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Lower-Energy Requirements for Power-Assist HEV Energy Storage Systems—Analysis and Rationale

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Executive Summary

- Performed simulations and analyzed test data in conjunction with an EES TT Workgroup in response to a USABC request
- Results suggested power-assist (PA) HEVs can still achieve high fuel savings with lower energy requirements and potentially lower cost
- Clarified energy definition
  - "Available" energy where power requirements simultaneously met, vs.
  - Energy window for vehicle use
- USABC/EES TT established new set of ESS targets and issued a Request for Proposal Information (RFPI)
  - The goal is to reduce the cost of fuel-saving HEV systems
  - Open to any ESS technology (very high power batteries, electrochemical double layer capacitors, or asymmetric supercapacitors)

EES TT = The FreedomCAR Electrochemical Energy Storage Technical Team
USABC = United States Advanced Battery Consortium
HEV, ESS = hybrid electric vehicle, energy storage system

Background

- Historic PNGV, FreedomCAR, and/or USABC targets
  - For the energy storage system (ESS) in a power-assist (PA) hybrid electric vehicle (HEV)
  - Established in the late 1990s and early 2000s
  - Call for 0.3-0.5 kWh of “available” energy
- Limitations of NiMH batteries result in large design margins
  - To achieve at least 8-10 year life
  - Lead to high-cost battery packs with total energy of 1.2 to 1.5 kWh
- Pursuing more cost-effective energy storage
  - EES TT and USABC assembled a workgroup to re-evaluate the energy required for PA-HEVs and milder hybrids
  - NREL was asked to provide analysis support

PNGV = Partnership for a New Generation of Vehicles
USABC = United States Advanced Battery Consortium
NiMH = Nickel metal hydride
EES TT = The FreedomCAR Electrochemical Energy Storage Technical Team

Motivation for this work:

Could required energy be reduced to save $ and expand technologies?

FreedomCAR Energy Storge System Performance Goals for Power-Assist Hybrid Electric Vehicles (November 2002)

* From USABC ESS Goals: http://www.uscar.org/guest/article_view.php?articles_id=85

Characteristics	Units	Power-Assist (Minimum)	Power-Assist (Maximum)
Pulse discharge power (10s)	kW	25	40
Peak regenerative pulse power (10s)	kW	20 (55-Wh pulse)	35 (97-Wh pulse)
Total available energy (over DOD range where power goals are met)	KWh	0.3(atC_1 /1rate)	0.5 (at C_1/1 rate)
Minimum round-trip energy efficiency	%	90 (25-Wh cycle)	90 (50-Wh cycle)
Cold cranking power at -30°C (three 2-s pulses, 10-rests between	kW	5	7
Cycle life for specified SOC increments	cycles	300,000 25-Wh cycles (7.5MWh)	300,000 50-Wh cycles (15 MWh)
Calendar Life	years	15	15
maximum weight	kg	40	60
Maximum volume	l	32	45
Operating Voltage limits	Vdc	max≤400 min≥(0.55 x Vmax)	max<400 min>(0.55 x Vmax)
Maximum allowable self-discharge rate	Wh/day	50	50
Temperature range: Equipment operation Equipment survival	°C	-30 to +52 -46 to +66	-30 to +52 -46 to +66
Production Price @ 1000,000 units/year	$	500	800

Total available energy (over DOD range where power goals are met) = 0.3-0.5 kWh

Approach Outline

Supporting FreedomCAR/USABC Workgroup's re-evaluation of HEV ESS requirements/goals per DOE's funding

Workgroup
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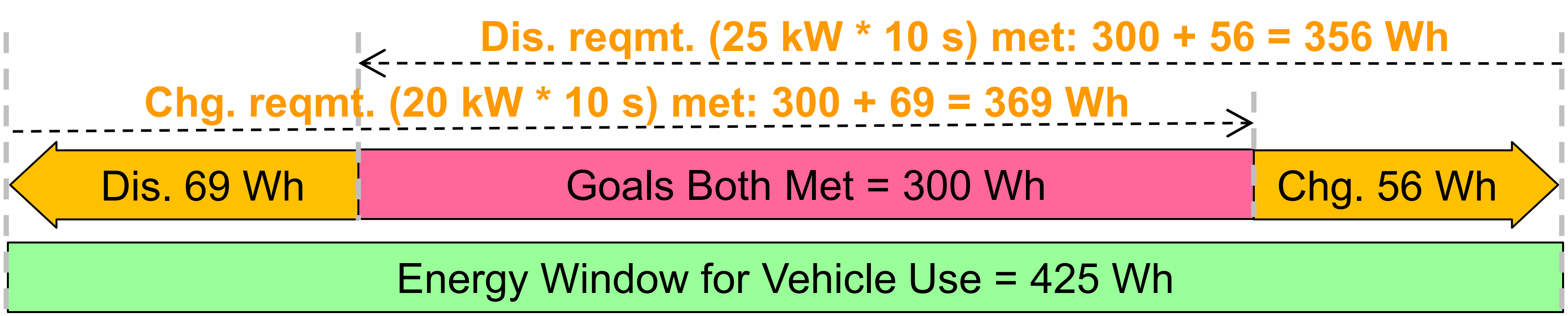
- HEV simulations
  - ESS energy vs. fuel use trends
  - Various degrees of hybridization and drive cycles
- Analysis of vehicle ESS test data
  - Production HEV dyno runs
  - Sanity check on ESS use over standard cycles
- Reprocessing of simulations for power analysis
  - Characterize power pulses
- (More closely examine energy definition)
  - "Available" energy over which pulse power goals met, vs.
  - Energy window for vehicle use



Base modeling process/assumptions

Used Powertrain System Analysis Toolkit (PSAT) simulation software

- Midsize parallel HEV

<u>Platform assumptions -- held constant</u>
<u>(Technology-neutral assessment of ESS capability)</u>

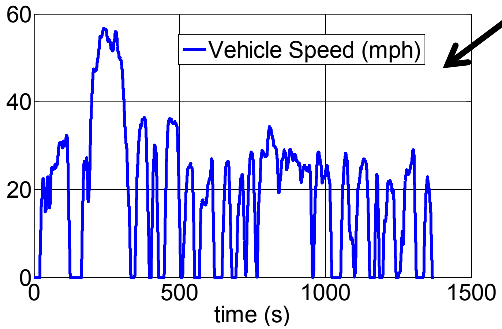
FA = 2.27 m^2	Test mass = 1675 kg
CD = 0.30	Accessory power:
Crr1 = 0.008	Electrical = 500 W
Crr2 = 0.00012	Mechanical = 230 W

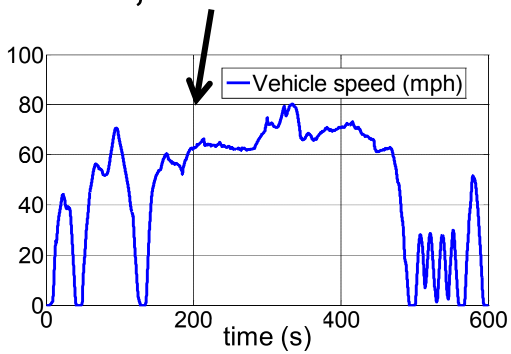
- Multiple degree of hybridization (DOH) cases
  - Based on consistent 0-60 mph acceleration

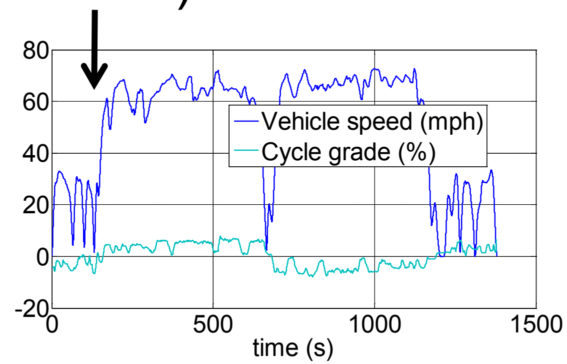
DOH = Motor Power/ (Engine + Motor)Power

DOH = 10%	**DOH = 19%**	**DOH = 38%**
15 kW motor 135 kW eng	25 kW motor 110 kW eng	45 kW motor 75 kW eng

- Multiple drive cycles (UDDS, US06 & Colorado foothills)





