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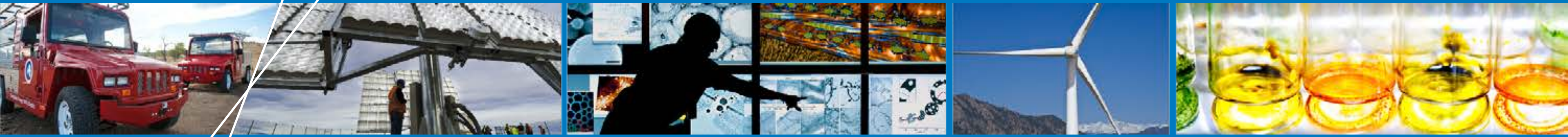
Lower-Energy Energy Storage System (LEESS) Evaluation in a Full-Hybrid Electric Vehicle (HEV)



Supercapacitors USA 2013

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National Renewable Energy Laboratory (NREL)

Transportation and Hydrogen Systems Center (THSC)

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LEESS Evaluation Presentation Overview

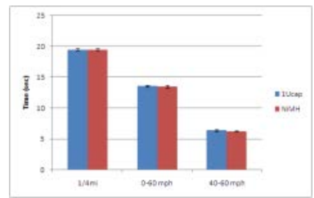
- What is the motivation for the DOE to look at LEESS devices in a vehicle application?
- NREL's past work with mild hybrids and ultracapacitors
- A NREL analysis of LEESS devices in full HEV applications
- HEV test platform development
- Bench testing of JSR LIC lower energy system
- On road and dynamometer comparison testing using stock NiMH and JSR LIC configurations
- A discussion of future configurations to be tested

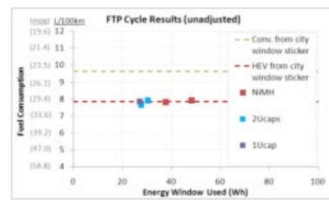
Motivation

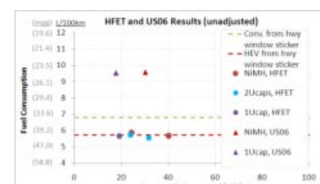
- HEVs are effective at reducing per-vehicle fuel use
- Incremental cost remains a barrier to wider market penetration
    - Energy storage system (ESS) arguably the largest contributor
- ESS cost reductions/performance improvements → improved vehicle-level cost vs. benefit
    - Increase market demand and aggregate fuel savings
- Lower-energy ESS (LEESS) considerations
    - Technical evaluation—can it do the job?
    - 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

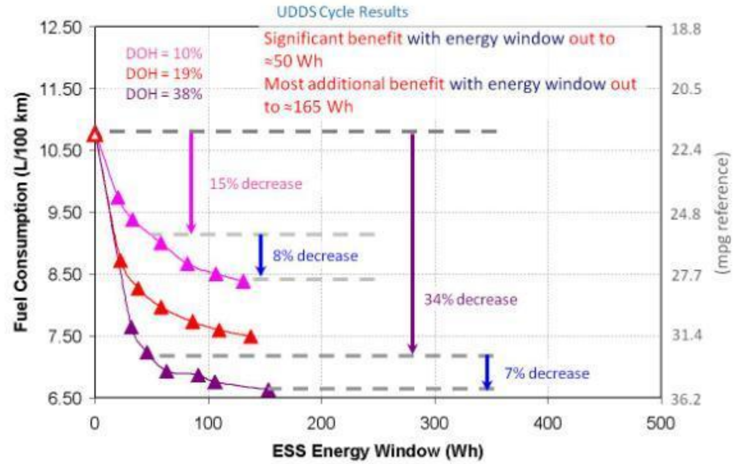
Findings: HEV with ultracapacitors performed at least as well as the stock configuration with a NiMH battery

BAS = belt alternator starter (“mild” HEV); NiMH = nickel-metal hydride; Ucap = ultracapacitor

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



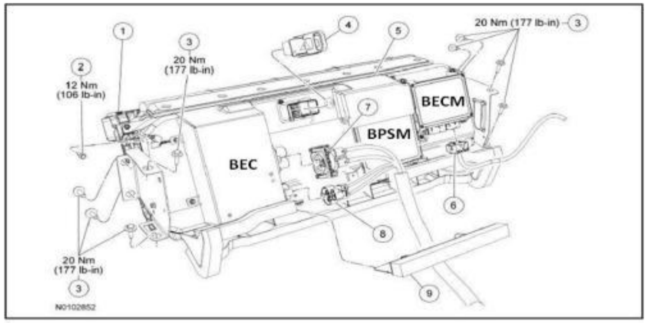
- USABC established targets and issued a Request for Proposal Information (RFPI) to support LEESS development
  - See: http://www.uscar.org/guest/article_view.php?articles_id=87
  - Open to any ESS technology (very high power batteries, electrochemical double layer capacitors, or asymmetric supercapacitors)

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
  - 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

