

Battery Choices for Different Plug-in HEV Configurations

Plug-in HEV Forum and Technical Roundtable

South Coast Air Quality Management District

Diamond Bar, CA

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National Renewable Energy Laboratory

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FreedomCAR and Vehicle Technologies Program
Office of Energy Efficiency and Renewable Energy
U.S. Department of Energy

NREL's Plug-in HEV R&D Activities

- Battery Level
 - R&D support to developers
 - Testing and evaluation – Sprinter PHEV testing
 - Thermal characterization and design
 - Supporting requirement analysis and development
- Vehicle Level
 - Real-world PHEV simulations - fuel economy and recharging
 - Support development of test procedures for PHEVs and MPG reporting
 - Evaluation of alternative PHEV design strategies
 - » all-electric vs. blended operation
 - PHEV design cost-benefit analysis
- Utility Level
 - Assessment of PHEV impacts on utilities
 - Exploring synergies between PHEVs and wind power
 - V2G opportunities for PHEVs in regulation services
- National Level
 - Benefits assessment - oil use and emissions
 - Renewable community – linking PHEV to renewable
- Analysis support to DOE, OEMs, and others
 - Working to identify and overcome barriers to PHEV adoption



Secretary of Energy visiting NREL on 7/7/06 for ribbon cutting of the new S&T Facility and then discussing plug-in hybrids with EnergyCS & Hymotion

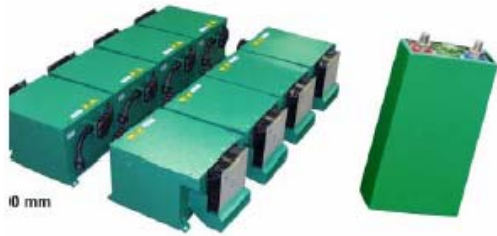
Topics of the Presentation

- Battery Technologies for PHEVs
 - State-of-the-art
 - Advances
- Impact of Vehicle Attributes on Battery
 - EV Range
 - System Architecture
 - Driving cycles and profiles
- Concluding Remarks and a Few Thoughts

Key Messages

- There is a broad spectrum of HEV-PHEV designs leading to different battery requirements.
- Batteries are available that could meet the energy and power demands for PHEVs, but cost and limited cycle/calendar life are major barriers for affordable PHEV introduction.
 - NiMH could do the job
 - Li-ion are potentially best candidates
 - All Li-ions are not “created equal”
- There are emission benefits with PHEVs, but the difference between pure EV range and blended EV range impacts may need to be understood
- PHEVs are the most cost-effective choice in a scenario of projected (low) battery costs and high fuel costs.

Batteries in Current PHEVs



Varta

NiMH

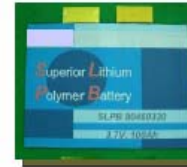


Electro Energy Inc.



Johnson Controls/SAFT

**Co/Ni based
Li-Ion**



Kokam



Valence Technology



**Iron phosphate
based Li-Ion**



A123 Systems

High Power Battery and Ultracapacitor Characteristics for Hybrid Vehicles

Parameter	VRLA	NiMH	Li Ion	Ultracap
Cell configuration	Parallel plates; spirally wound cylindrical	Spirally wound cylindrical; parallel plates	Spirally wound cylindrical & elliptic	Spirally wound cylindrical & elliptic
Nominal cell voltage (V)	2	1.2	3.6	1.8
Battery electrolyte	Acid	Alkaline	Organic	Organic
Specific energy, Wh/kg	25	40	60 to 80	5
Battery/Module specific power, 10 sec, W/kg				
23°C, 50% SOC	400	1300	3000	>3000
-20°C, 50% SOC	250	250	400	>500
Charge acceptance, 10 sec. W/kg				
23°C, 50% SOC	200	1200	2000	>3000
2010 Projected Cost >100,000 per year				
\$/kWh, Module	100.00	500.00	700.00	20,000.00
\$/kWh, Full pack	140	600	1100	25000
\$/kW, pack	9.00	18.00	22.00	40.00
Energy efficiency	Good	Moderate	Good	Very Good
Thermal managements requirements	Moderate	High	Moderate	Light
Electrical control	Light	Light	Tight	Tight