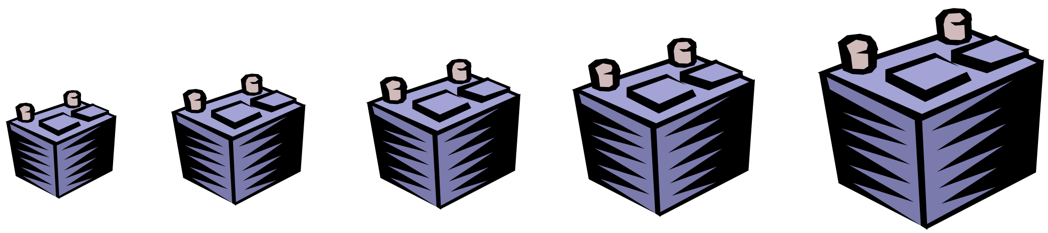


Simulate and analyze ESS in all base cases

Identify actual energy window used to support HEV functions

- Investigate range of ESS energy content
  - ESS power limited by lesser of motor power or driving demand

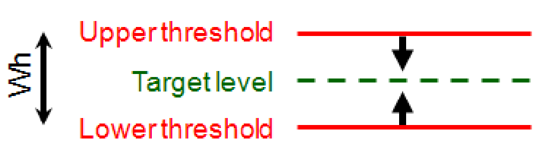
Smallest ESS case

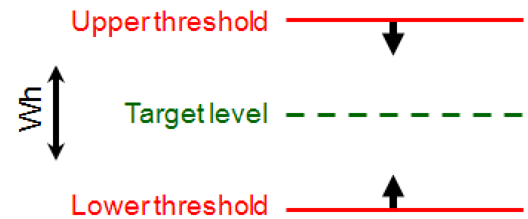


Largest ESS case

- Constant SOC-based controls → changing Wh control window

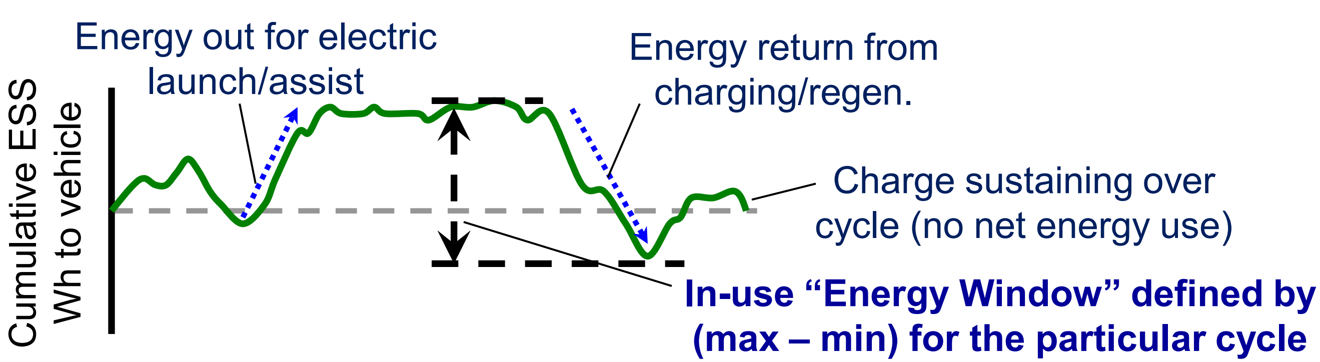
Smallest ESS case

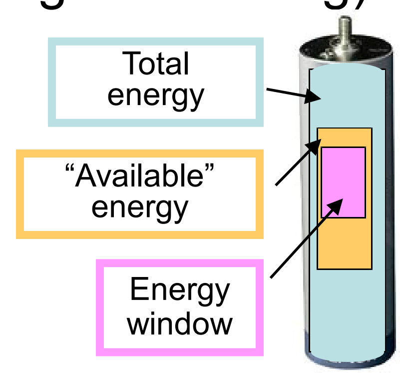




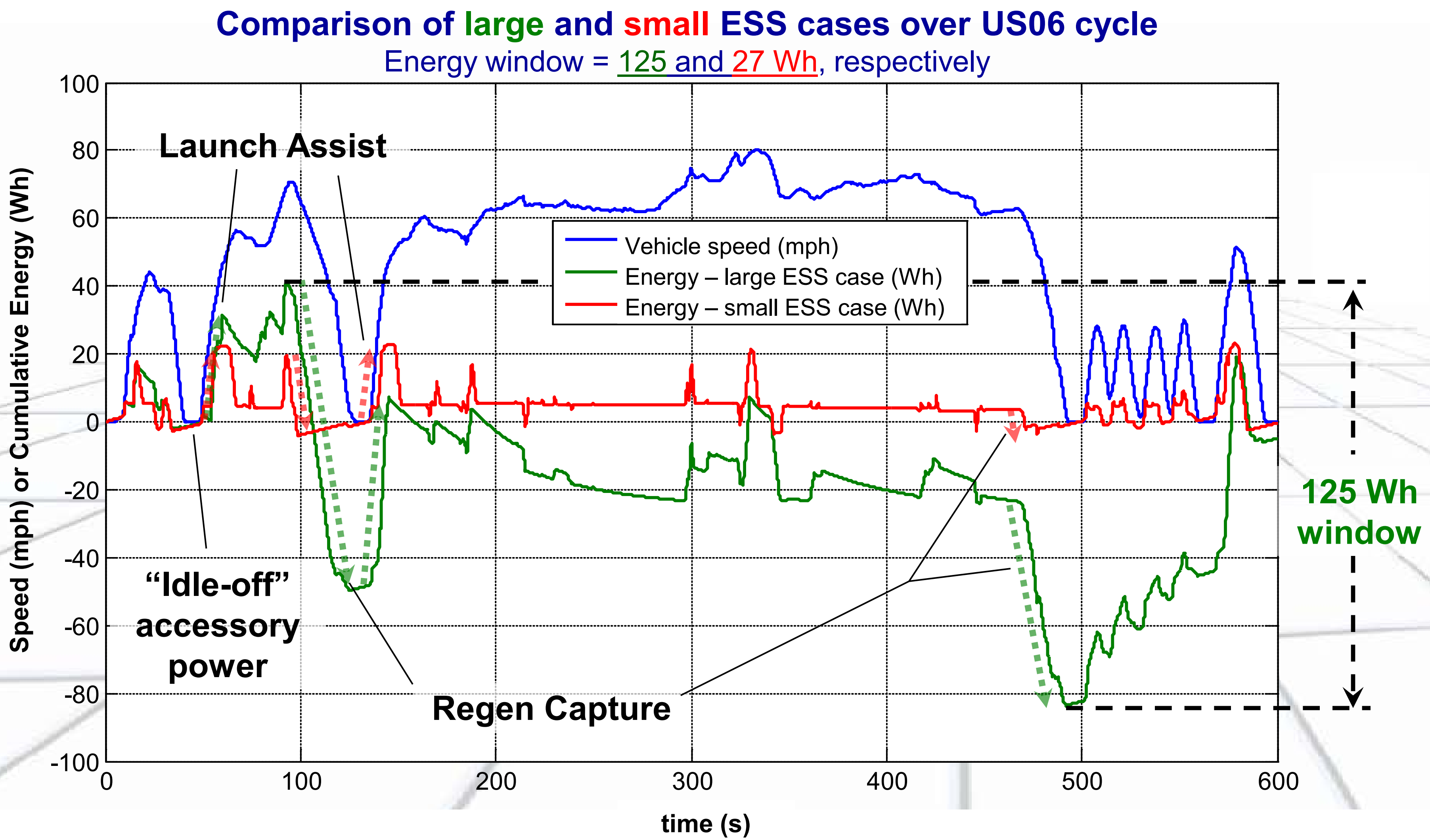
Largest ESS case

- Capture in-use energy window for each simulation (charge sustaining)