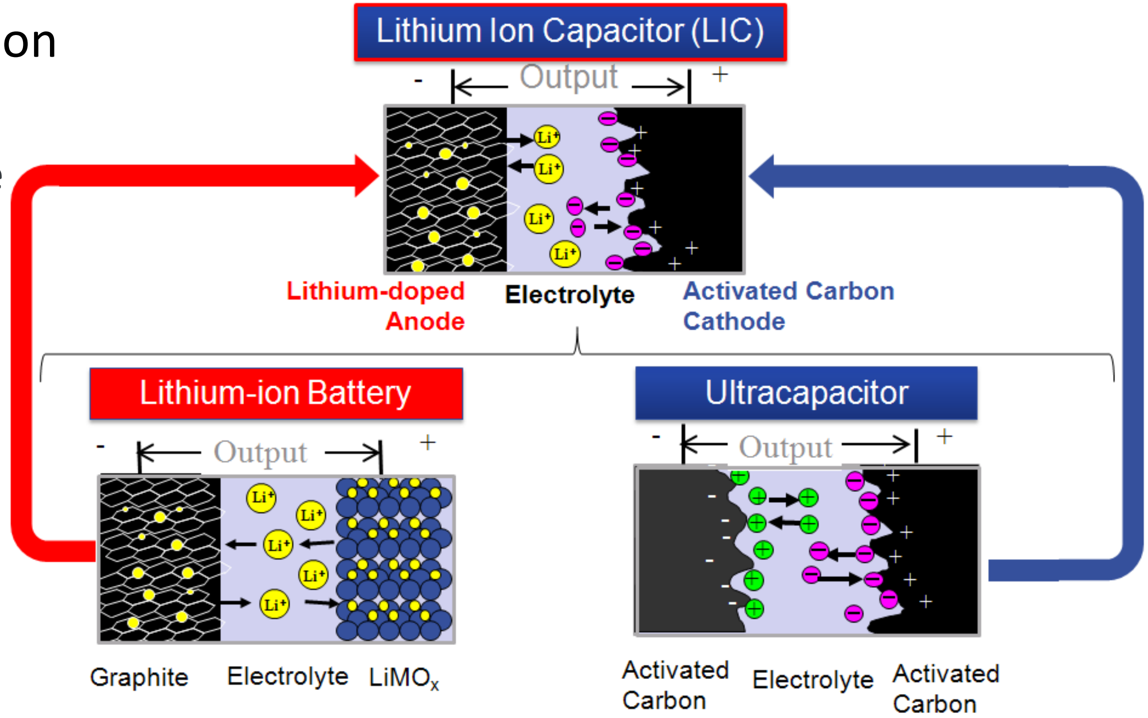
Photos by John Ireland, NREL



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 evaluation

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



- 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**
6 JSR 192 F LIC Modules	72	225	180**

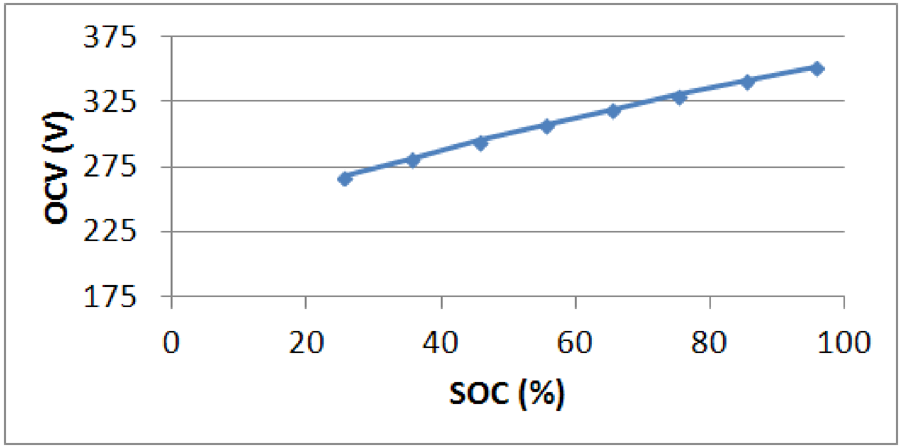
*Based on fact sheet published by Idaho National Laboratory (INL)
**Assuming 175 V – 350 V maximum in-vehicle operating window