Qualitative Comparison of Large-Format Battery Technologies for PHEVs

Attribute	Lead Acid	NiMH	Li-Ion
Weight (kg)	Poor	Fair	Good
Volume (lit)	Poor	Good	Good
Capacity/Energy (kWh)	Poor	Fair	Good
Discharge Power (kW)	Good	Fair	Good
Regen Power (kW)	Poor	Fair	Good
Cold-Temperature (kWh & kW)	Good	Fair	Poor
Shallow Cycle Life (number)	Fair	Good	Good
Deep Cycle Life (number)	Poor	Good	Fair
Calendar Life (years)	Poor	Fair	Fair
Cost (\$/kW or \$/kWh)	Good	Poor	Poor
Safety- Abuse Tolerance	Good	Good	Fair
Maturity - Technology	Good	Good	Fair
Maturity - Manufacturing	Good	Fair	Poor

Key
(relative to
each other)

Poor

Fair

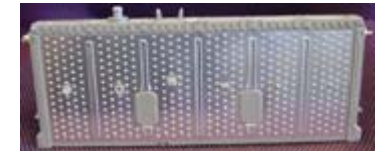
Good

NiMH has Matured in Power and Energy

Specific energy ranging from 45 Wh/kg to 80 Wh/kg depending on the power capability.