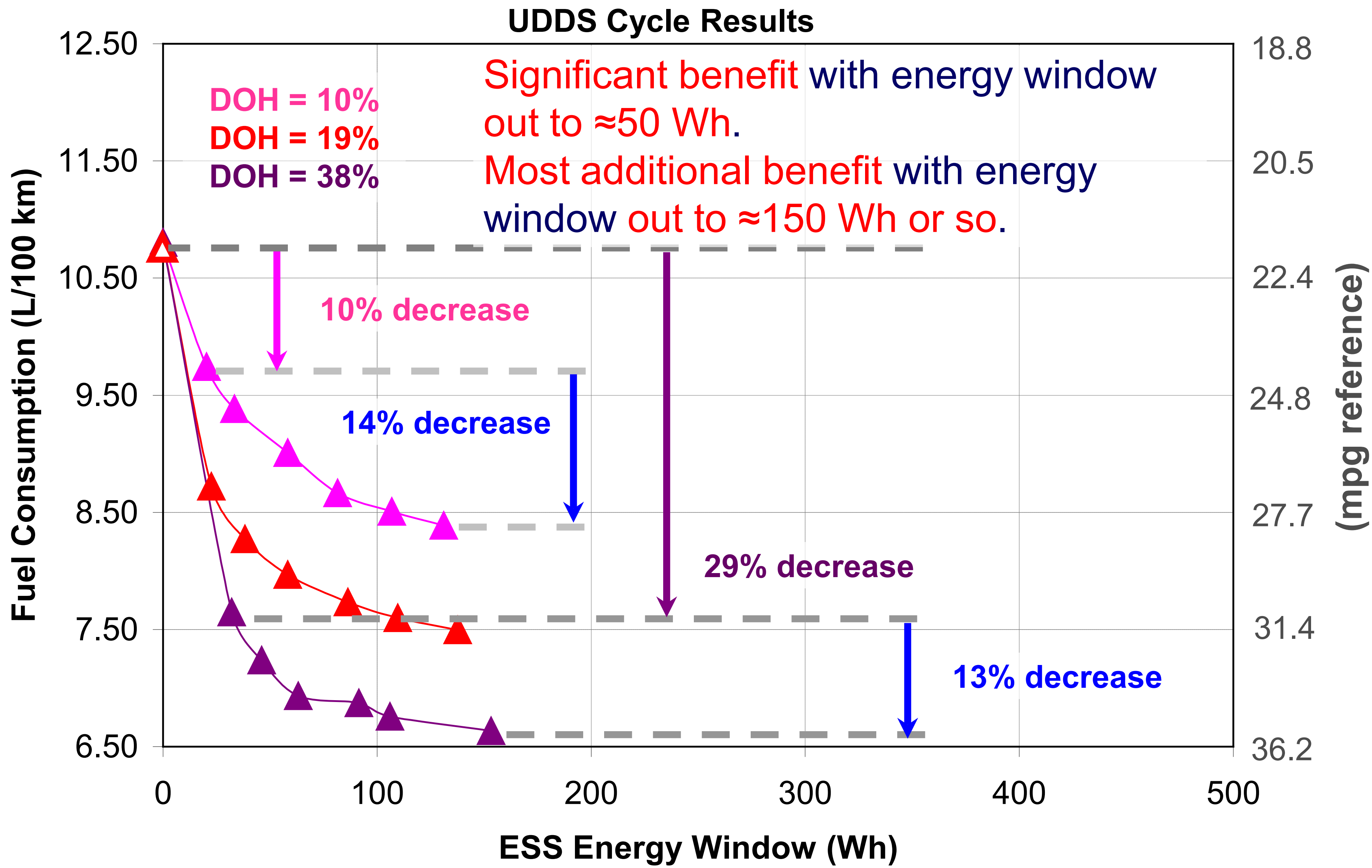


Example in-use ESS energy comparison

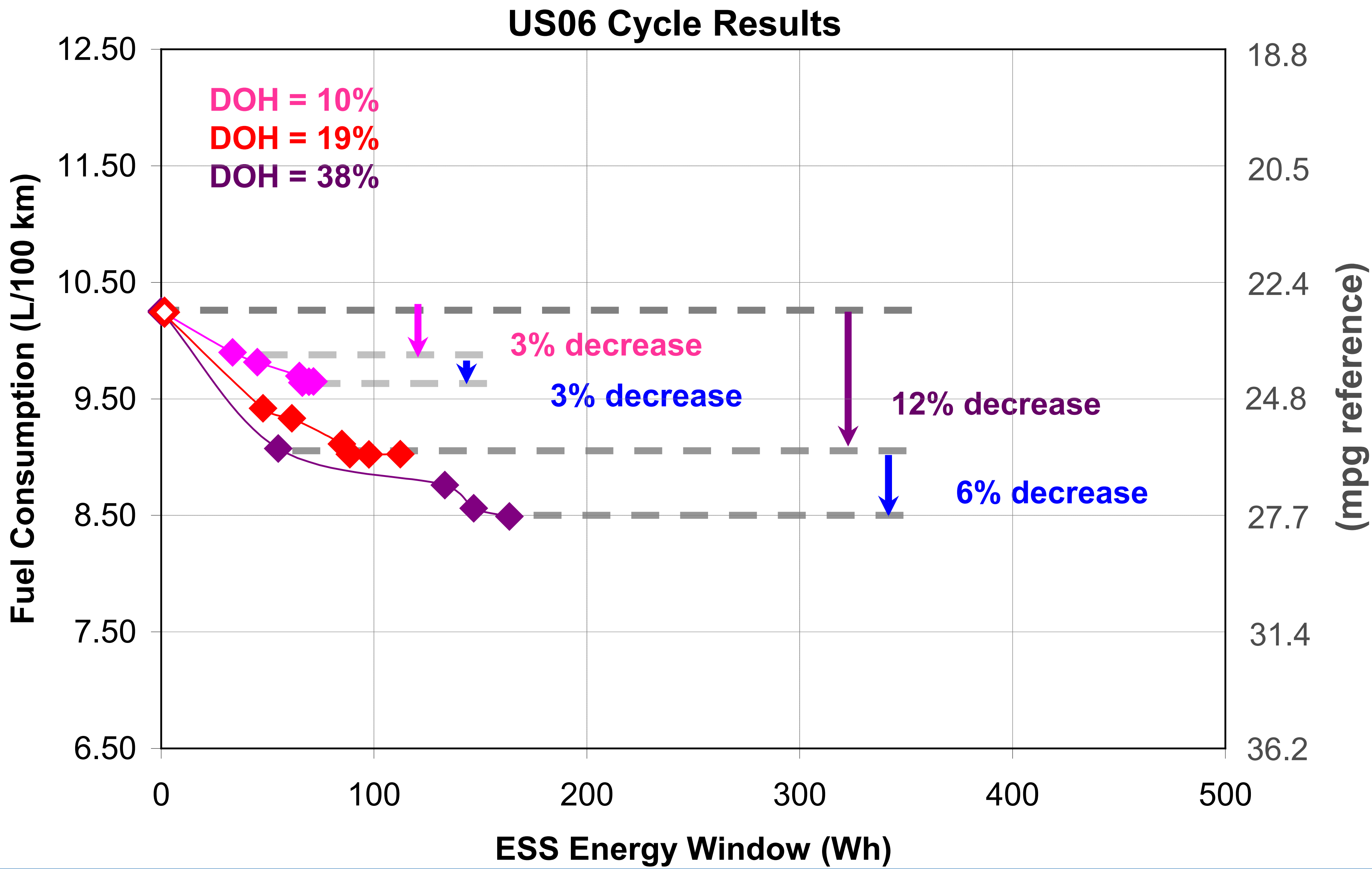


Simulation Results: Trends from fuel consumption results:

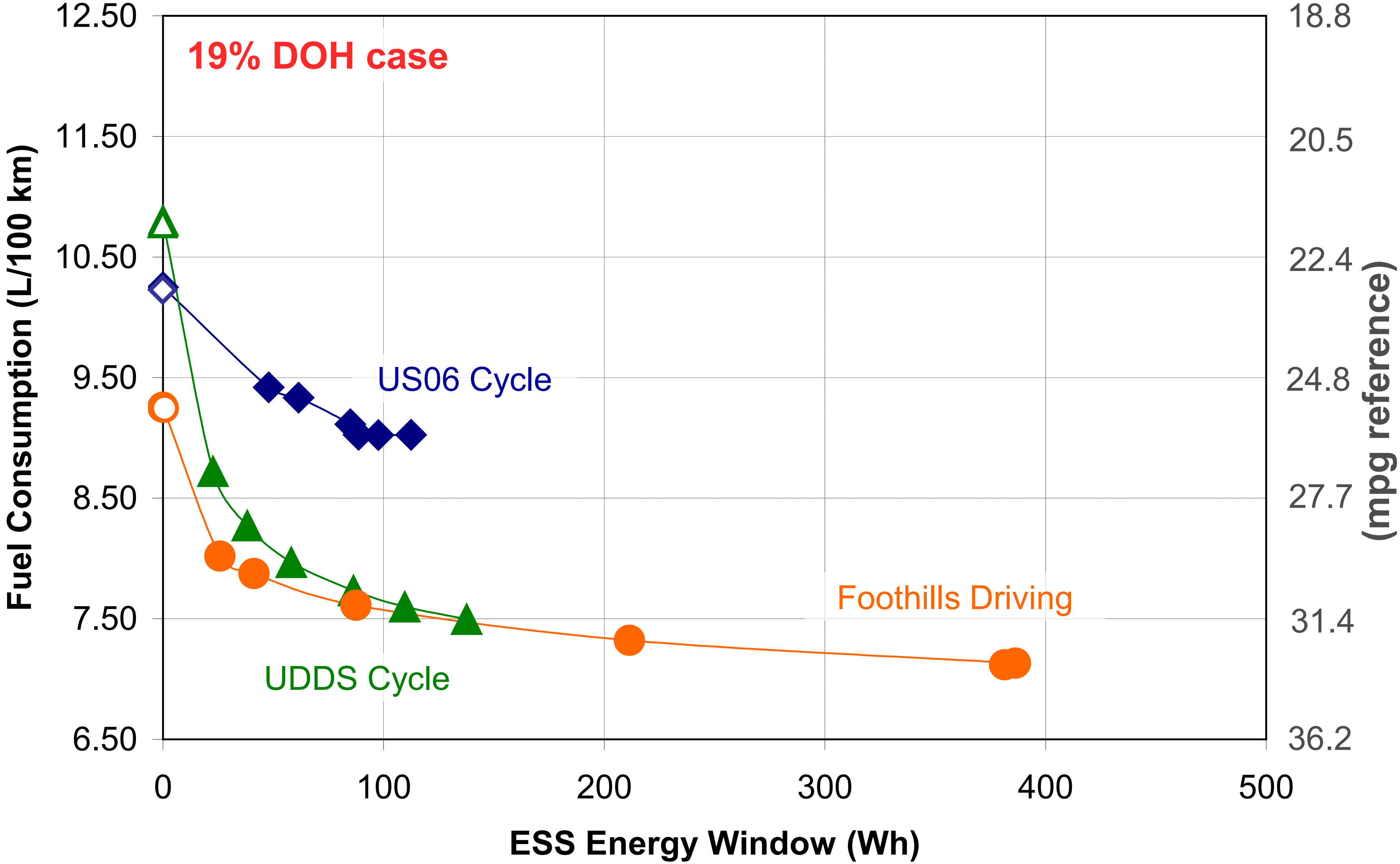
* Fuel savings increase with higher DOH (engine downsizing)
* Fuel savings increase, but taper with larger energy window



Simulation Results: Similar trends for other drive cycles

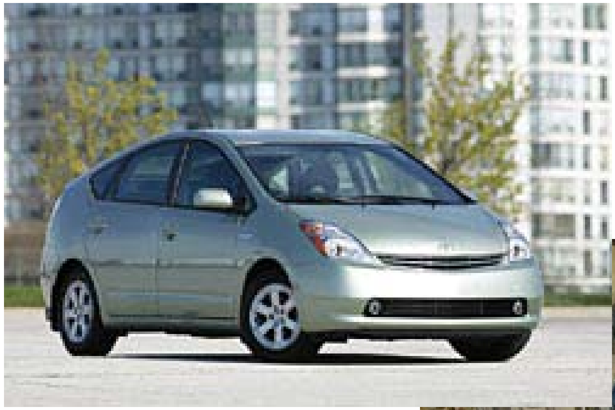


Simulation Results: Some additional, limited benefit for higher energy window use in foothills-type driving

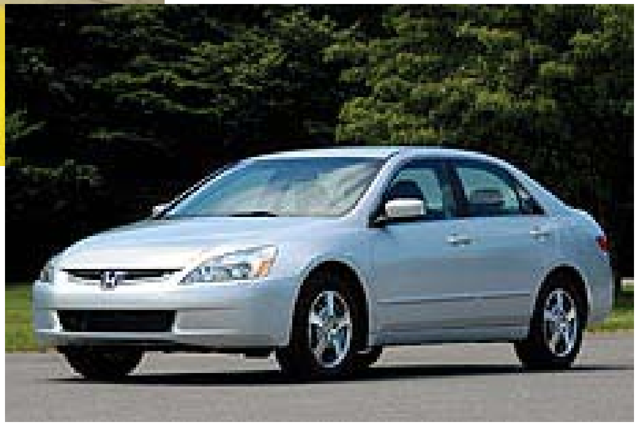


Actual driving data from existing commercial HEVs

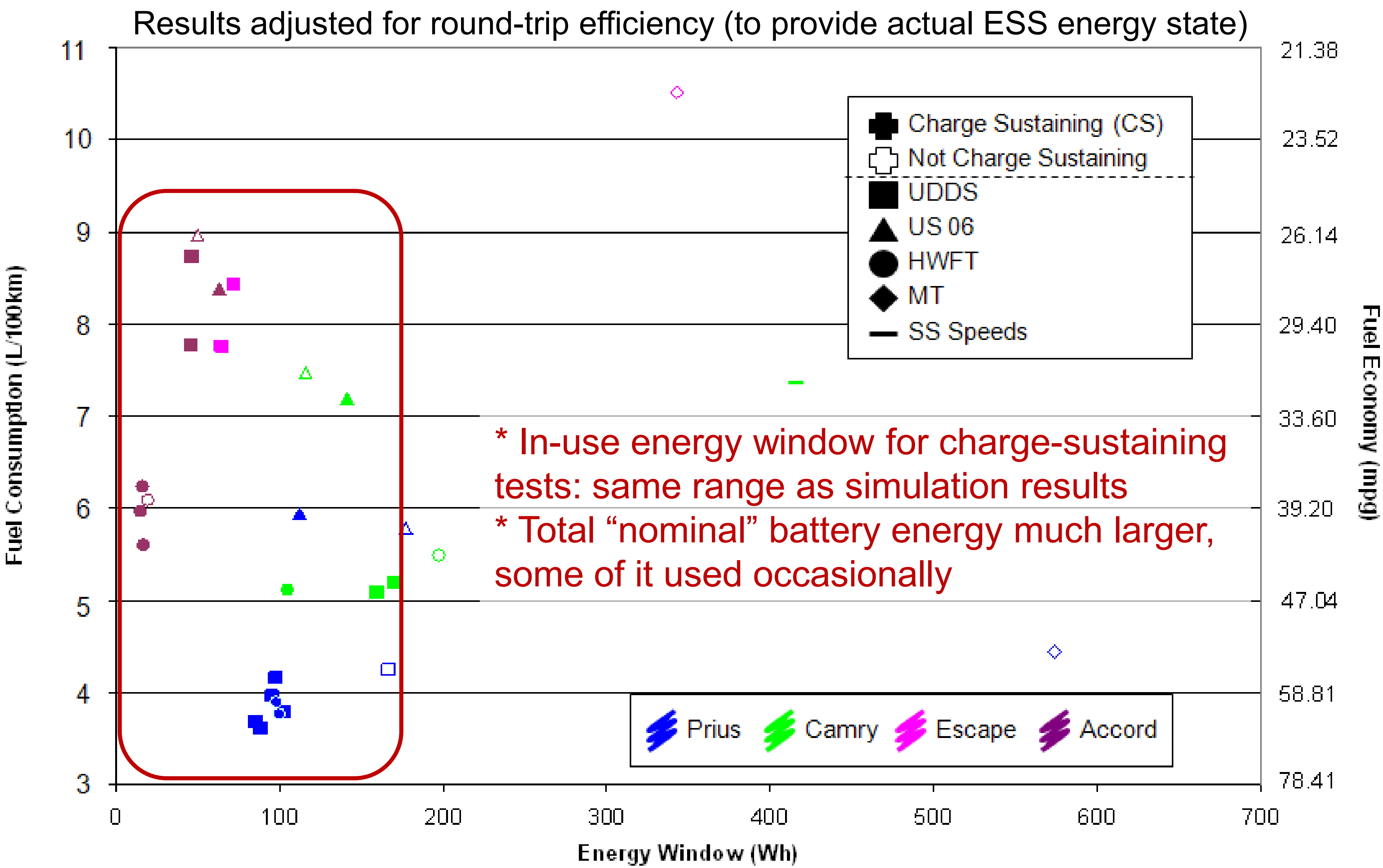
Used to complement and provide a sanity check on the simulation results



