

Advanced HEV/PHEV Concepts



DOE Annual Merit Review

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Organization: NREL

May 9, 2011

Project ID: VSS051

**This presentation does not contain any
proprietary, confidential or otherwise
restricted information**

HEV = hybrid electric vehicle; PHEV = plug-in HEV

Project Overview

Timeline

Activities specific to current effort:

- Started in 2010
- Ending in 2012
- Project is 20% complete

Budget

Corresponding funding:

- Total (all DOE): \$350k
 - ES share: \$100k
 - VSA share: \$250k (arriving March 2011)
- Anticipated industry support
 - In-kind

ES = energy storage

VSA = vehicle systems analysis

Barriers Addressed

- Cost
- Setting/validating technical targets
- Design optimization for maximum mpg
- Infrastructure and convenience for advanced technology vehicle consumers

Project Partners

(See collaboration slides for details)

- USABC/ES Tech Team Workgroup
- Repeated-route vehicle manufacturer(s)
- PREA collaboration participants

USABC = United States Advanced Battery Consortium

PREA = Partnership for Roadway Electrification & Automation

Project Summary

HEVs/PHEVs have considerable room for improvement

- Note many generations of conventional vehicle design optimization
- Possible to increase **per-vehicle fuel savings**
- Also **important to increase consumer value proposition**
 - Leads to greater technology market penetration
 - And larger aggregate fuel savings

Activity seeks to refine/validate three advanced concepts

1. **Lower-Energy Energy Storage System (LEESS)** for HEVs
 - Maintain high HEV fuel savings while reducing overall cost
2. **Route-Based Control (RBC)** for HEVs/PHEVs
 - Use available route information to increase individual HEV/PHEV mpg
3. **Drive-On Charging (DOC)** for Electrified Vehicles
 - Maximize total petroleum displacement with domestic electricity

Presentation Organization

Note that for reviewer convenience per the AMR instructions the slides are organized under headings for each of the review criteria.

However, some may find the presentation easier to follow by reading the slides for each distinct sub-project one at a time. To facilitate rearranging in this manner, each slide contains a color-coded label in the upper left corner to specify the sub-project to which it refers.

Sub-Project Details

Lower-Energy Energy Storage System

Motivation

- Previous HEV ESS targets set in late 1990s/early 2000s

Characteristics	Units	Power-Assist (minimum)	Power-Assist (maximum)
Pulse discharge power (10 s)	kW	25	40
Peak regenerative pulse power (10 s)	kW	20 (55-Wh pulse)	35 (97-Wh pulse)
Total available energy (over DOD range where power goals are met)	kWh	0.3 (at $C_1/1$ rate)	0.5 (at $C_1/1$ rate)
System price @ 100k units/year	\$	500	800

- High kWh requirements exclude technologies and contribute to high cost

Background

- NREL asked to re-assess the relationship between HEV kWh and mpg
- Analysis led USABC to set new “LEESS” targets and issue an RFPI
 - http://www.uscar.org/commands/files_download.php?files_id=219 (FY10)

ESS = energy storage system; DOD = depth of discharge
 RFPI = request for proposal information

Route-Based Control

Motivation

- General HEV controls are not optimal over all cycles
- Route-based control could improve fuel economy
 - Benefit any vehicle with regular or predictable driving
- In PHEVs, can ensure full and optimal electricity use
 - Driving type *and distance* important



Background

- In a previous FY Milestone NREL demonstrated via simulation 2-4% additional fuel savings possible in HEVs with RBC
 - Significant in aggregate (≈ 6.5 million gallons of fuel annually in U.S.)
- PHEV savings could be even higher

Drive-On Charging for Electrified Vehicles

Motivation

- PHEV fuel savings dependent on how often vehicles plug in
- Convenience critical to ensure that users always plug in
 - Especially at most frequently visited locations
- Value proposition further increased if charging enabled between stops
 - E.g., at stoplights or properly equipped sections of roadway



Background

- PHEVs in early deployments have not always plugged in when they could have (>25% of the time*), resulting in sub-optimal fuel economy
- Progress by KAIST (South Korea), U. of Auckland, ORNL, UC Berkley, et al. also suggests potential for electrical transfer to vehicles in motion
- Initial NREL analysis points to such an electrified roadway concept as the most cost competitive vehicle electrification strategy

* See pg. 3 of <http://avt.inel.gov/pdf/phev/HymPriusPersonal-useChAndDrSept08-Mar10.pdf> and pg. 3 of <http://avt.inel.gov/pdf/phev/HymPriusCommercial-useChADrAll2009.pdf>

Relevance

Address ESS Cost/Technical Targets

Help maximize aggregate fuel savings

- HEV market penetration limited by technology cost
- ESS is one of the largest cost components
- If a lower-energy ESS cost less but still delivered high fuel savings, more HEVs could reach the market and increase total fuel savings



Provide technical performance targets for developers

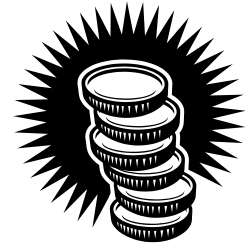
- Encourage device development based on in-use fuel savings potential
- Confirm performance (from vehicle systems perspective) of devices under development



Fuel Efficiency Design Optimization

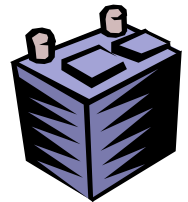
Cost-effective fuel savings

- Significant recurring costs for alternatives with similar fuel savings
 - Lightweight materials, high efficiency components, etc.
- RBC requires only software changes
 - Low cost → wide penetration possible