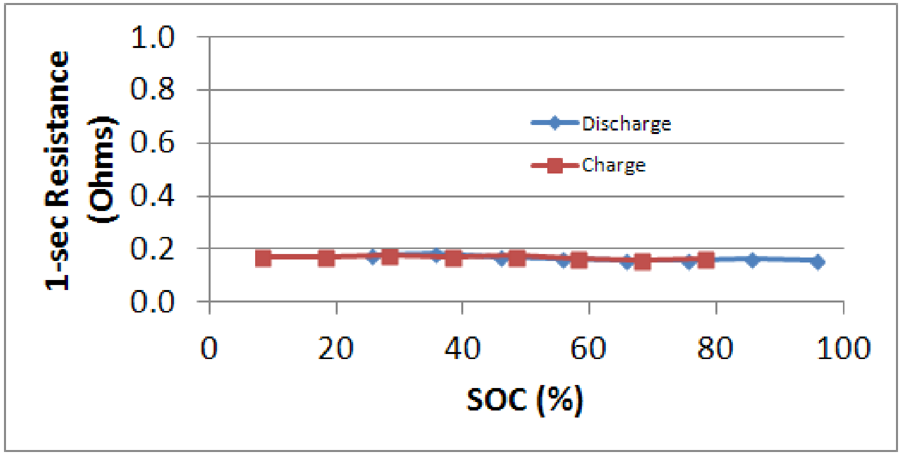
JSR LIC Pack Characterization

- 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

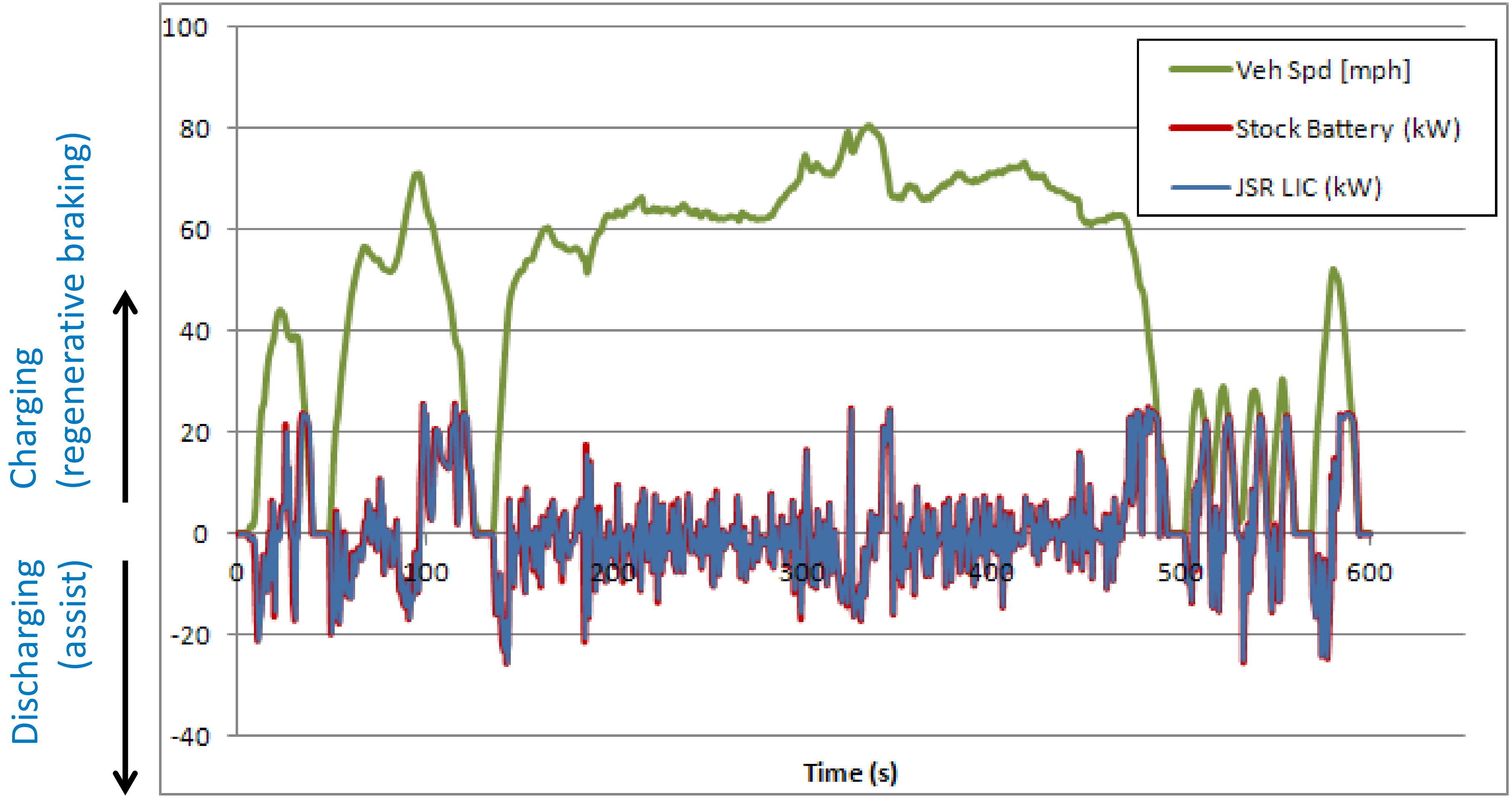




*Based on calculations from INL fact sheet

OCV = open circuit voltage

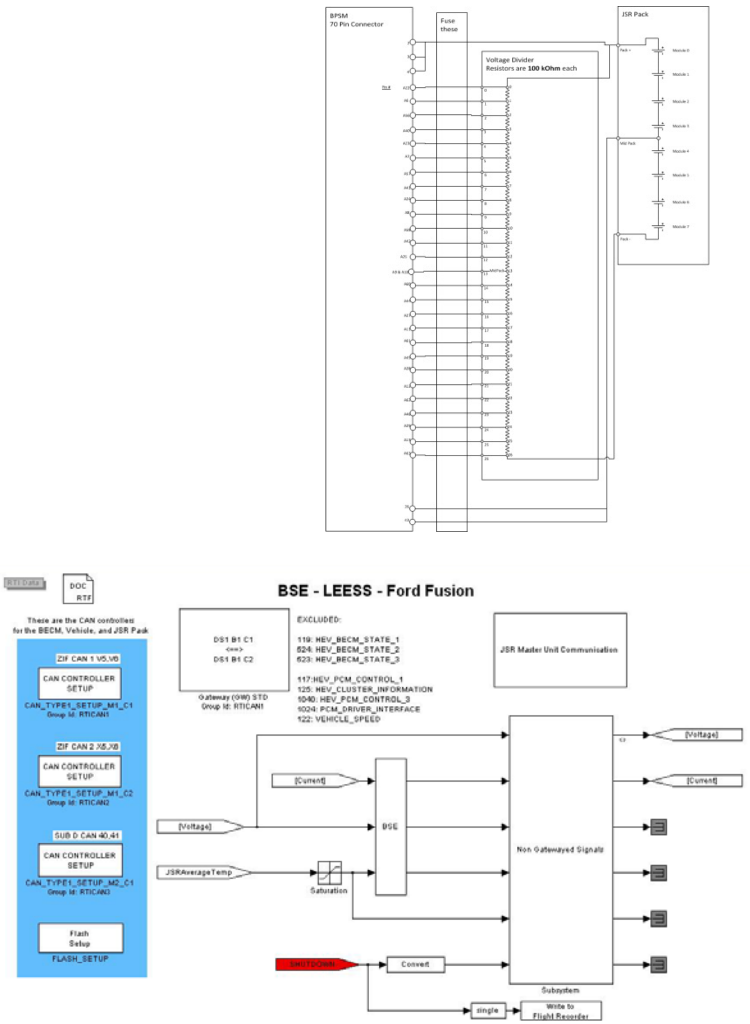
US06 Stock vehicle (NiMH) & LEESS (JSR LIC) lab comparison



Stock battery data courtesy of Argonne National Laboratory chassis dynamometer testing

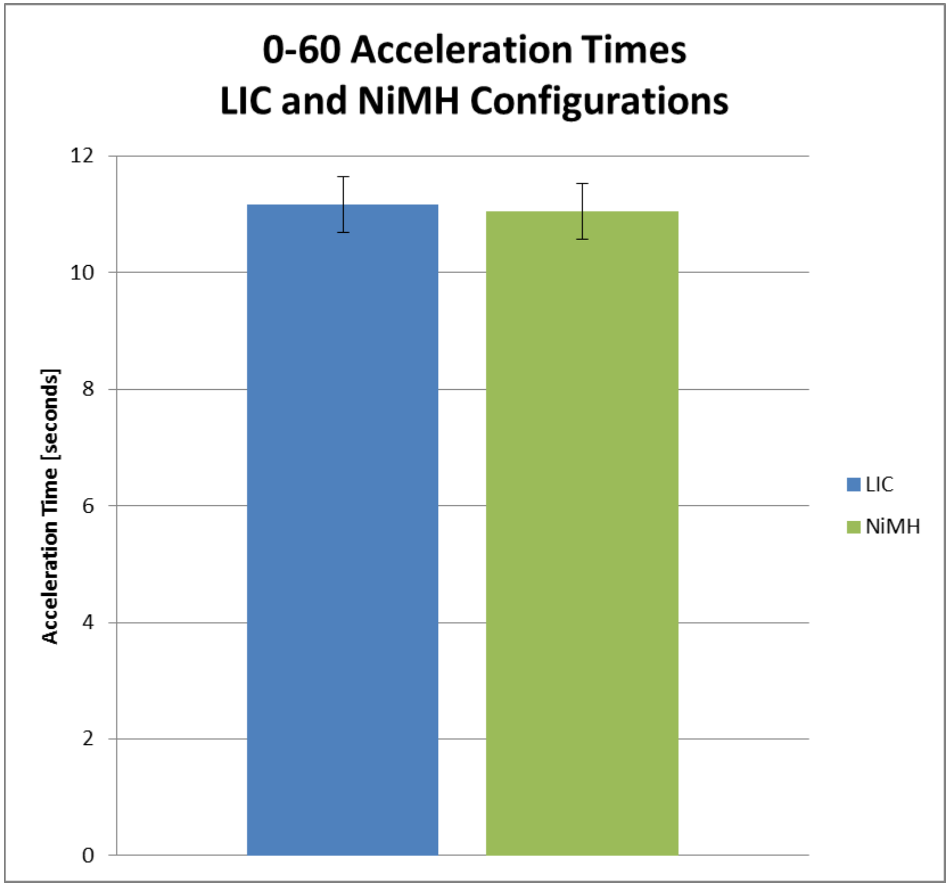
LEESS Control and Vehicle Interface: MABx, LIC state estimation, and vehicle communication

- Controls for LIC state estimation, safety, etc. implemented via rapid control prototyping (RCP) 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 CAN lines, and Ford ECUs to accomplish control



Voltage divider to interface with Ford ECUs and Simulink state estimation model currently deployed on the MABx for control.