Chassis dynamometer (dyno) test cell



Consistent findings from analysis of production HEV dyno data*



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

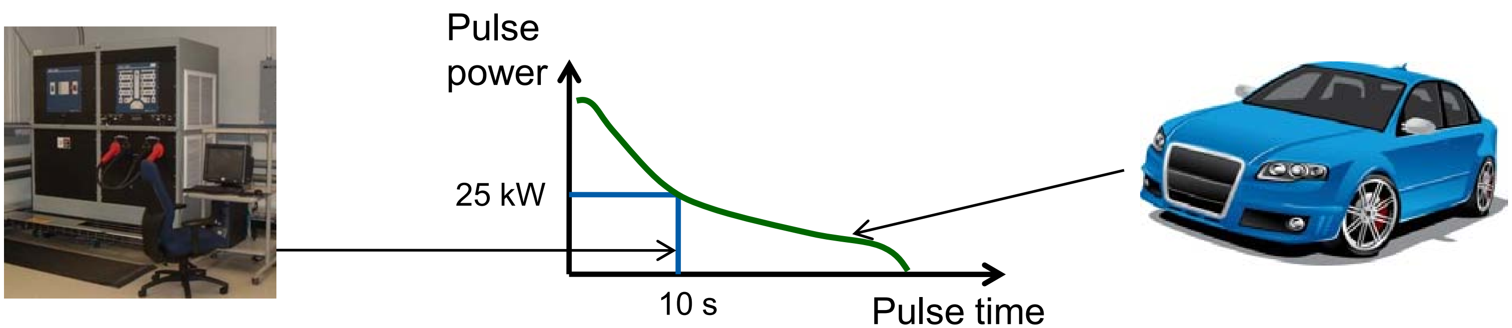
Summary of in-use ESS energy window analysis

- Even small energy windows can provide HEV fuel savings
- Significant fuel savings can be achieved with a ≈150-200 Wh energy window (less than the previous 425 Wh minimum goal)
- Reasons for large total "nominal" energy in current-production HEVs
  - Infrequent drive cycle use (e.g., long uphill/downhill grades)
  - Achieving longer cycle life from reduced SOC swings
  - Energy comes along with sizing for power capability (particularly at cold temperatures)
    - Note that power dominates cost in HEV batteries (high P/E ratio)

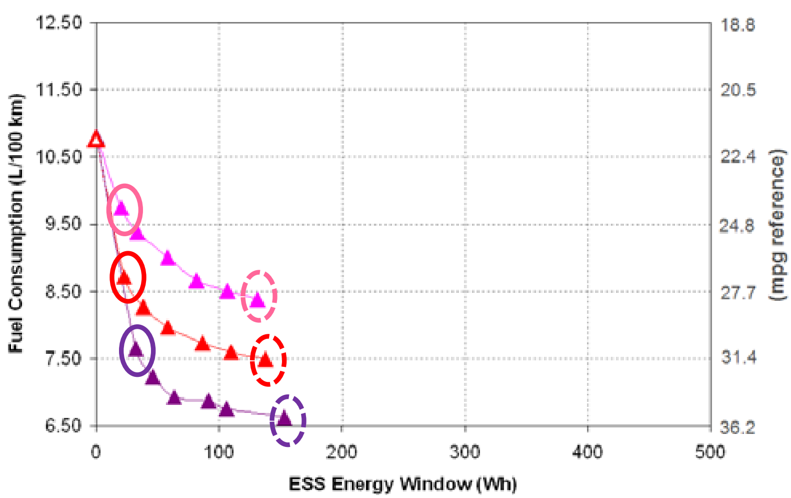
Next question: What goals for ESS power capability tests should be combined with a reduced in-use energy goal?

Power pulse analysis considerations/approach

- Standard lab test vs. in-vehicle ESS capability
  - Actual use depends on DOH, drive cycle, engine vs. motor control decisions, etc.