Additional benefits possible

- Emissions reduction from pre-emptive engine start
 - Avoid starting HEV/PHEV engine cold/under significant load
- Improved battery life
 - Advanced cycle knowledge could also help minimize battery wear



Infrastructure for Electrified Vehicles

Reduce petroleum dependency

- Electricity supplied to vehicles can displace petroleum
- Provides domestic energy options and means to eliminate GHG emissions through renewably produced electricity



Charge-depleting (CD) vs. charge-sustaining (CS) operation

- PHEV mpg no better than HEV if most driving is CS
 - Consumer may not plug in every time
 - Difficult for fuel savings to offset large battery cost



Electrified roadway would remove PHEV and EV barriers

- EV range issues virtually eliminated and PHEV mostly CD mode
 - From electrifying just 1% of roadways (interstate)
- Retain fuel savings of a typical plug-in vehicle at reduced battery cost
 - Concept enables smaller battery and less cycling/wear

GHG = green house gas; EV = electric vehicle

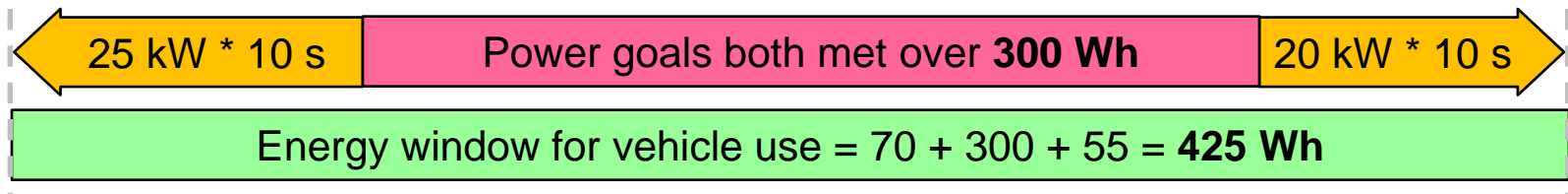
Approach

Complementary Analysis

Using Simulation and In-Vehicle Data

Overall research steps

- Simulate HEV mpg with range of ESS sizes
 - Variety of drive cycles and vehicle hybridization degrees
- Analyze ESS use in current production HEVs
- Translate between in-vehicle and ESS bench test metrics
 - For energy and power
 - E.g., energy window analysis applied to historic requirements:



Current activities

- Examine test condition that drives the most challenging power target—and mpg impact from reducing the power capability
- Compare HEV fuel economy with traditional ESS to that with a LEESS
- Deliver report to DOE (Sept 2011)

Simulation Guiding Hardware Implementation

Overall research steps

- Background/opportunity evaluation
- Code development via generic model simulation
 - Control optimization for a particular driving type
 - On-the-fly optimization for any predicted driving profile

Planned activities

- Cooperative research agreement with repeatable-route vehicle manufacturer (e.g., HEV transit bus)
- Collect duty cycles specific to actual fleet application
- Apply RBC tuning to model of actual vehicle, controls and drive cycles
- Implement control variations into vehicle hardware (using simulation results as a guide)
- Compare vehicle operation with route-specific controls against the baseline performance
- Deliver interim (Sept 2011) and final (Sept 2012) reports to DOE

High-Level and Specific Options Analysis

Overall research steps

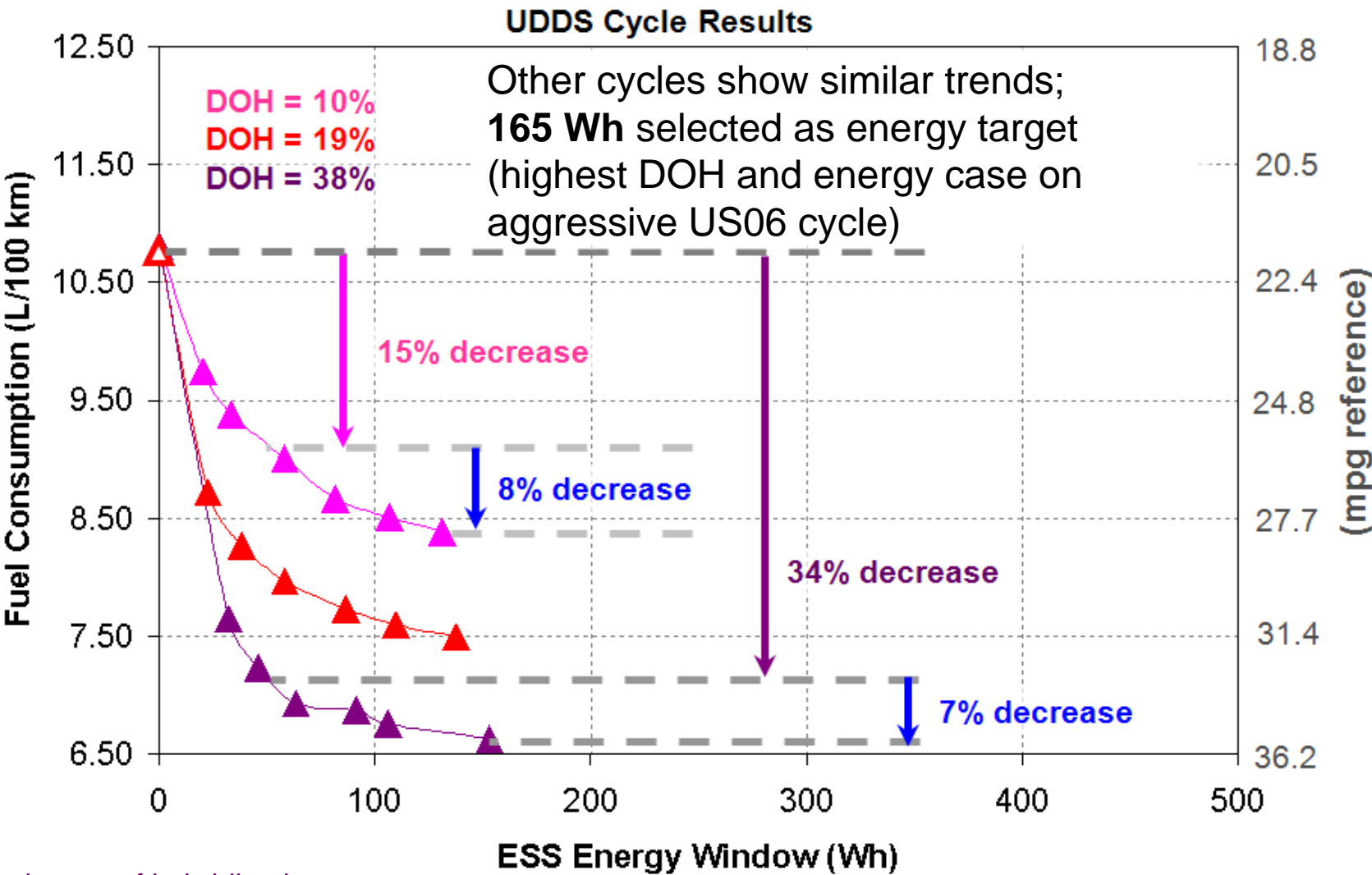
- Review potential approaches and others' related activities
- Identify/develop necessary analysis tools
- Analyze high-level cost/benefit relative to other technologies