In Vehicle Comparison: 0-60 Accelerations
Stock battery (NiMH) & LEESS (JSR LIC)



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

In Vehicle Comparison: Dynamometer testing

Test Schedule

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

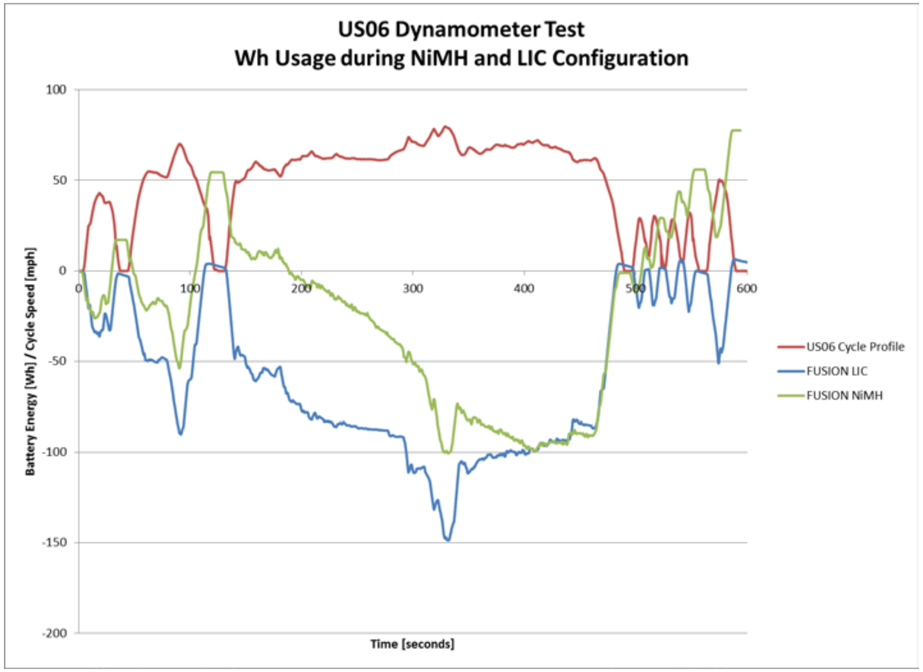
Dynamometer Facility

- Testing details
  - Bag emissions sampling to measure fuel consumption

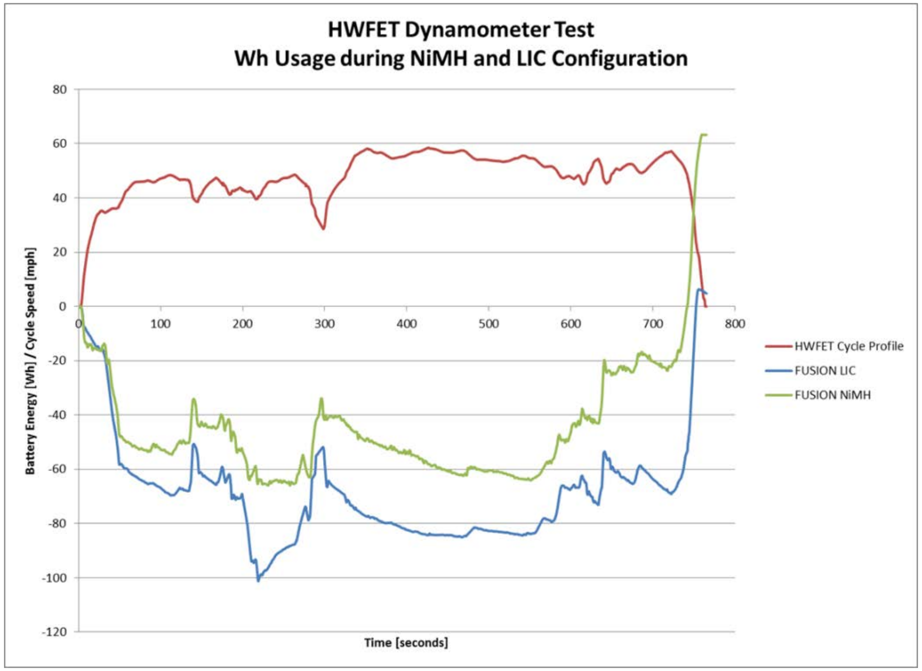
Fusion test vehicle on 2WD dyno at test facility

