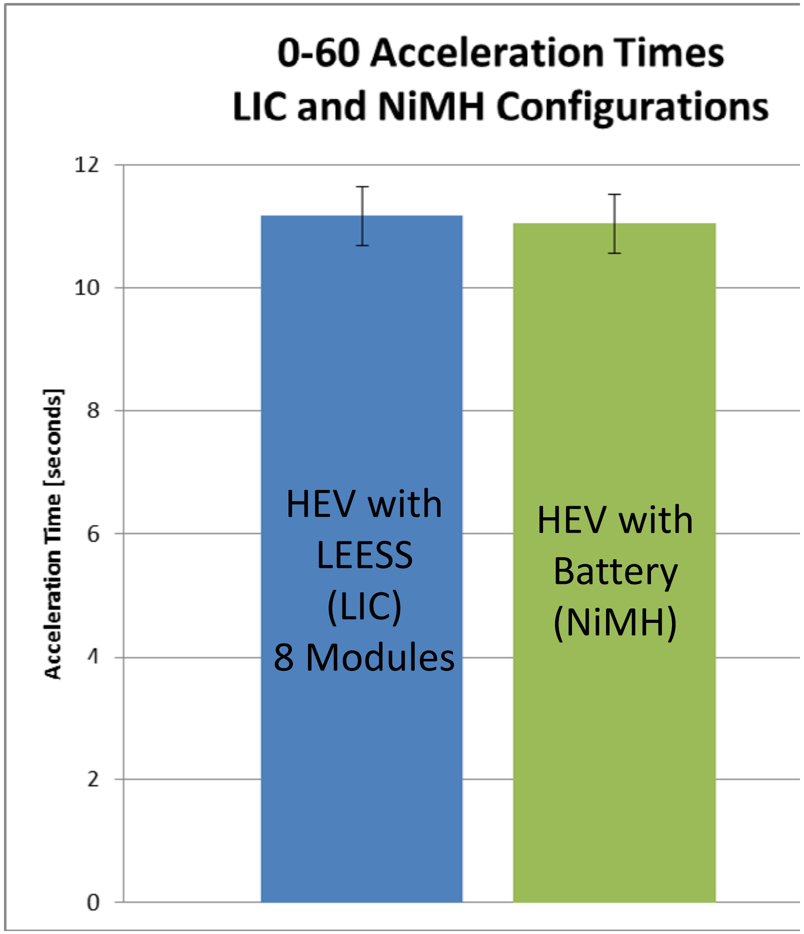


Photo by Jon Cosgrove, NREL

Simulink state estimation model currently deployed on the MABx for control, and photo of LEESS installation in the trunk space showing the JSR LICs and MABx

In-Vehicle Comparison: 0-60 Accelerations of HEV Test Bed with Stock Battery (NiMH) & LEESS (JSR LIC)



These results aren't intended to be factory published comparison times due to difference in altitude, additional weight of LIC, control modules, computers, etc.

NREL HEV Test Bed at Front Range Airport, Colorado

Photo by Petr Sindler, NREL

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

In-Vehicle Comparison: Dynamometer Testing of HEV Test Bed with Stock Battery (NiMH) & LEESS (JSR LIC)

Test Schedule

- Performed standard drive cycles with vehicle in NiMH Battery and LIC LEESS configurations
  - Test cycles included:
    - UDDS
    - US06
    - HWFET
  - Vehicle CAN traffic recorded using the MABx