Near-term activities

- Evaluate different types of connection mechanisms
 - Conductive, inductive/evanescent, etc.
- Perform detailed system cost effectiveness estimation
 - For use with EVs, PHEVs and HEVs
- Determine how best to leverage infrastructure, e.g.:
 - 22% of travel occurs on 1% of roadway (interstate)
 - Use GPS driving data to evaluate detailed utilization (including arterials, etc.)
- Assess fuel savings, GHG benefit and utility impact for different scenarios
 - Various powertrains, levels of parked vs. roadway charging, etc.

Technical Accomplishments/Progress

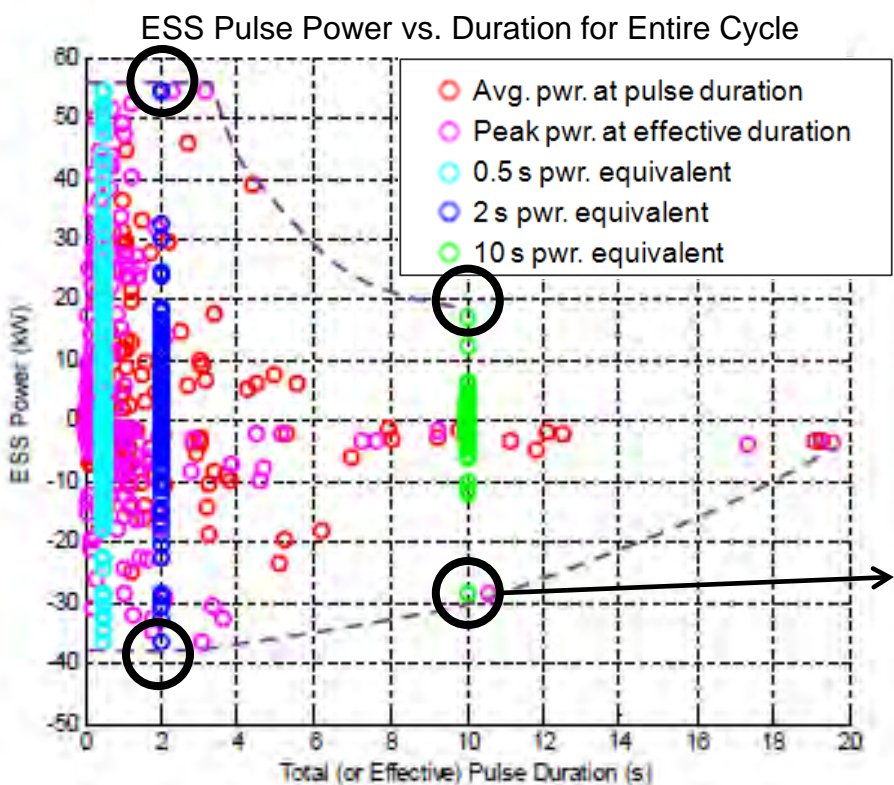
Simulated Fuel Consumption vs. ESS Energy



DOH = degree of hybridization
UDDS = Urban Dynamometer Driving Schedule (historic city test cycle)

Setting Power Goals/Examining Reduction

US06 cycle, highest DOH and energy case

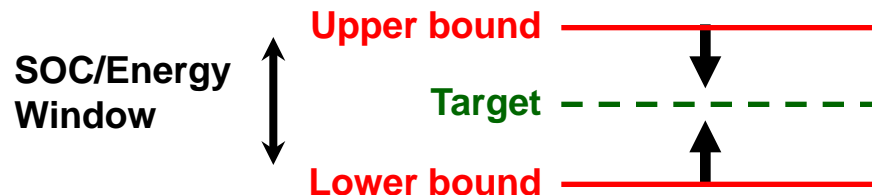
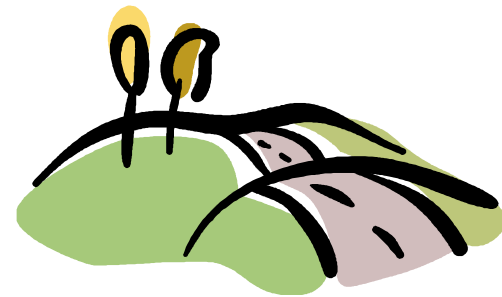