In Vehicle Comparison: Dynamometer testing
US06 and HWFET Drive Cycles

US06 – Aggressive Cycle



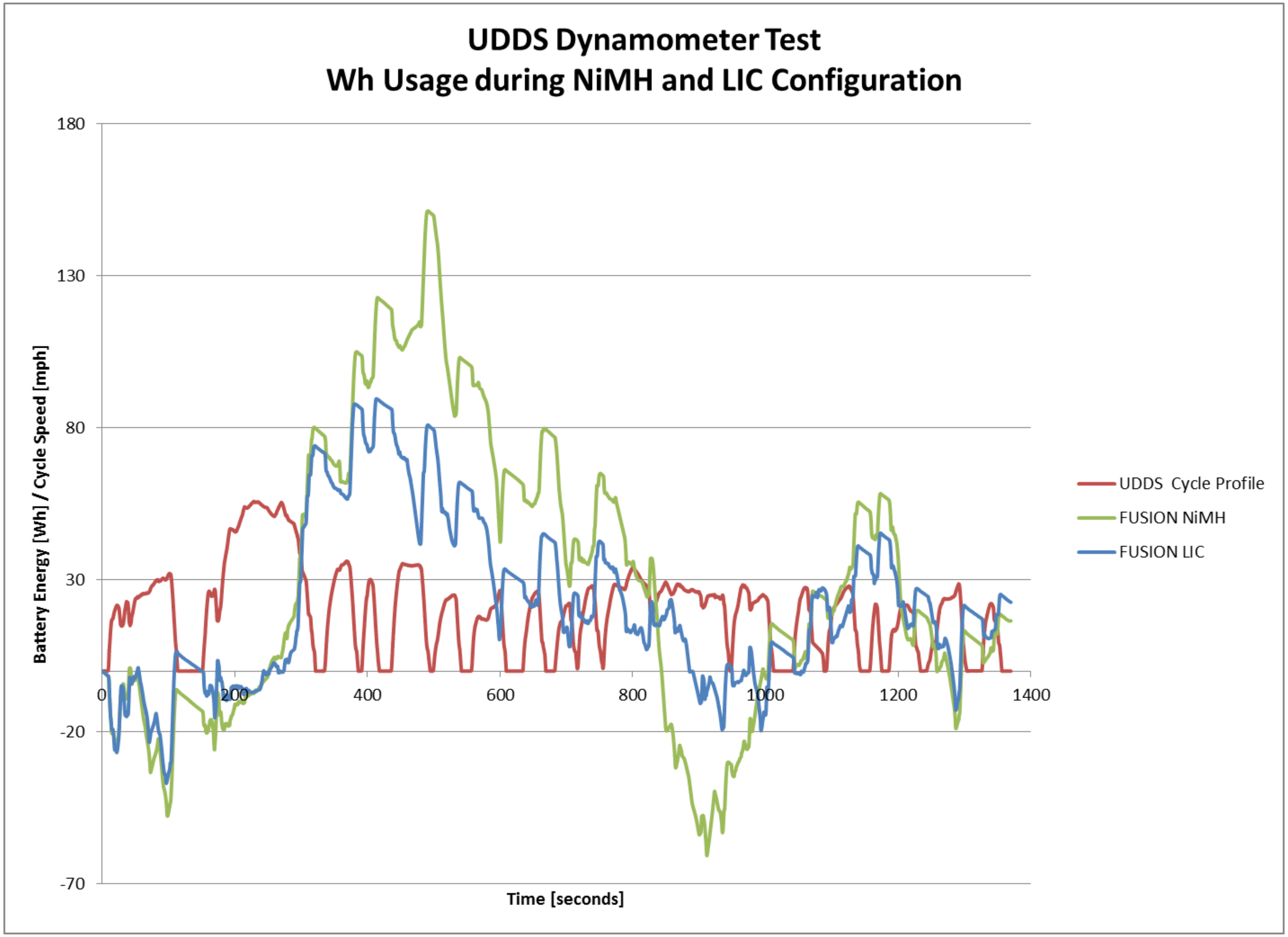
HWFET – Highway Fuel Economy Cycle



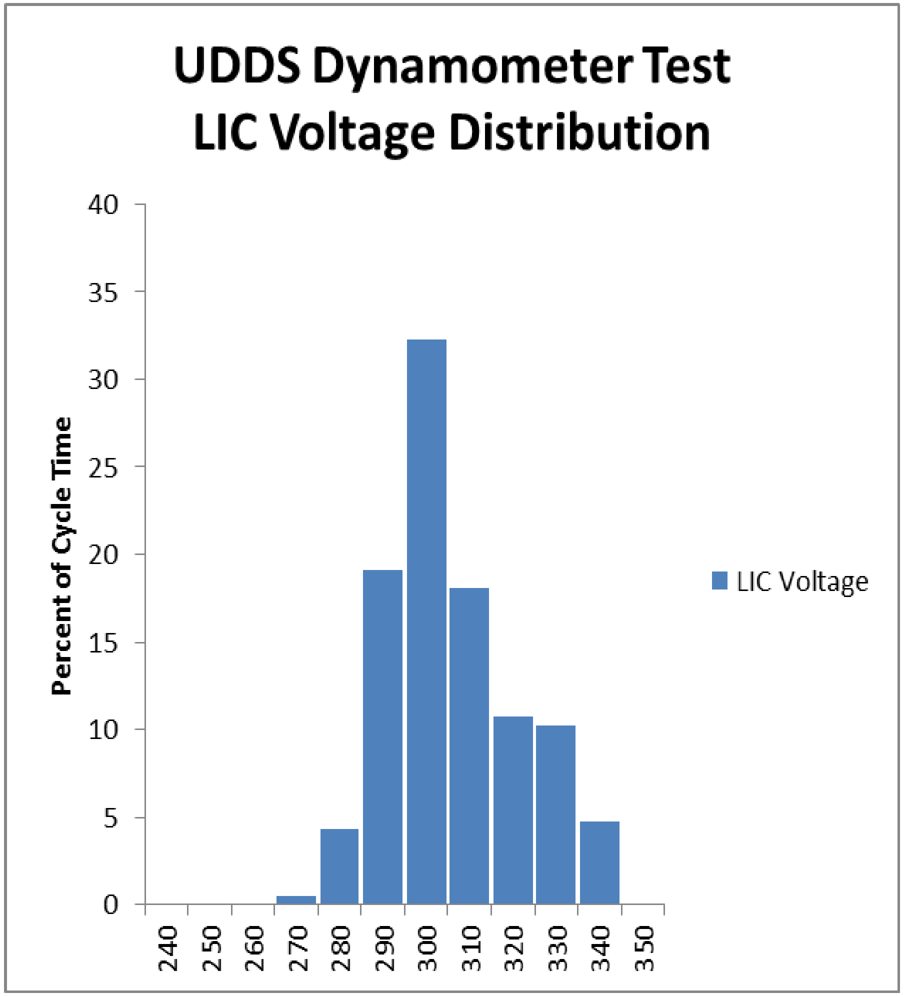
Fusion NiMH results from ANL dyno testing of stock Fusion