● Ovonic

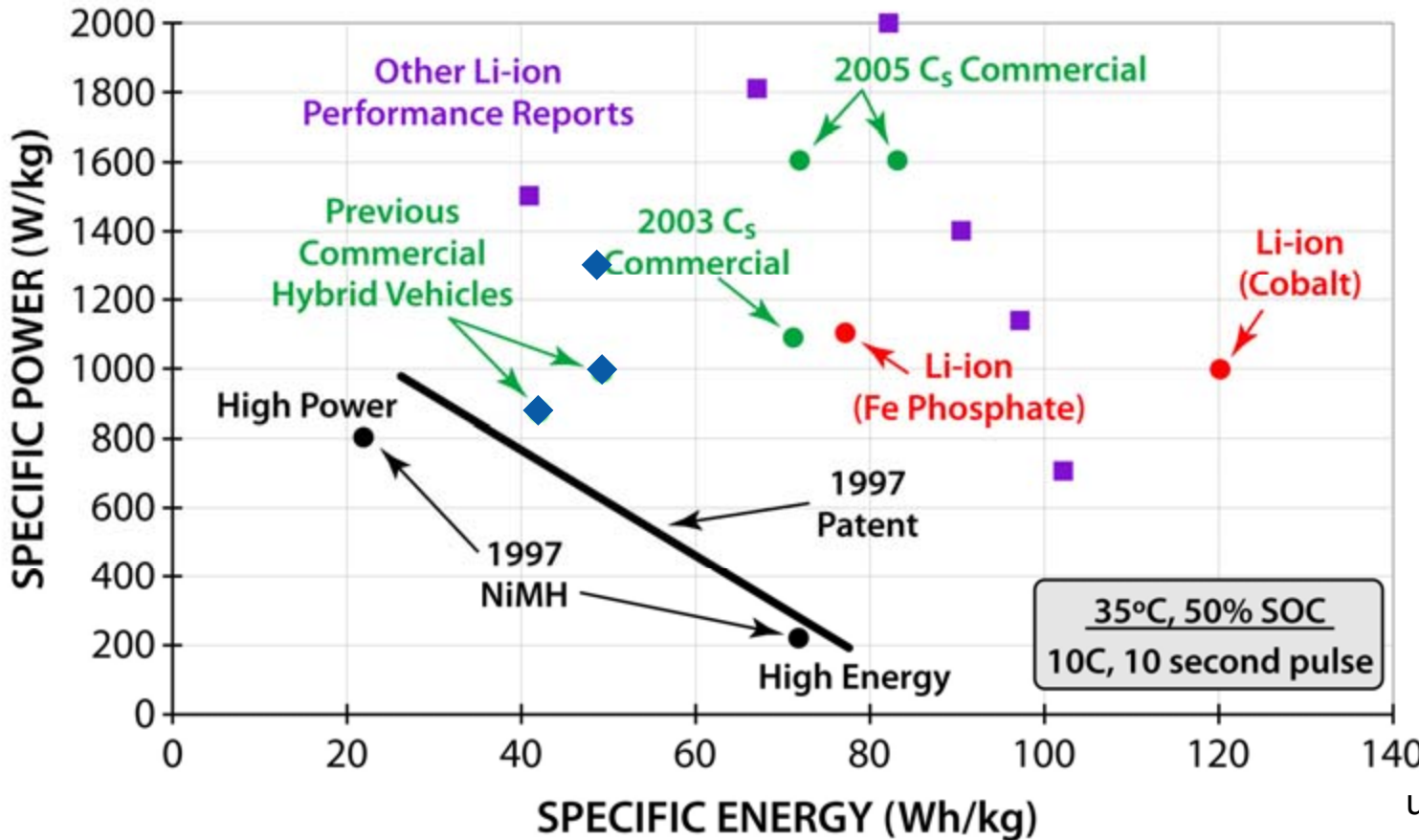


◆ Panasonic EV

EV-95



95 Ah EV module used in Toyota RAV 4



Source: Reproduced from A. Fetcenko (Ovonic Battery Company) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

NiMH batteries are forecasted to dominate the HEV market for a while

Panasonic



6.5 Ah Battery for Toyota

Sanyo



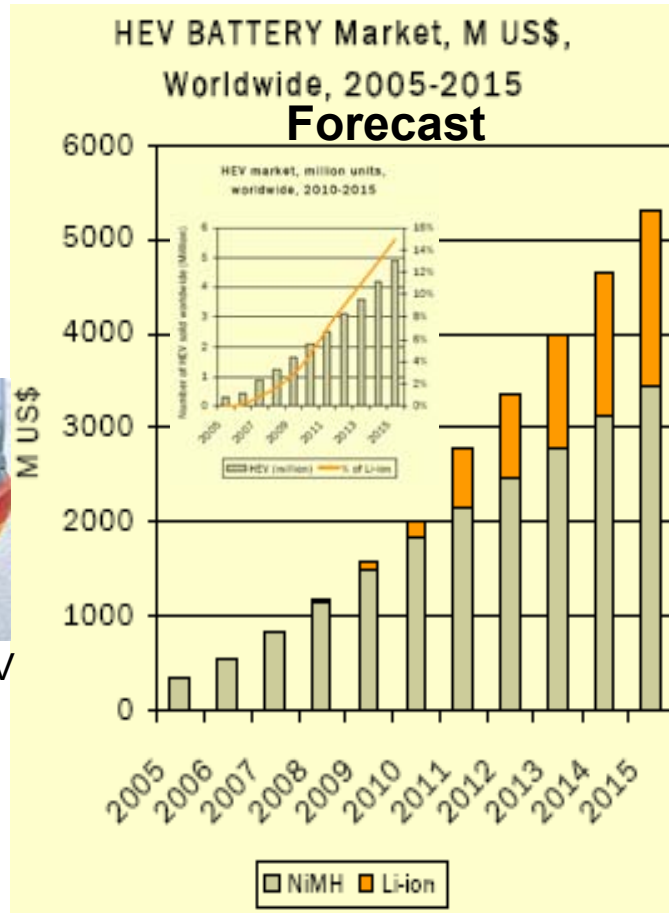
6.5 Ah HEV cells in Ford Escape HEV

Source: Sanyo website news

Cobasys



EV module (left) and 42V HEV batteries



Source: C. Pillot (Avicenne) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