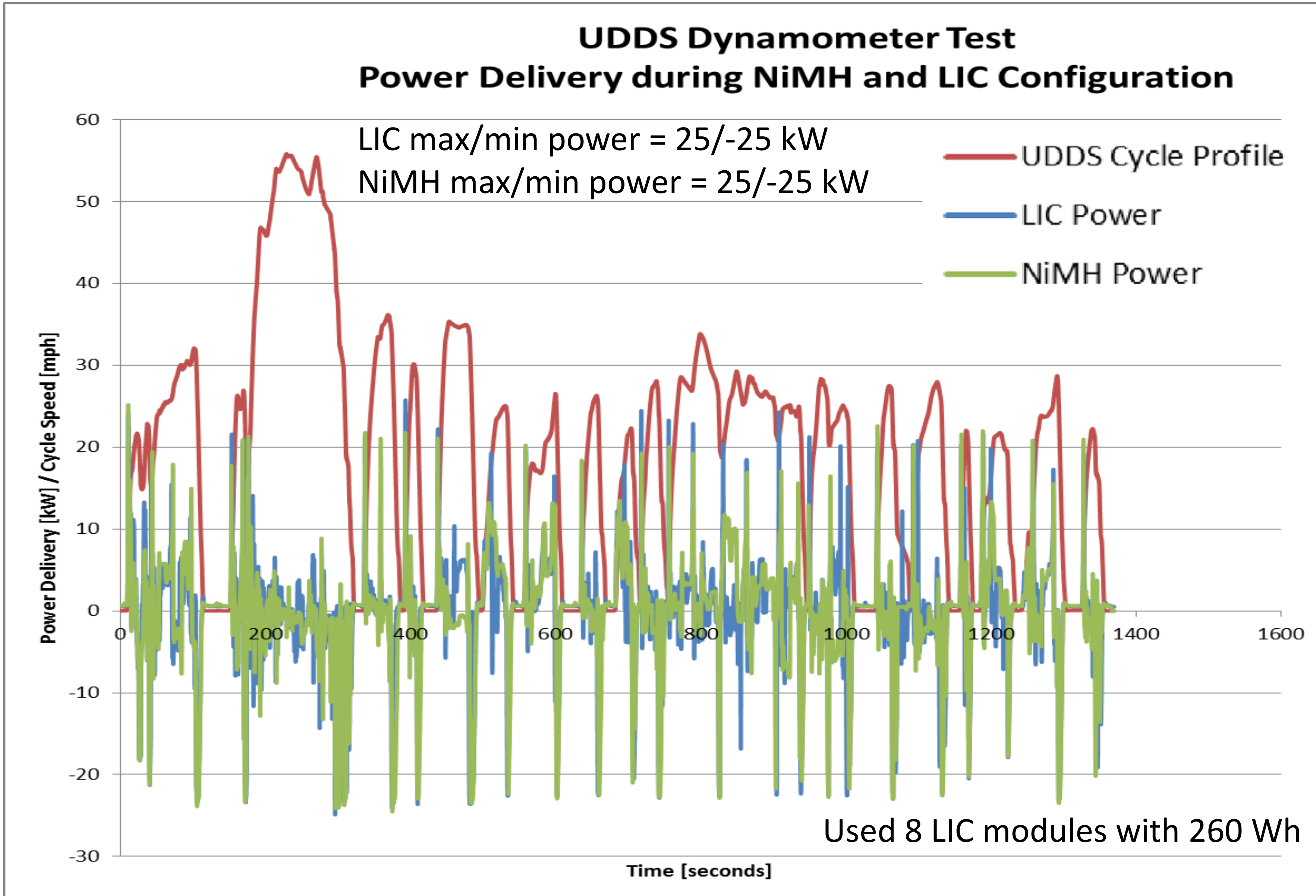
Dynamometer Facility

- Environmental Testing Corporation
- Testing details
  - Bag emissions sampling to measure fuel consumption