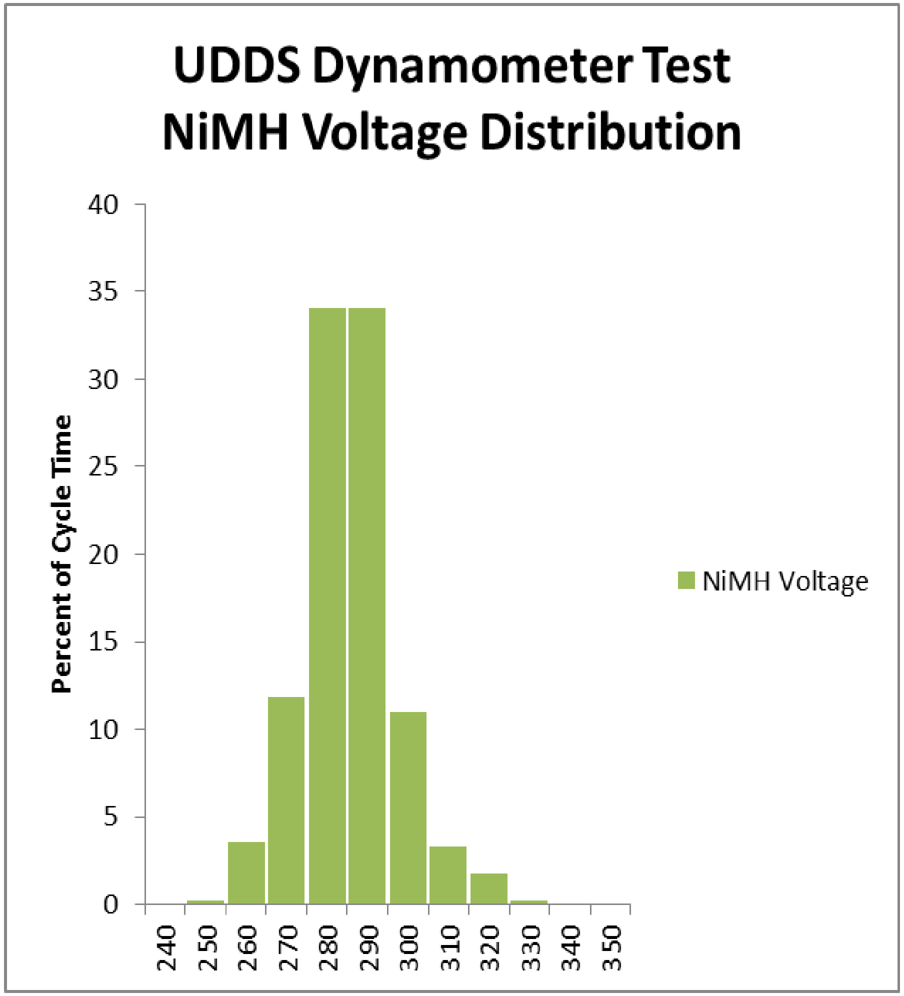
Fusion NiMH results shown are from a charge gaining cycle

In Vehicle Comparison: Dynamometer testing
UDDS Drive Cycle



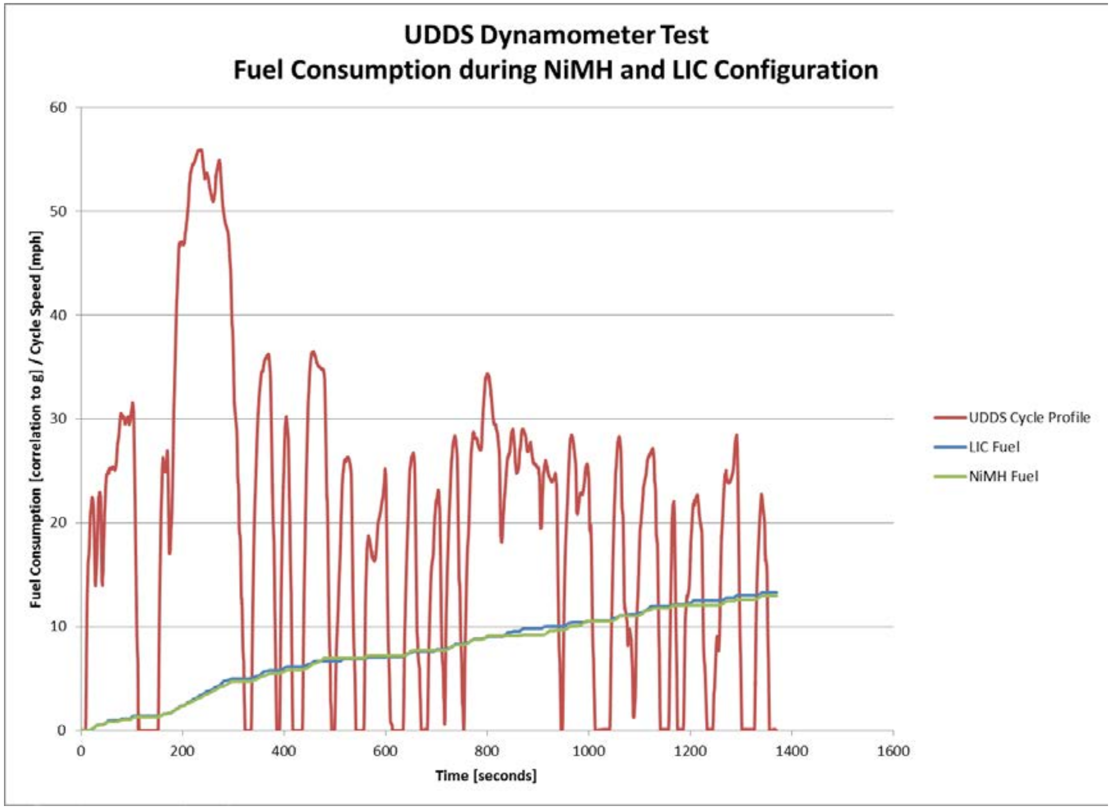
In Vehicle Comparison: Dynamometer testing Voltage Distributions During UDDS

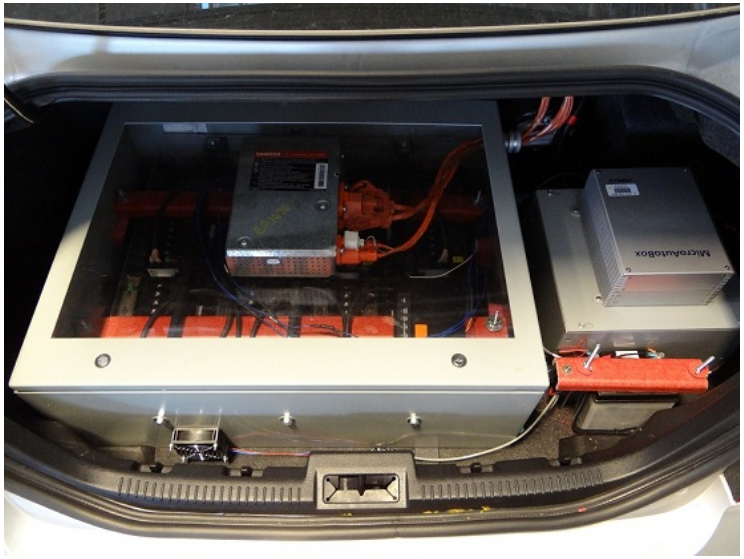




In Vehicle Comparison: Dynamometer testing Cumulative Fuel Consumption During UDDS