Little regenerative energy missed from reducing 10-sec power target to 20 kW

Identified Source of Potential Fuel Savings

(Needing to respect battery limits through unknown future driving)

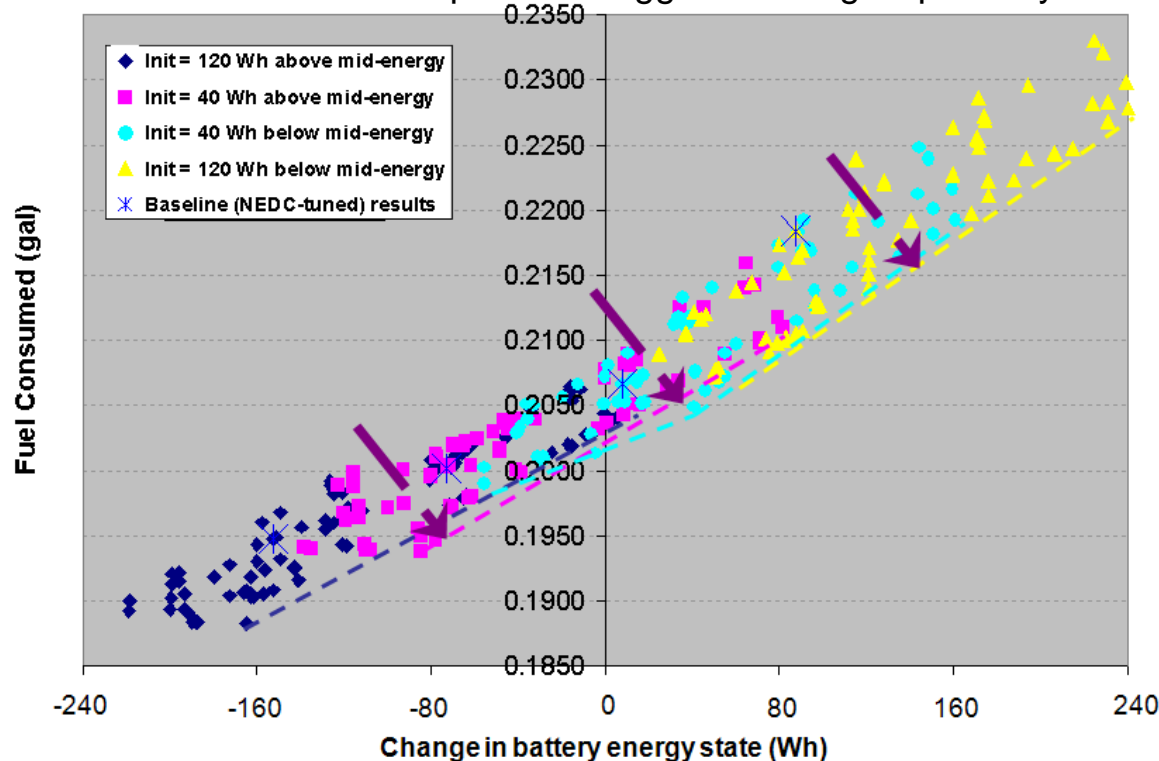
- Basic HEV control strategy goals
 - Minimize fuel use and emissions
 - Good driveability
 - Maintain component life (e.g. – battery SOC/ energy window constraints; current and voltage limits)
- ‘Hard’ efficiency losses
 - High window bound limits regenerative charging
 - Low window bound prevents electric operation/assist
- ‘Soft’ efficiency losses
 - Decisions based on SOC control inputs
 - Detracts from primary strategy goals



SOC = state of charge

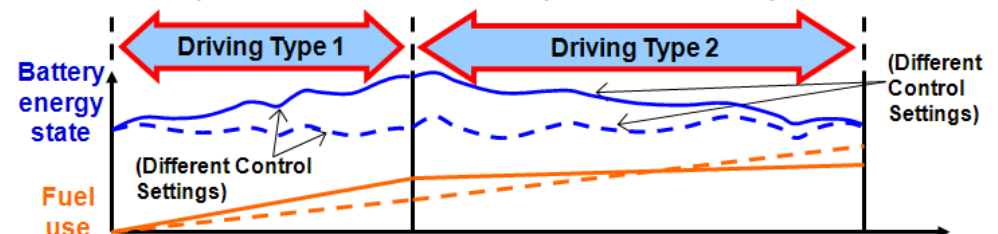
Optimize for Fuel and Battery Use Tradeoffs

Results of Control Options on Aggressive High-Speed Cycle



- Select best controls for each driving type
 - Minimize fuel use
 - Maximize battery energy state
- Select best order over known sequence of different driving types
 - Utilize trade-offs between fuel and energy state changes