Electro Energy



Pack with bipolar Cells/Modules

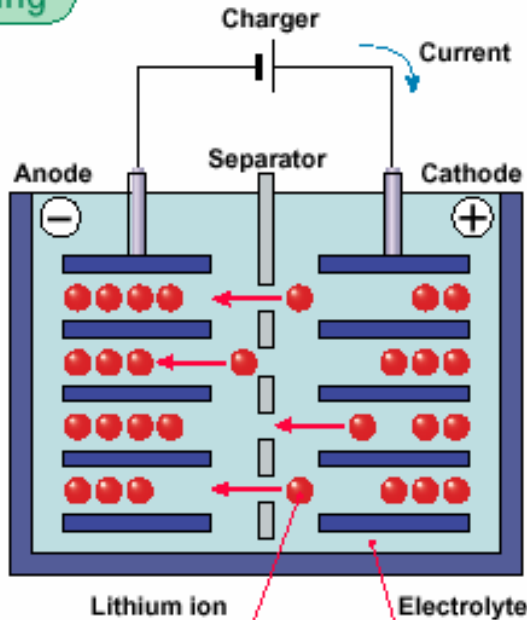


Bipolar pack in a Plug-In Prius

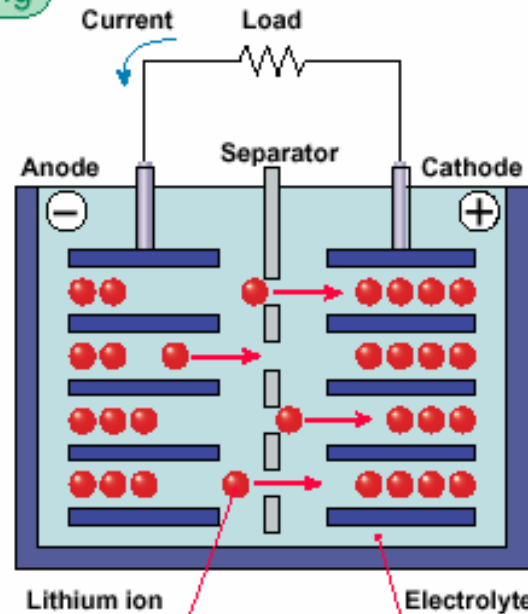
Source: Images provided by James Landi of Electro Energy Inc.

Li Ion Technology – Diverse Chemistry & Opportunity

Charging



Discharging



Voltage ~3.2-3.8 V
 Cycle life ~1000-3000
 Wh/kg >150
 Wh/l >400
 Discharge -30 to 60°C
 Shelf life <10%/year

Many anodes are possible

Carbon/Graphite
 Titanate ($\text{Li}_4\text{Ti}_5\text{O}_{12}$)
 Titanium oxide based
 Thin Oxide based
 Tungsten oxide

Many electrolytes are possible

LiPF_6 based
 LiBF_4 based
 Various solid electrolytes
 Polymer electrolytes

Many cathodes are possible

Cobalt oxide
 Manganese oxide
 Mixed oxides with Nickel
 Iron phosphate
 Vanadium oxide based

Source: Robert M. Spotnitz, Battery Design LLC, "Advanced EV and HEV Batteries," 2005 IEEE Vehicle Power and

11 Propulsion Conference, September 7-9, 2005, IIT, Chicago, IL

Characteristics of Cathode Materials

Theoretical values for a battery system relative to graphite anode and LiPF₆ electrolyte

Material	Δx	mAh/g	avg V	Wh/kg	Wh/l
LiCoO ₂	0.55	151	4.00	602	3073
LiNi _{0.8} Co _{0.15} Al _{0.05} O ₂	0.7	195	3.80	742	3784
LiMn ₂ O ₄	0.8	119	4.05	480	2065
LiMn _{1/3} Co _{1/3} Ni _{1/3} O ₂	0.55	153	3.85	588	2912
LiFePO ₄ *	0.95	161	3.40	549	1976

*Typically diluted with 10% carbon for electronic conductivity

Lower potential can provide greater stability in electrolyte

Cobalt oxide most widely used in consumer cells but recently too expensive

LiMn_{1/3}Co_{1/3}Ni_{1/3}O₂ newer than LiNiCoO₂

Mn₂O₄ around for many years – not competitive for consumer – good for high power

LiFePO₄ – very new – too low energy density for consumer electronics

- safe on overcharge but need electronics to prevent low voltage

- may require larger number of cells due to lower voltage

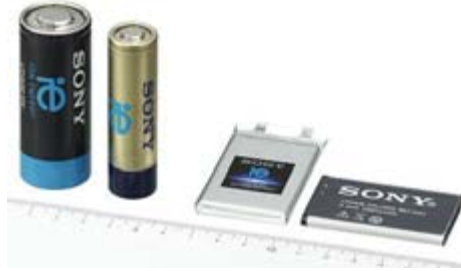
Nano-materials in Li-Ion Batteries Improve Performance & Life

- Easier diffusion of Li-ion into and out of the host
 - High specific capacity at high rate
- Increased electrode surface area and thus higher rates
- Stable 3 dimensional host materials
- Small dimensional change as Li-ions are cycled in and out
 - Improved cycling life due to less structural change
 - Low irreversible capacity loss
- Exhibit of both faradaic and non-faradaic capacity
 - Higher capacity retention
- Enabling new materials

Source: Expects A. Singhal (NEI Corporation) and E. House (Altair Nanotechnologies) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