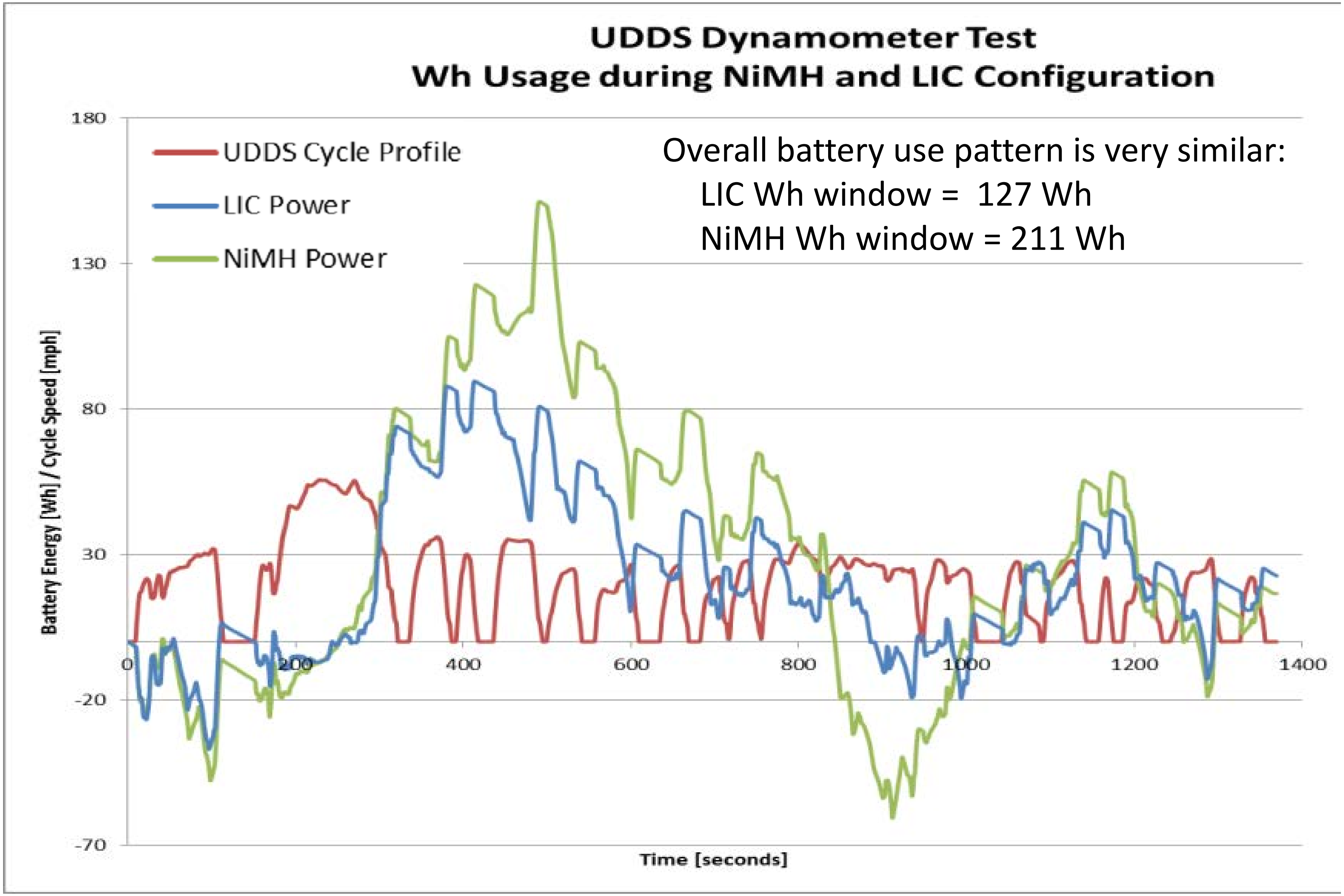
Fusion HEV test bed on 2WD dyno at ETC test facility