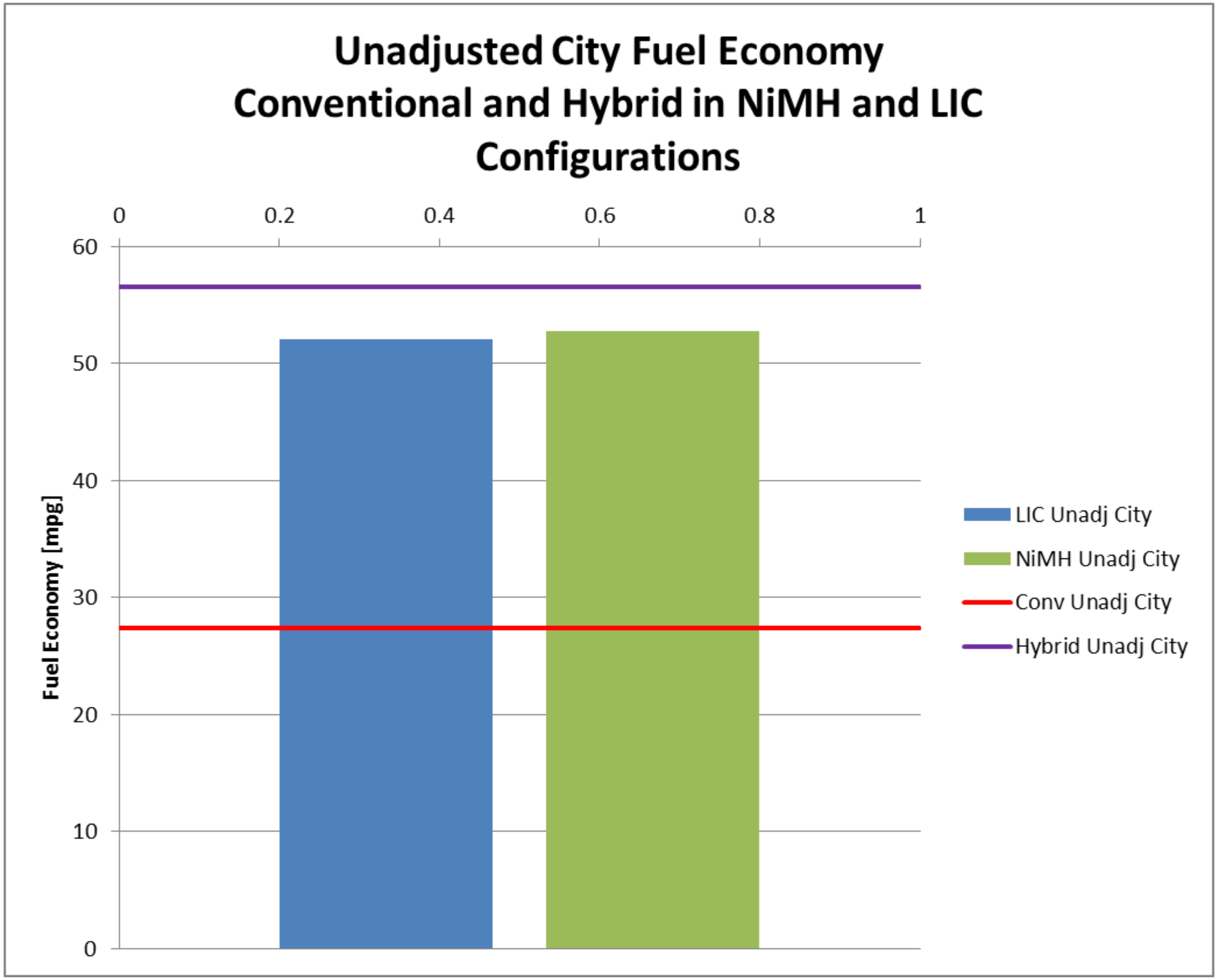
	Phase 1 [g]	Phase 2 [g]	Total [g]
JSR LIC	239.36	189.06	428.12
Stock NiMH	259.16	177.51	436.67





LEESS installation in the trunk space
Showing the JSR LICs and MABx

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

Summary

- 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
- Lower-energy ESS (LEESS) considerations
  - Technical evaluation
    - Initial results show no differences in acceleration times
    - Initial results show 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
  - Potential for lower cost with less energy?
  - Potential benefits from alternative technology?
    - Better life, better cold temperature performance

Potential Next Steps

- 6 module configuration of JSR LIC modules
  - 180 Wh configuration
  - Additional dyno testing to compare with 8 module (260 Wh) configuration
- Assess cold temperature performance differences in vehicle
  - Dynamometer testing with soak temperatures to -20 degrees F.
  - Additional bench cold soak bench testing of LIC and other LEESS devices
- Further evaluation using additional LEESS devices including more traditional ultracapacitors among others

Acknowledgments

- JSR Micro
  - Providing LIC 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

Questions?

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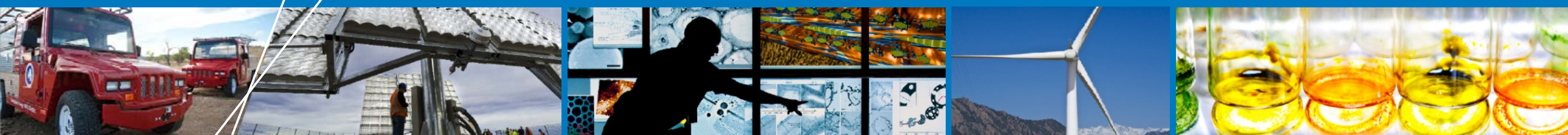