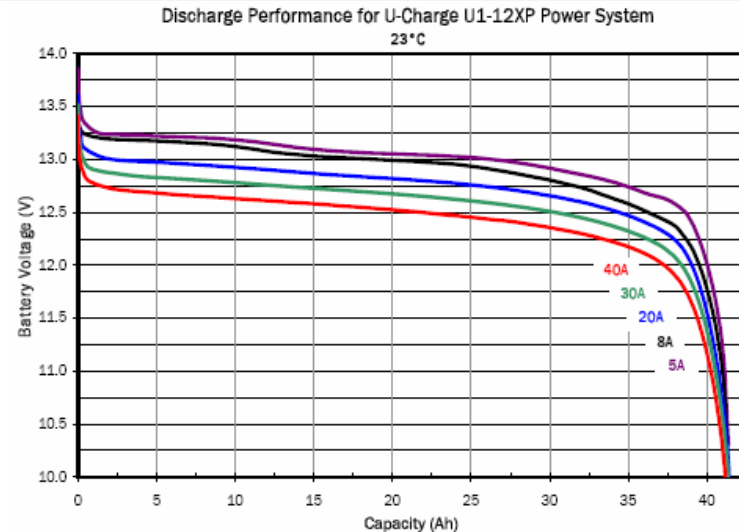
Many Oxide Based Li-Ion Batteries are Available

- Johnson Control
- Saft
- LG Chem
- Kokam
- Sony
- Sanyo
- Samsung
- Panasonic
- Electrovaya
- NEC Lamilion Energy
- Nissan
- Lishen
- Pionics
- SK Corp
- GS Yuasa
- Altair Nanotechnologies



Lithium Iron Phosphate (LiFePO_4) Cathodes

- + High stability and non-toxic
 - + Good specific capacity
 - + Flat voltage profile
 - + Cost effective (less expensive cathode)
 - + Improved safety
 - Lower voltage than other cathodes
 - Poor Li diffusion ($D_{\text{Li}} \sim 10^{-13} \text{ cm}^2/\text{Sec}$)
 - Poor electronic conductivity ($\sim 10^{-8} \text{ S/cm}$)
- Approach many use to overcome poor characteristics
 - Use nano LiFePO_4 – carbon composite
 - Use larger number of cells
 - Nano structured materials



Source: On line brochures from Valence Technology, <http://www.valence.com/ucharge.asp>

Source: Various papers from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

Improvements in Iron Phosphate Li-Ion Batteries

Valence Technology 18650 Cells

100 Wh/kg in cell 84 Wh/kg in U Charge module



The battery with standard lead acid battery form factor includes a battery management system.

Specifications		U1-12XP	U24-12XP
Voltage		12.8 V	12.8 V
Capacity (C/5)		40 Ah	100 Ah
Specific energy		84 Wh/kg	82 Wh/kg
Energy density		110 Wh/l	126 Wh/l
Standard Discharge	Max. cont. current	80 A	150 A
	Max. 30 sec. pulse	120 A	300 A
	Cut-off voltage	10 V	10 V

Source: On line brochures from Valence Technology, <http://www.valence.com/ucharge.asp>

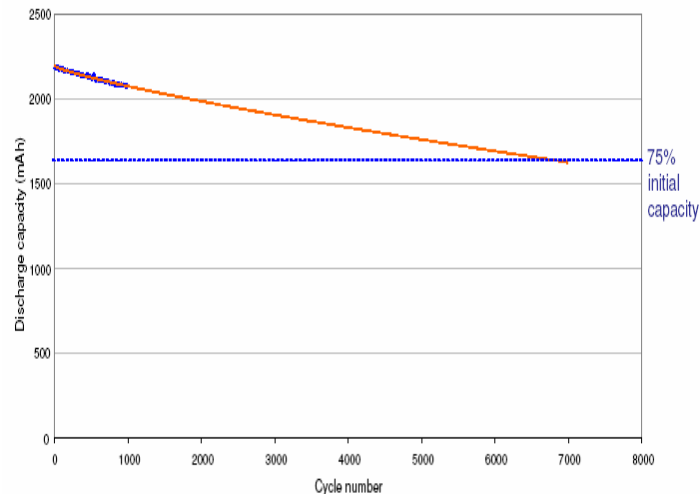
Power Density (<3Ah cy cells)	Weight to discharge @1500W	Safety	Life at 100% DoD 1C rate	Environmental
3600 W/Kg	0.9 lbs	✓	~7000	✓

Based on: Novel nano scale doped phosphate active materials (pat. pending)
Low impedance cell design and electrolyte (pat. pending)



**A123 Systems
with 26650 Cells
100 Wh/kg**

Source: Andrew Chu (A123 Systems) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