Photo by Jon Cosgrove, NREL

In-Vehicle Comparison: Dynamometer Testing Power Delivery during UDDS



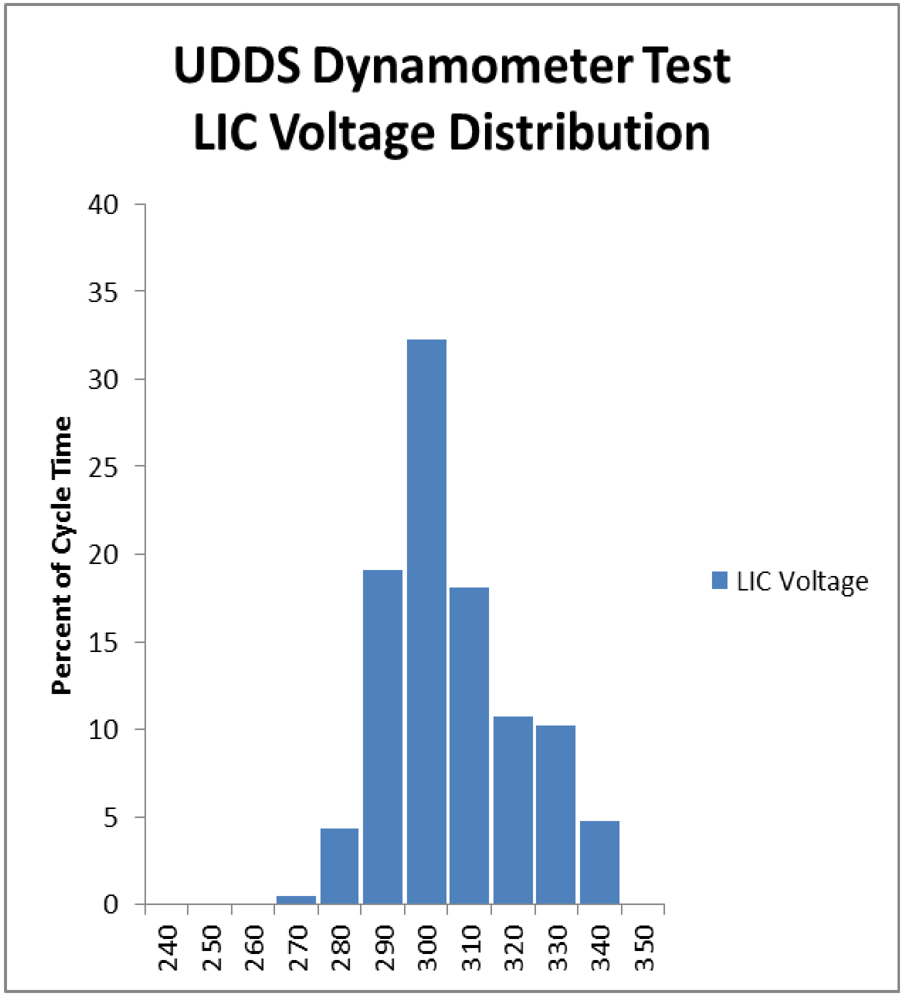
HEV Dynamometer Testing: Charge Sustaining Operation - Energy Window Usage during UDDS Drive Cycle