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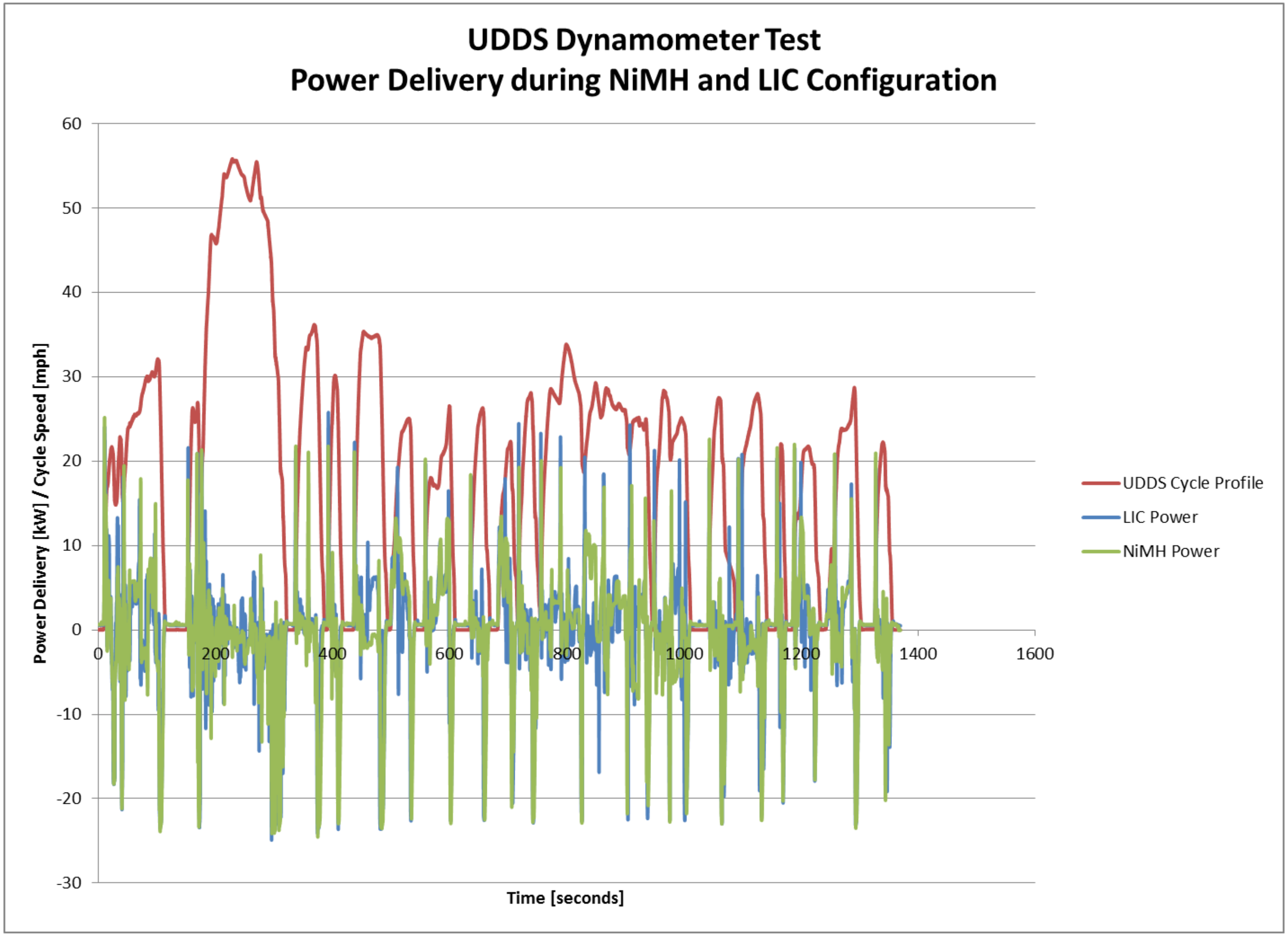
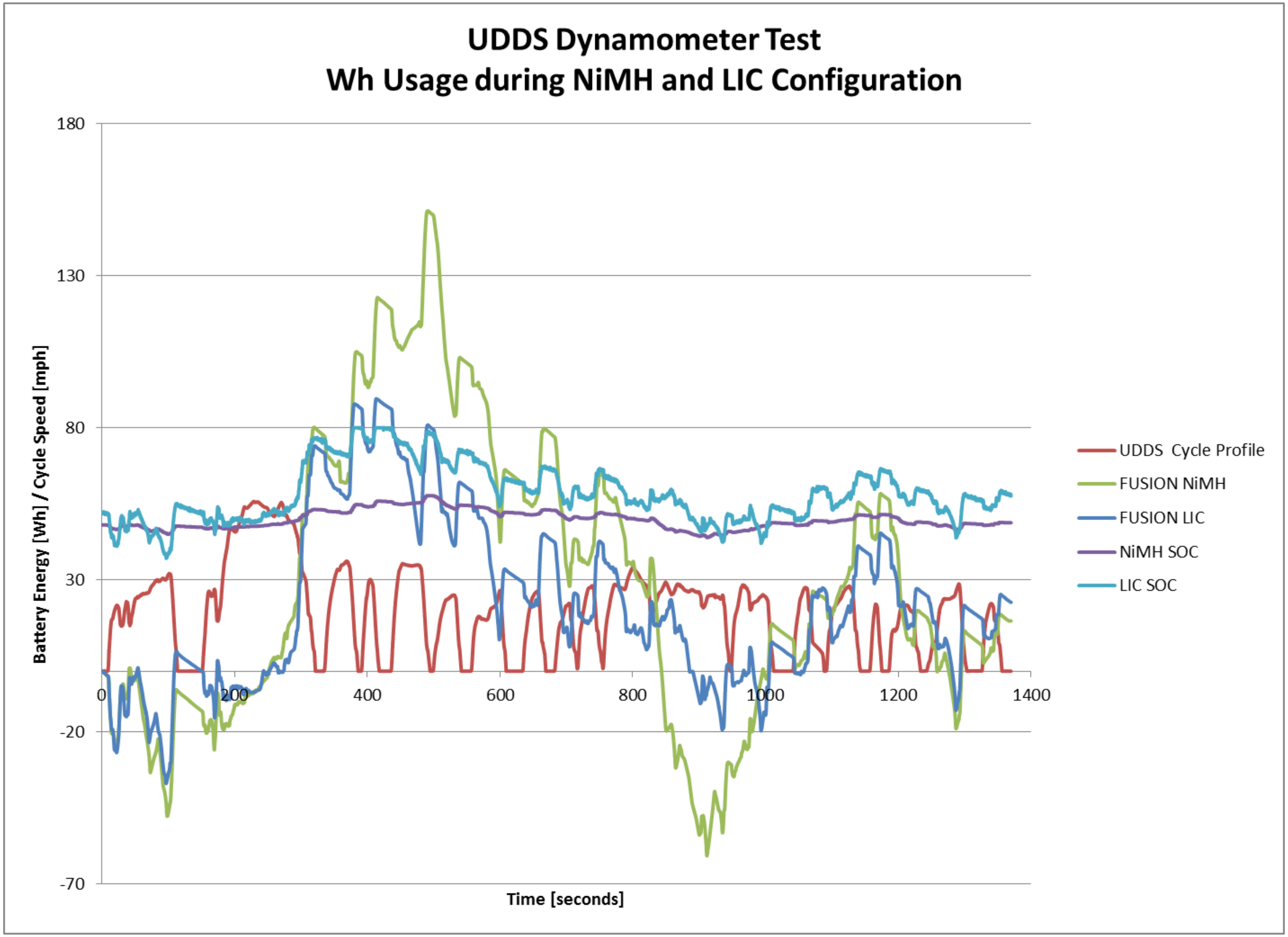
In Vehicle Comparison: Dynamometer testing
Power delivery during UDDS



In Vehicle Comparison: Dynamometer testing
UDDS Drive Cycle



In Vehicle Comparison: Dynamometer testing Temperature Profiles During UDDS