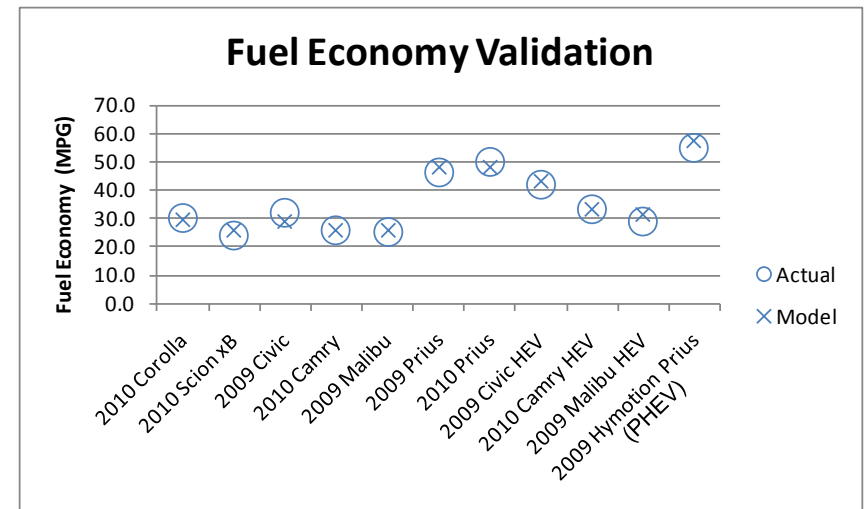
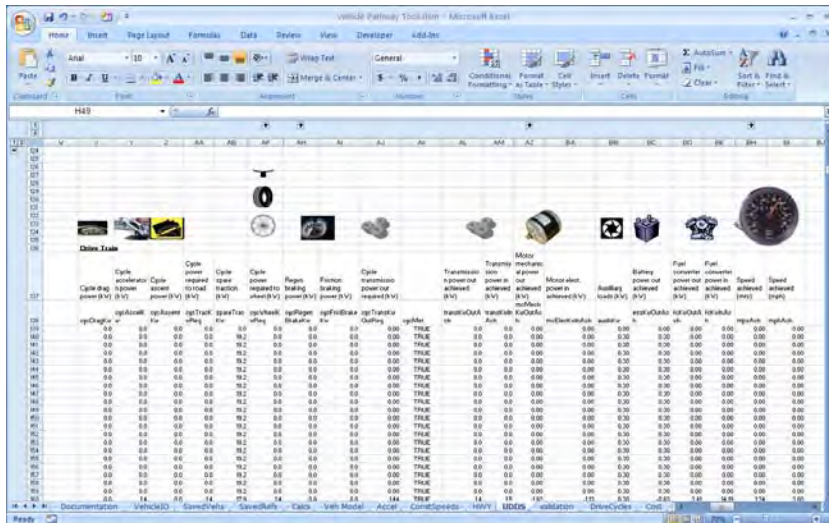
Illustrating Potential Fuel/Energy Sequencing Tradeoffs



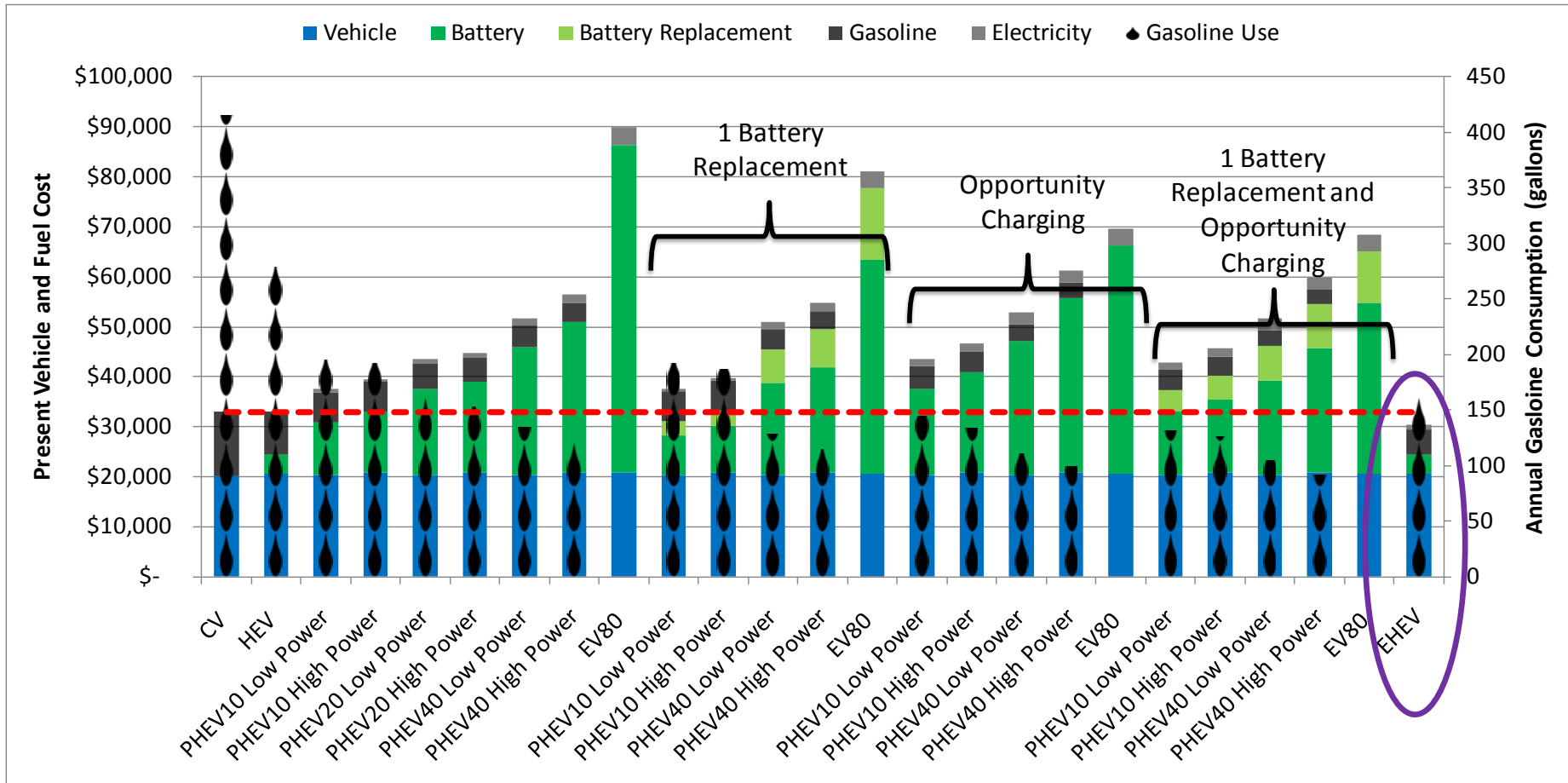
NEDC = New European Drive Cycle: provides good general tuning for baseline comparison