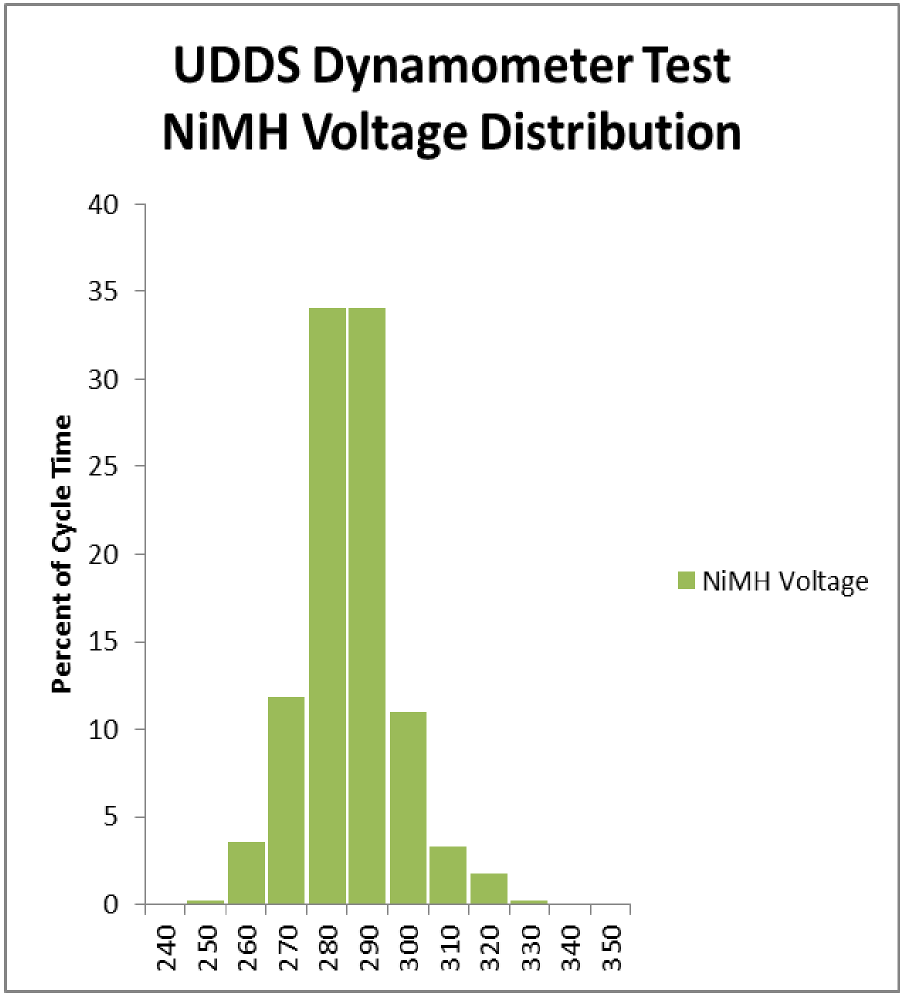


HEV Dynamometer Testing: Charge Sustaining Operation - Voltage Distributions of Battery and LEESS during UDDS

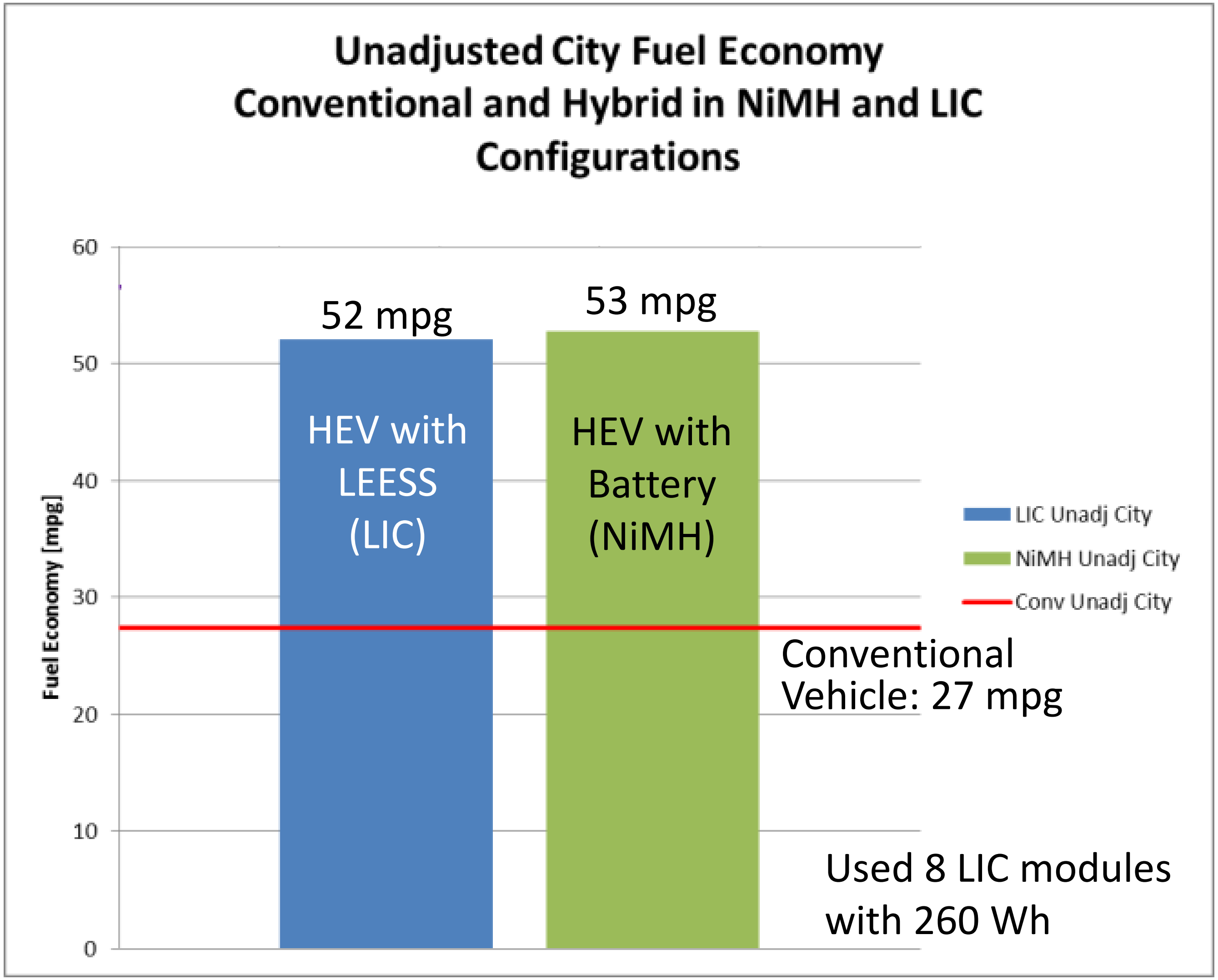
LICs have higher average voltage (301 vs. 281 for NiMH) and a slightly flatter distribution