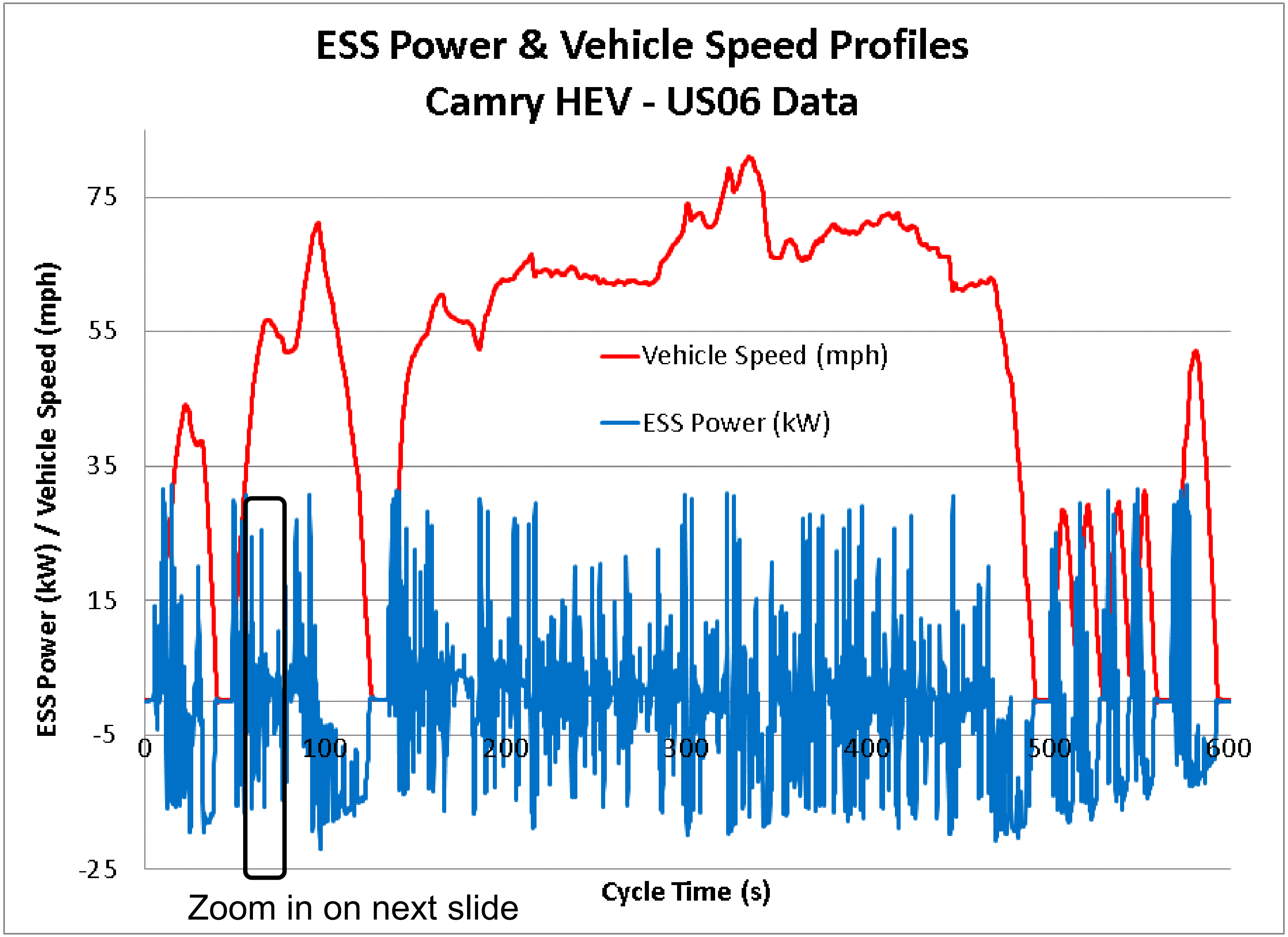


- Analyze pulses from past simulation cycles, observe trends



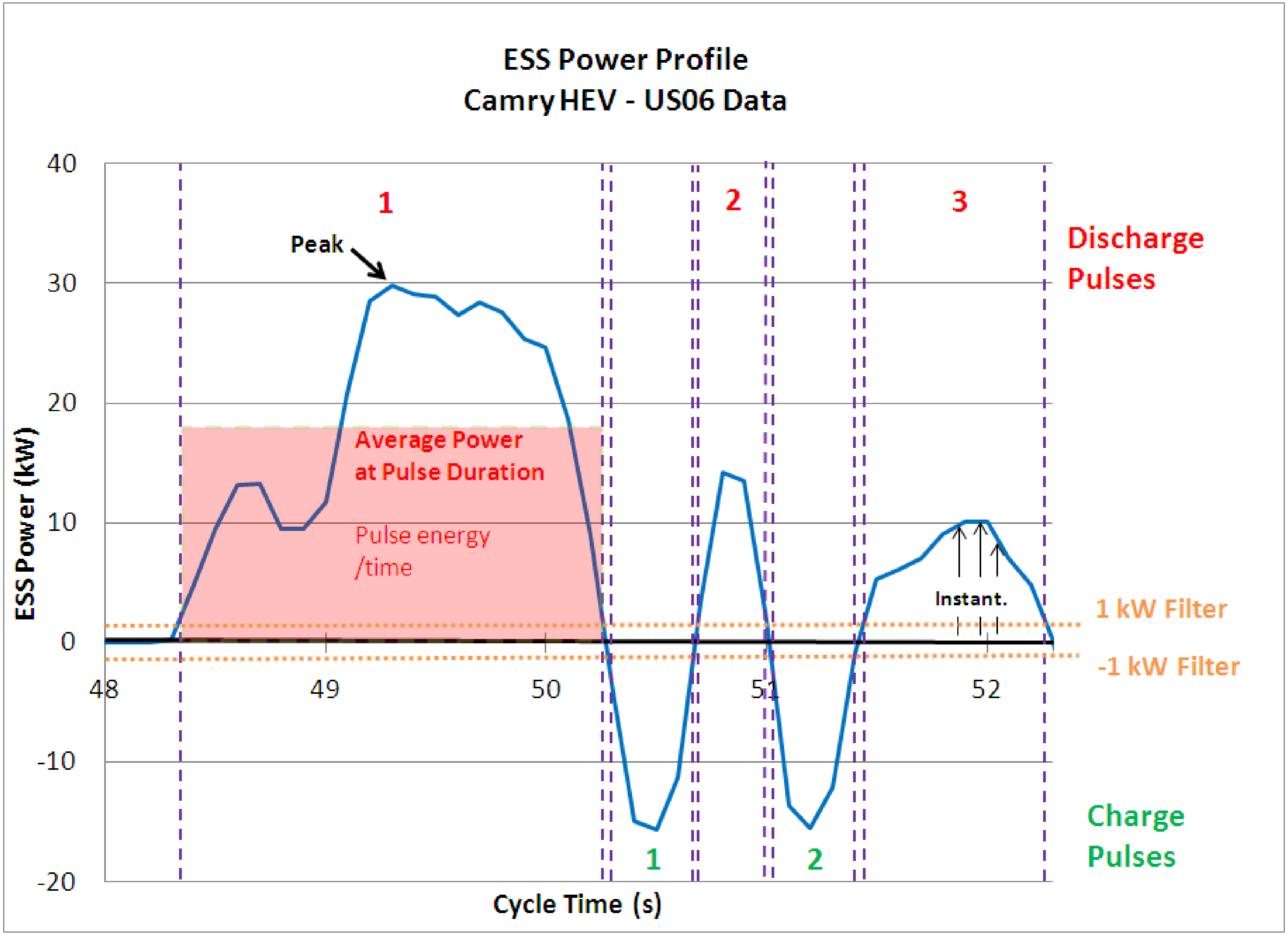
Process for translating complex pulse profiles into "standard pulse test" equivalents