Technology Comparison Tool Development

- Capture important considerations
 - Cost; Battery life; Vehicle performance; Fuel economy/efficiency
- Include only the most important factors
 - Powertrain type; Drive cycle; Driving distance distribution; Component efficiency maps; Energy management strategies; Etc.
- Fast calculating and easy to use (runs in Excel)
 - 2.5 sec for HEV fuel economy, performance, battery life and cost
- Validate key outputs (efficiency, performance, battery life, cost)



Scenario Analysis



The externally electric powered hybrid electric vehicle (EHEV) was the only cost effective option using current battery technology

Collaborations

USABC and ES Tech Team Workgroup

Analysis discussions and iterations with workgroup

- Including ES experts from big three U.S. automakers



CHRYSLER



Support new target setting

- NREL recommendations adopted by USABC



LEESS Targets for Power-Assist HEV Applications

End of Life Characteristics	Unit	Requirement	
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)	
Selling System Price @ 100k/yr	\$	400	

HEV Bus Manufacturers

Potential collaboration discussions

- ISE Corp.



- Navistar International Corp.



- Allison Transmission, Inc.



Multi-Party Coordination on Related Activities

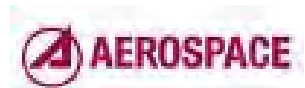
Expert interaction on past and on-going efforts

- Inductive/evanescent power transfer – hardware developers
 - Korea Advanced Institute of Science and Technology (KAIST)
 - University of Auckland
 - Oak Ridge National Laboratory (ORNL)
- U.S. university research programs
 - UC Berkeley (PATH program)
 - Utah State



Others subcontracting NREL for research support

- Utah State University
 - Add infrastructure cost for different scenarios to EHEV analysis
- The Aerospace Corporation
 - Analysis for San Jose Automated Transit Network



PREA = Partnership for Roadway Electrification & Automation;

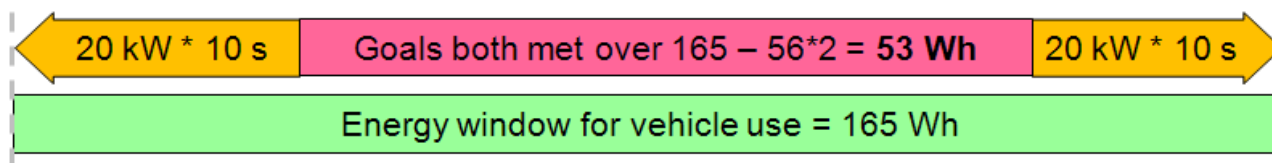
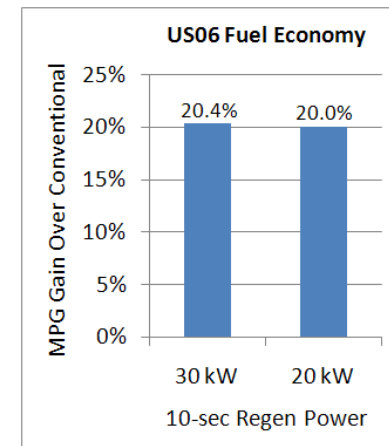
PATH = Partners for Advanced Transportation Technology

Future Work

Refine Targets, Confirm Performance

Support relaxing 10-sec regenerative power requirement

- Recent analysis suggests 30 kW target drives size/cost
- Reducing to 20 kW has negligible mpg impact
 - No difference for UDDS cycle
 - Conservative estimate for US06 also minimal
- Revision would also impact “available energy over which power requirements simultaneously met”



Confirm prototype devices deliver full HEV fuel savings

- As they become available from USABC contractors
- Evaluate over a variety of drive cycles

Near-Term Focus: Execute Approach Plan

Hardware demonstration/validation over repeated cycles



Potential long-term focus areas

- Refined analysis of benefits beyond HEV fuel savings
 - Battery life and pollutant emissions benefits
 - PHEV considerations
- Partner with light-duty vehicle manufacturer
 - More challenging, but more vehicles over which fuel savings can spread
 - Potentially integrate with dashboard “ECO” displays

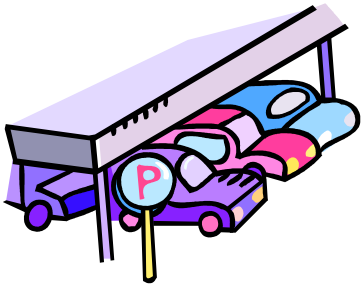


Near-Term Focus: Execute Approach Plan

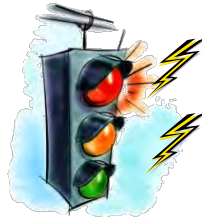
Evaluate different vehicle/infrastructure/connection options

Automatic charging connection...