NIMH	242/323	81V
LIC	263/341	78V





In Vehicle Comparison: Dynamometer Testing - Cumulative Fuel Consumption during UDDS Cycle



Plot showing UDDS bag measured fuel use during NiMH and LIC configurations

Similar overall fuel consumption in both configurations

Hybrid performance far exceeds conventional in both cases

High-energy NiMH system provides other functions such as electric AC operation during stops

Summary

- **HEVs are effective at reducing per-vehicle fuel use**
- **Incremental HEV cost remains a barrier to wider market penetration**
  - ESS arguably the largest contributor
- **ESS cost reductions lead to improved vehicle-level cost vs. benefit**
  - Increase market demand and aggregate fuel savings
- **LEESS are considered an option for reducing cost of HEVs**
- **Developed an HEV test bed to evaluate the performance LEESS options**
- **Initial testing of HEV tested bed with NiMH and LIC LEESS showed:**
  - No differences in acceleration times
  - No appreciable difference in fuel economy between NiMH and LIC configurations
  - Any existing fuel economy difference could potentially be eliminated with better calibration of state estimation model and power request controls
  - Vehicle comfort and drivability not affected while operating in LEESS configuration
- **Higher available energy from stock NiMH may provide other benefits during idle-off stops, but was not explored**

Future Work

- **Test 6-module configuration of JSR LIC modules**
  - Configuration with up to 180 Wh available
  - Additional dyno testing to compare with 8-module configuration (with up to 260 Wh available)
- **Assess cold temperature performance differences in vehicle**
  - Dynamometer testing with soak temperatures below freezing
  - Additional cold soak bench testing of LIC and other LEESS devices
- **Evaluate and compare functionalities that higher-energy stock NiMH provides**
- **Acquire and install additional LEESS devices, including symmetric carbon-carbon ultracapacitors and other asymmetric (hybrid) ultracapacitors**

Acknowledgments

- **JSR Micro**
  - Providing LIC modules for evaluation
  - Related technical information and support
- **Ford Motor Company**
  - CRADA facilitating vehicle conversion
- **USABC**
  - Collaborated on precursor analysis for this effort and established LEESS performance targets for power-assist HEVs
- **U.S. Department of Energy**
  - Cost-shared support from two Vehicle Technologies Office activities
    - Energy Storage (Brian Cunningham)
    - Vehicle Systems Simulation and Testing (David Anderson)

Questions?

Author contacts:

Jon Cosgrove

Jon.Cosgrove@NREL.gov

303-275-4425

Jeff Gonder

Jeff.Gonder@NREL.gov

303-275-4462