Example complex in-vehicle power profile*

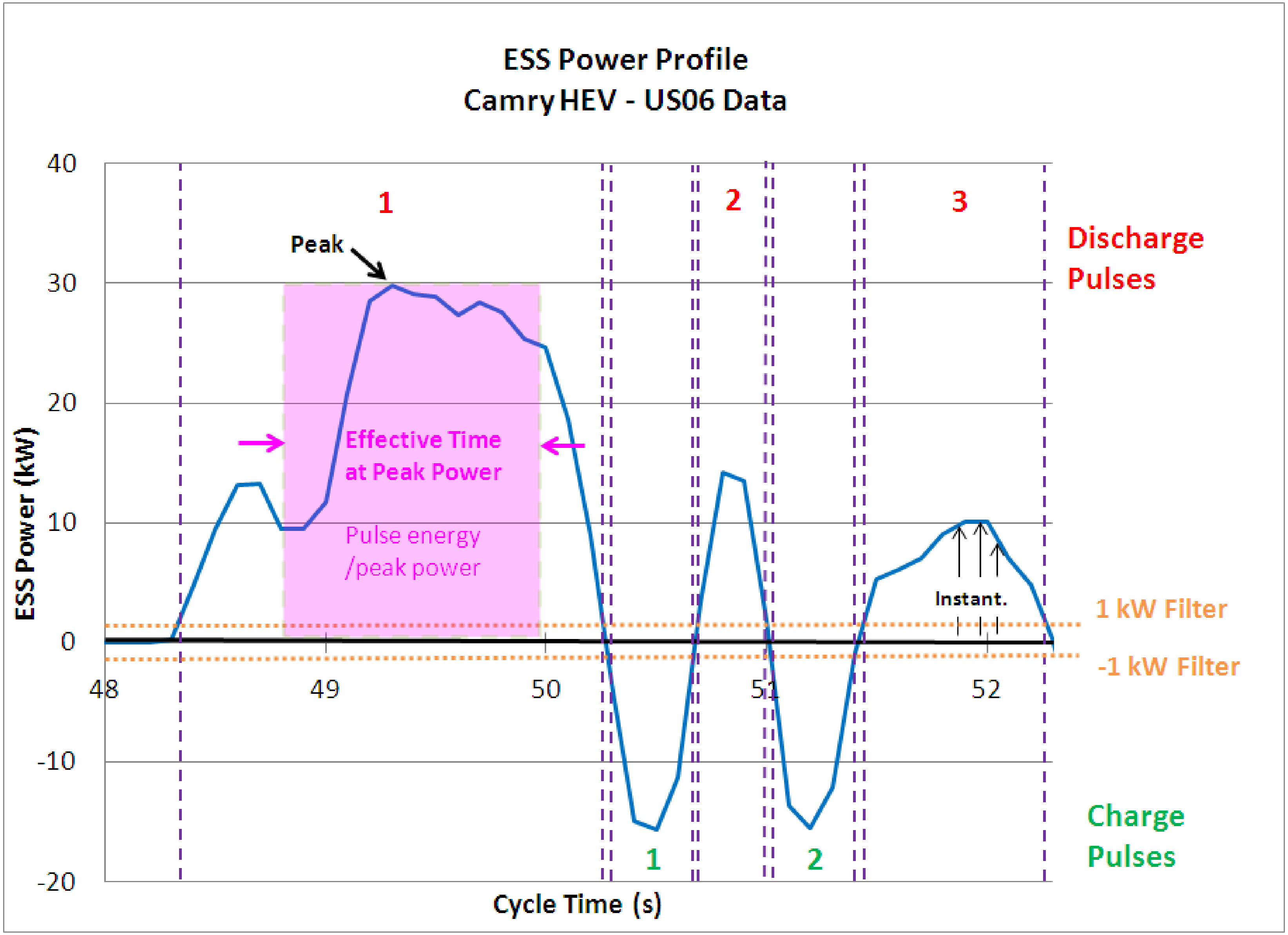


* From aforementioned ANL dyno testing

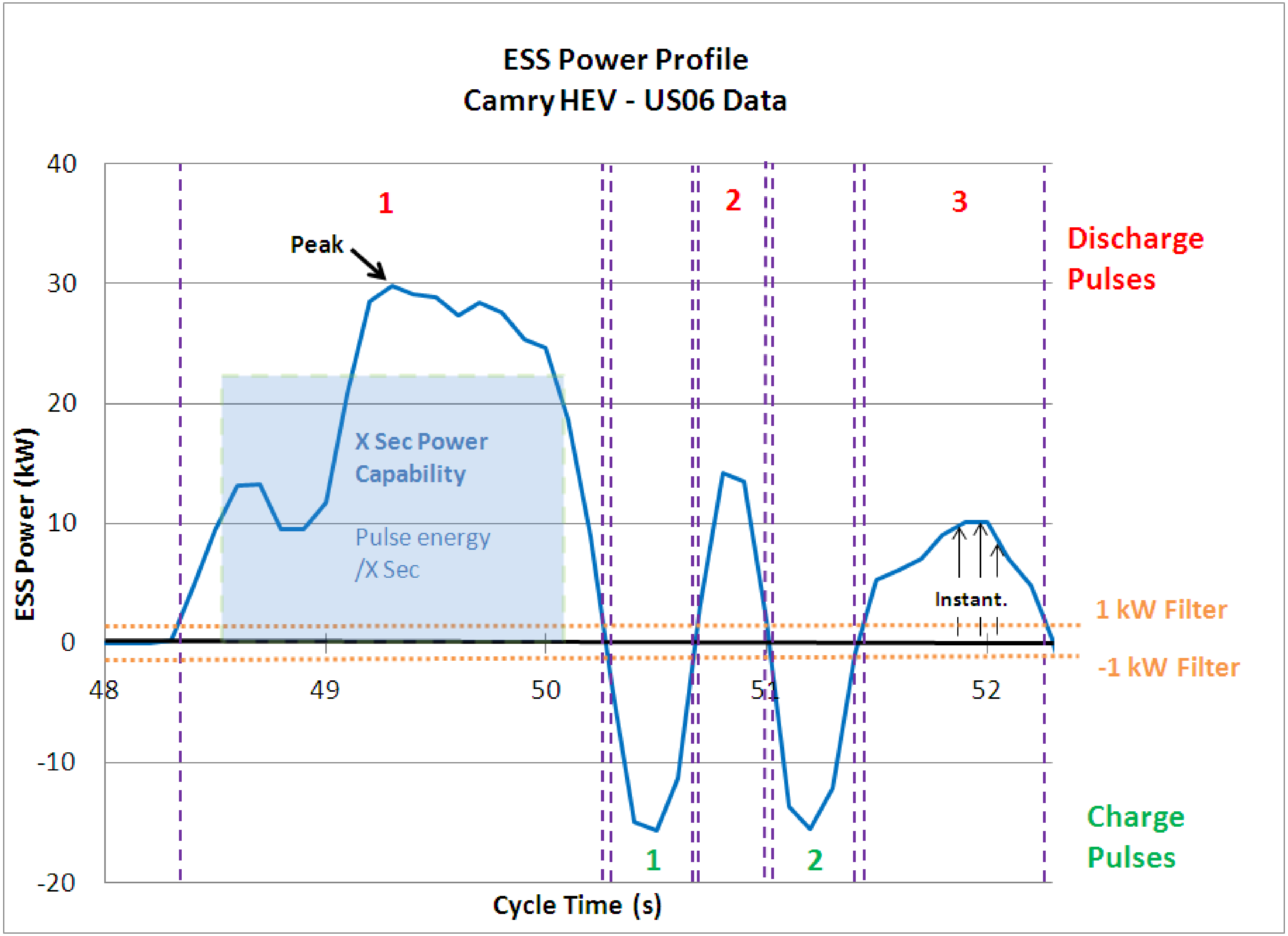
Quantifying pulse characteristics - 1



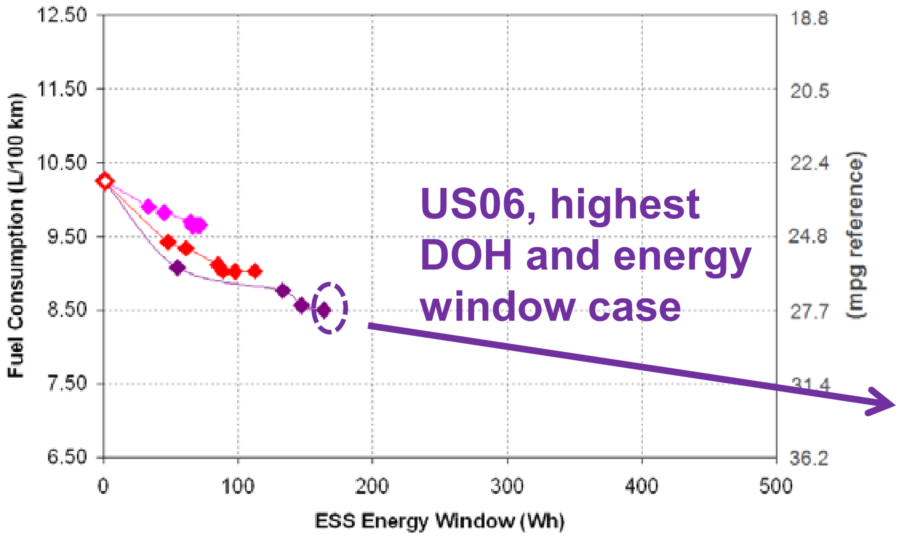
Quantifying pulse characteristics - 2

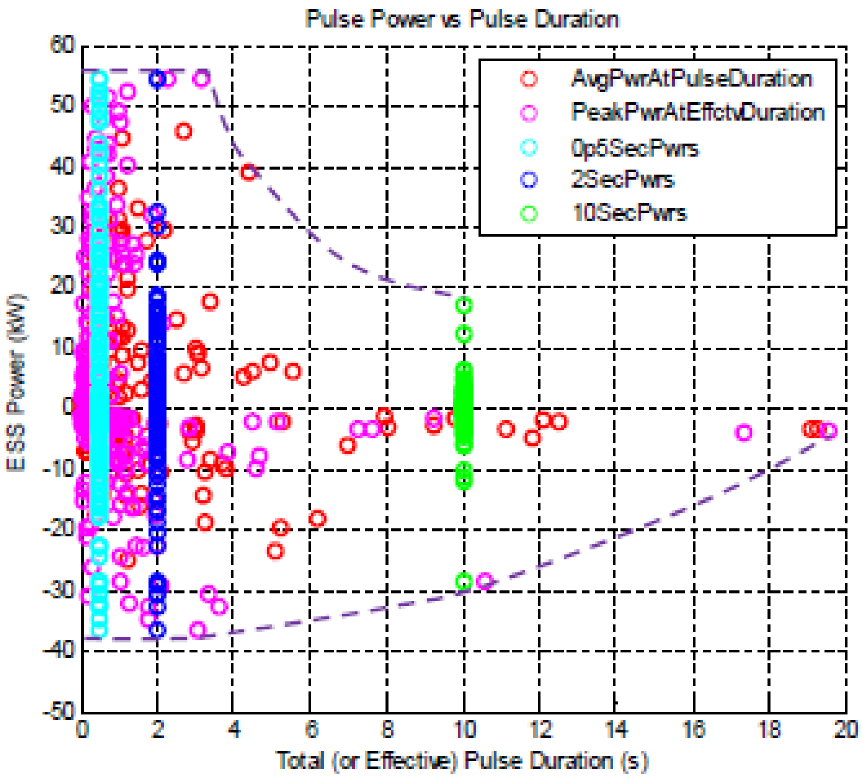


Quantifying pulse characteristics - 3



Example results from power pulse analysis



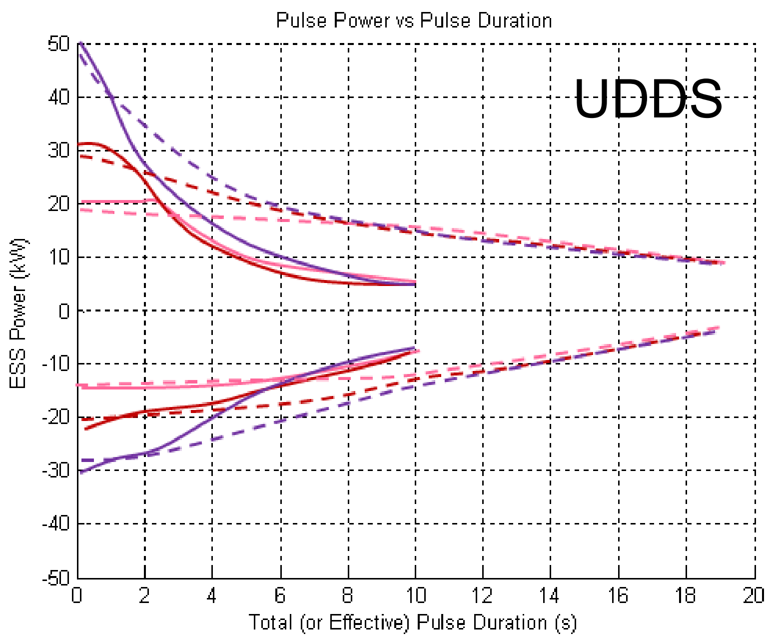


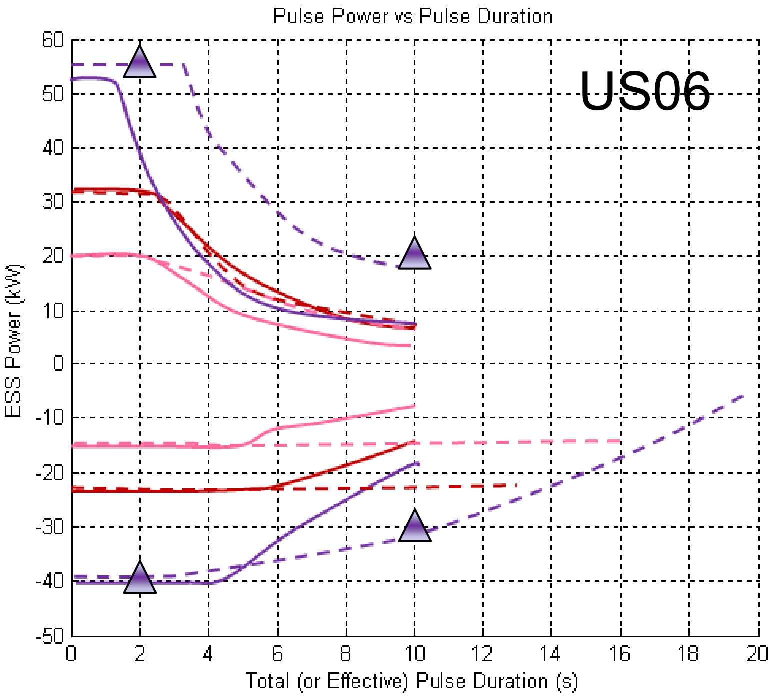
- Bound observations for in-use power pulses
  - Max discharge
  - Max charge/regen

Summarized pulse power bounds for multiple cases

<u>Each DOH configuration</u>
DOH = 10%
DOH = 19%
DOH = 38%

<u>Two in-use energy window cases</u>
Smallest energy: ————————
Largest energy: - - - - - - - - -

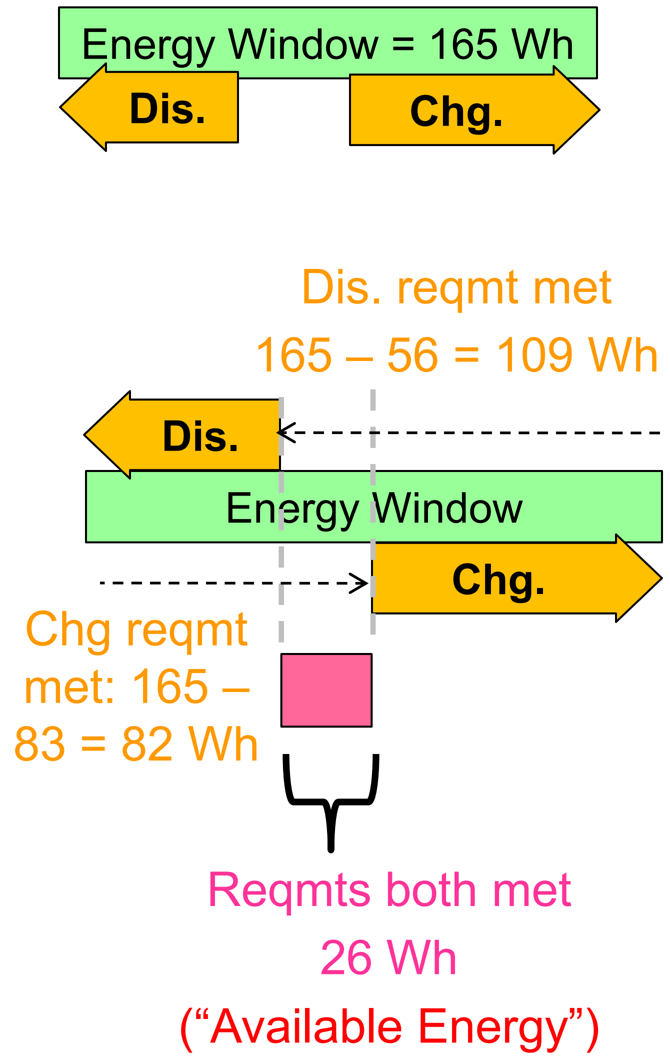




- EES TT Workgroup: Use 2 sec and 10 sec values from highest ESS power and energy case on US06 as basis for power goals

Proposed method to obtain value for battery testing from an "energy window for vehicle use"

1) Begin with the stated **"energy window for vehicle use"** (e.g., 165 Wh)
2) Calculate **energy for pulse requirements**
   a) Discharge (e.g., 10 sec x 20 kW → 56 Wh)
   b) Charge (e.g., 10 sec x 30 kW → 83 Wh)
3) Subtract pulse energy from ends of vehicle use energy (e.g., 165 Wh – 83 Wh – 56 Wh = **26 Wh**)
4) This gives **"available energy over which pulse power requirements must be met"** (e.g., perform size factor analysis with ≥ 26 Wh bounded by 10 s power requirements)
5) Repeat if needed for other pulse power levels (e.g., if energy from 2 sec power requirements happens to be greater than that from the 10 sec power requirements)
6) Note: restrict "energy over which pulse power requirements must be met" to ≥ 0



Comparing New Proposed Lower Energy ESS requirements with other existing requirements

Proposed requirements

End of Life Characteristics	Unit	FSS (42V Start-Stop) Reference UC	PA (Lower Energy) New	PA - Minimum Reference Battery
2 sec Discharge / Regen Pulse Power	kW	6 (Dis) / NA (Rgn)	55 (Dis) / 40 (Rgn)	NA
10 sec Discharge / Regen Pulse Power	kW	NA	20 (Dis) / 30 (Rgn)	25 (Dis) / 20 (Rgn)