When parked



At stops



Added to
existing roads



Along a
guide way



Potential additional long-term activities

- Continual model enhancements to improve cost effectiveness estimates
 - Cost and battery life modules
- Hardware demonstration of promising design alternatives
 - Could be at fractional scale
- Evaluate synergies of combining with automated vehicle control
- Consider development role of transit vs. commercial vs. private vehicles

Reiterating Project Summary

HEVs/PHEVs have considerable room for improvement

- Note many generations of conventional vehicle design optimization
- Possible to increase per-vehicle fuel savings
- Also important to increase consumer value proposition
 - Leads to greater technology market penetration
 - And larger aggregate fuel savings

Refining/validating these advanced concepts could:

- Maintain high HEV fuel savings while reducing overall cost
- Use available route information to increase individual HEV/PHEV mpg
- Maximize total petroleum displacement with domestic electricity
 - Increasing convenience/guaranteeing PHEV charging while parked
 - Potentially increasing fuel displacement/decreasing vehicle cost through roadway electrification (power transfer while in motion)

Special thanks to:

- Lee Slezak, David Anderson, and David Howell,
DOE Vehicle Technologies Program

NREL contacts:

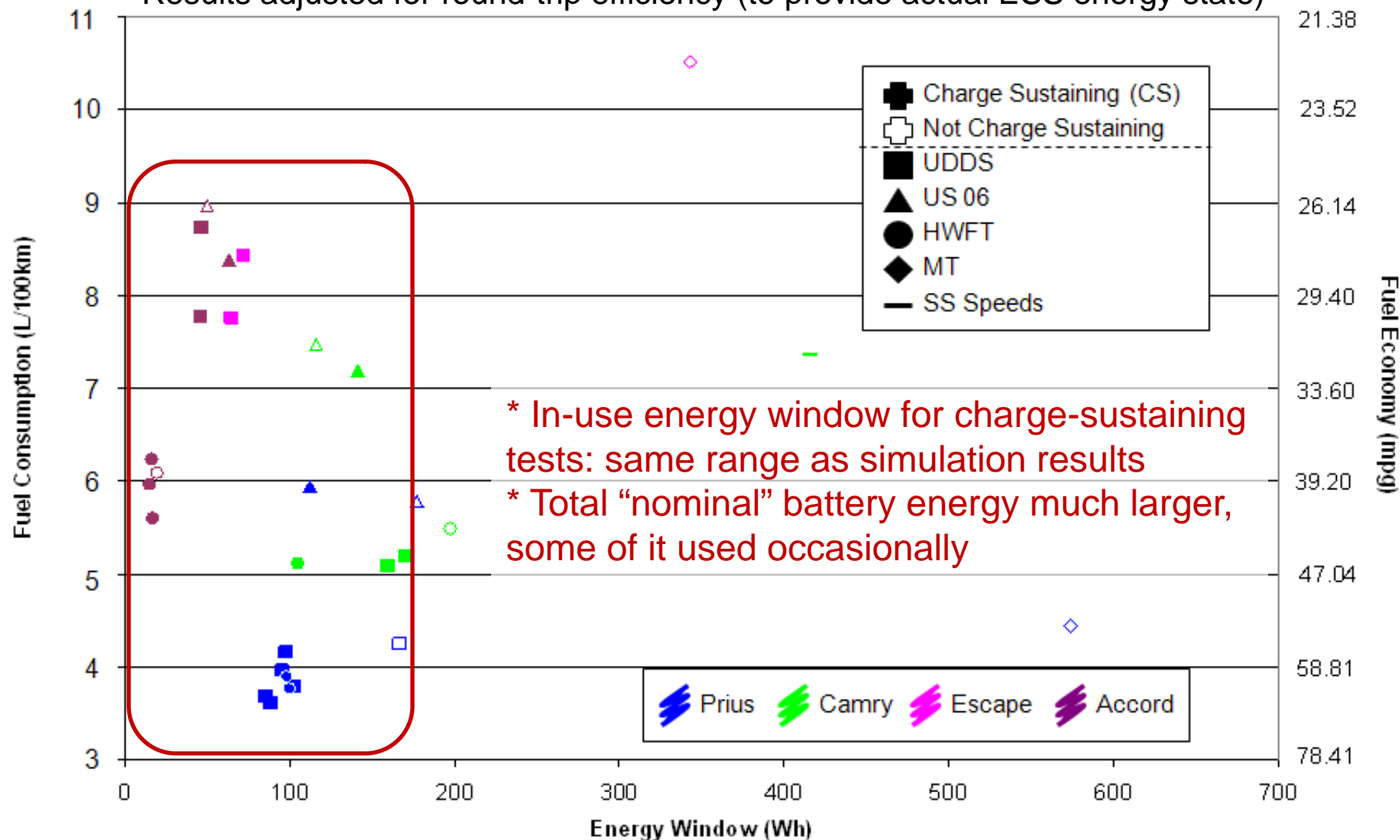
- Jeff Gonder – jeff.gonder@nrel.gov
- Robb Barnitt – robb.barnitt@nrel.gov
- Ahmad Pesaran – ahmad.pesaran@nrel.gov

Technical Back-Up Slides:

Description of Additional Accomplishments and Related/Synergistic Activities

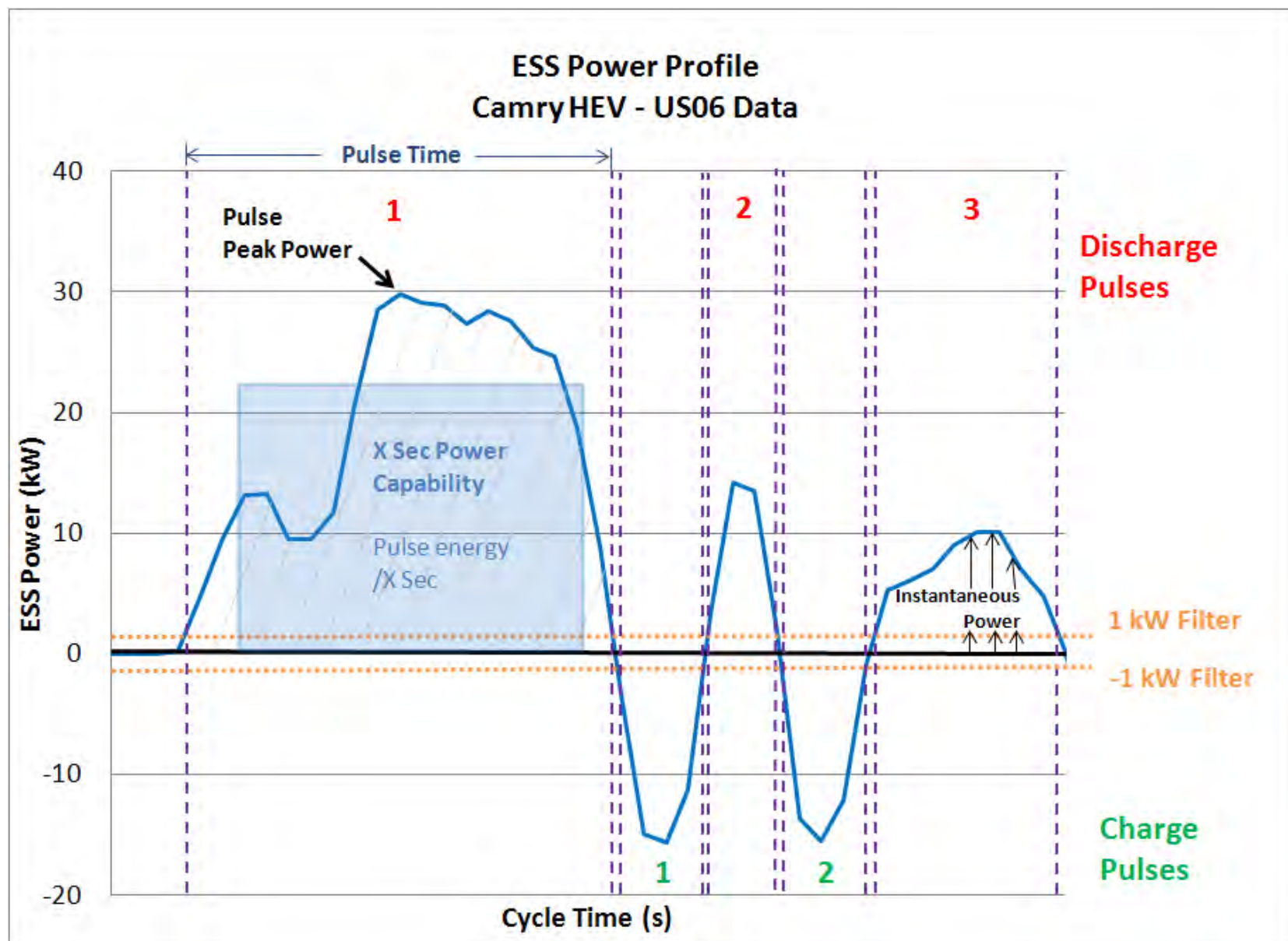
Consistent Findings from Production HEV Dyno Data Analysis*

Results adjusted for round-trip efficiency (to provide actual ESS energy state)



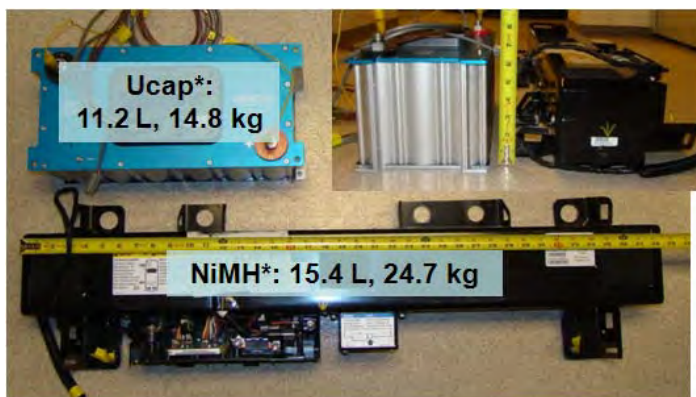
* Thanks to ANL for providing access to some of the raw dynamometer test data

Quantifying Pulse Characteristics



Related CRADA Project Overview: GM funded NREL to evaluate replacing NiMH batteries with ultracapacitors in a 42 V Saturn Vue BAS HEV ('08-'10)

- Based on USABC analysis findings and 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 courtesy of J. Gonder

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

CRADA = cooperative research and development agreement; NiMH = nickel metal hydride;
BAS = belt alternator starter; Ucap = ultracapacitor

GPS Drive Cycle Data Availability

From the NREL-hosted Transportation Secure Data Center (TSDC)

www.nrel.gov/vehiclesandfuels/secure_transportation_data.html

- Secure archival of and access to detailed transportation data
 - Travel studies increasingly use GPS → valuable data
 - TSDC safeguards anonymity while increasing research returns
- Various TSDC functions
 - Advisory group supports procedure development and oversight
 - Original data securely stored and backed up
 - Processing to assure quality and create downloadable data
 - Cleansed data freely available for download
 - Controlled access to detailed spatial data
 - User application process
 - Software tools available through secure web portal
 - Aggregated results audited before release



NRC report*

Sponsored by the U.S. Department of Transportation (DOT)
Operated by the NREL Center for Transportation Technologies and Systems (CTTS); Contact: Jeff.Gonder@nrel.gov

GPS = global positioning system

* See recommendations from this 2007 National Research Council report: books.nap.edu/openbook.php?record_id=11865