Energy from pulse requirements	Wh	3	56 / 83	69 / 56
Energy over which requirements both met	Wh	30	26	300
Energy window for vehicle use	Wh	33	165	425
Energy Efficiency	%	95	95	90
Cycle-life	Cycles	750,000 (UC)	300,000 (HEV)	300,000 (HEV)
Cold-Cranking Power at -30°C (after 30-day stand at +30°C)	kW	8/21V_{min}	5	5
Calendar-life, Years	Years	15	15	15
Maximum System Weight	kg	10	20	40
Maximum System Volume	Liter	8	16	32
Selling Price/System @ 100k/yr)	$	80	400	500
Maximum Operating Voltage	Vdc	48	≤ 400	≤ 400
Minimum Operating Voltage	Vdc	27	$\geq 0.55\ V_{max}$	$\geq 0.55\ V_{max}$
Operating Temperature Range	°C	-30 to +52	-30 to +52	-30 to +52
Survival Temperature Range	°C	-46 to +66	-46 to +66	-46 to +66

Previous USABC requirements

From Analysis to New Requirements

- New set of targets/goals established for PA-HEVs
  - Selected by EES TT and USABC
  - Based on the analysis and discussions of the Workgroup
  - Referred to as lower-energy energy storage system (LEESS) goals
- USABC announces a Request for Proposal Information (RFPI)
  - Asking for proposals for technologies meeting the LEESS requirements
  - Systems satisfying the requirements could be based on batteries, symmetric or asymmetric capacitors, or some other device
  - http://evworld.com/news.cfm?newsid=22459
  - http://www.uscar.org/guest/article_view.php?articles_id=87

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- Clarified energy definition
  - "Available" energy where power requirements simultaneously met, vs.
  - Energy window for vehicle use
- USABC/EES TT established new set of ESS targets and an RFPI
  - With goal of reducing cost for fuel-saving HEV systems
  - Open to any ESS technology (batteries, ultracapacitors, hybrid battery-ultracapacitors)

Acknowledgments

- Funded by DOE Energy Storage Program Manager
  - David Howell, Office of Energy Efficiency and Renewable Energy, Vehicle Technologies Program

- Direction provided by USABC Managing Committee

- Technical discussions with Workgroup of FreedomCAR Electrochemical Energy Storage Technical Team
  - H. Tataria; R. Elder; C. Ashtiani; J. Belt; V. Bataglia;
  - C. Bae; R. Spotnitz; K. Snyder; J. Deppe