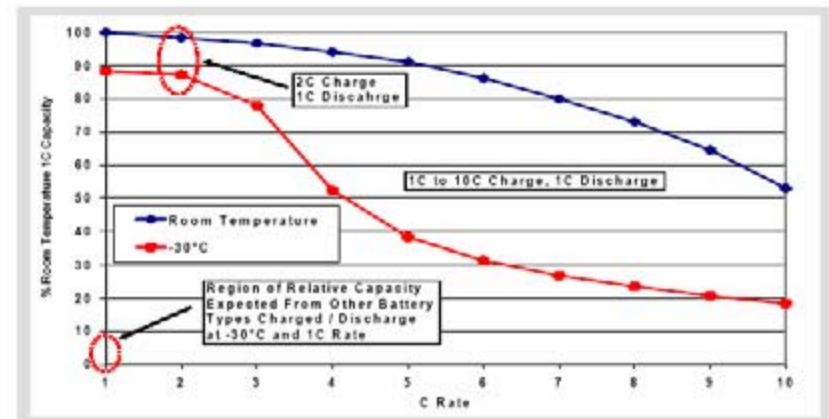


100%DOD 1C charge, 1C discharge cycling data.
Using first 1000 cycles, extrapolated cycle life: ~7000 cycles.

Improving Li-Ion Batteries with Titanate Anode

Characteristic	Traditional Li Ion Batteries	Li Ion Batteries Using Altairnano materials
Electrode Materials		
Anode	Graphite	Lithium titanate spinel
Cathode	Cobaltate	Nano-Structured oxides
Performance		
Charge rate	1/2 C	20 C and greater
Discharge rate	4 C	40 C and greater
Cycle life	300-500 cycles	9,000 cycles (full DOD)
Calendar life	2-3 years	10-15 years

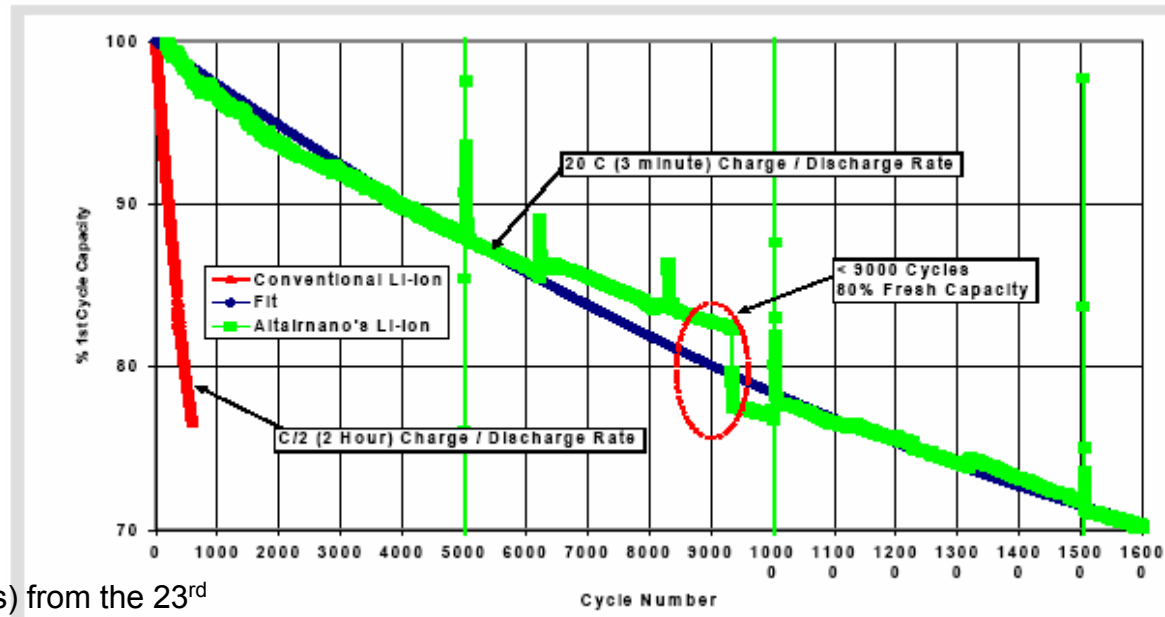
Long Life, POWER Lithium Ion Batteries



~90% SOC of RT Cell at -30°C and 1-2C Charge Rate!

Altaire Nanotechnologies Inc.

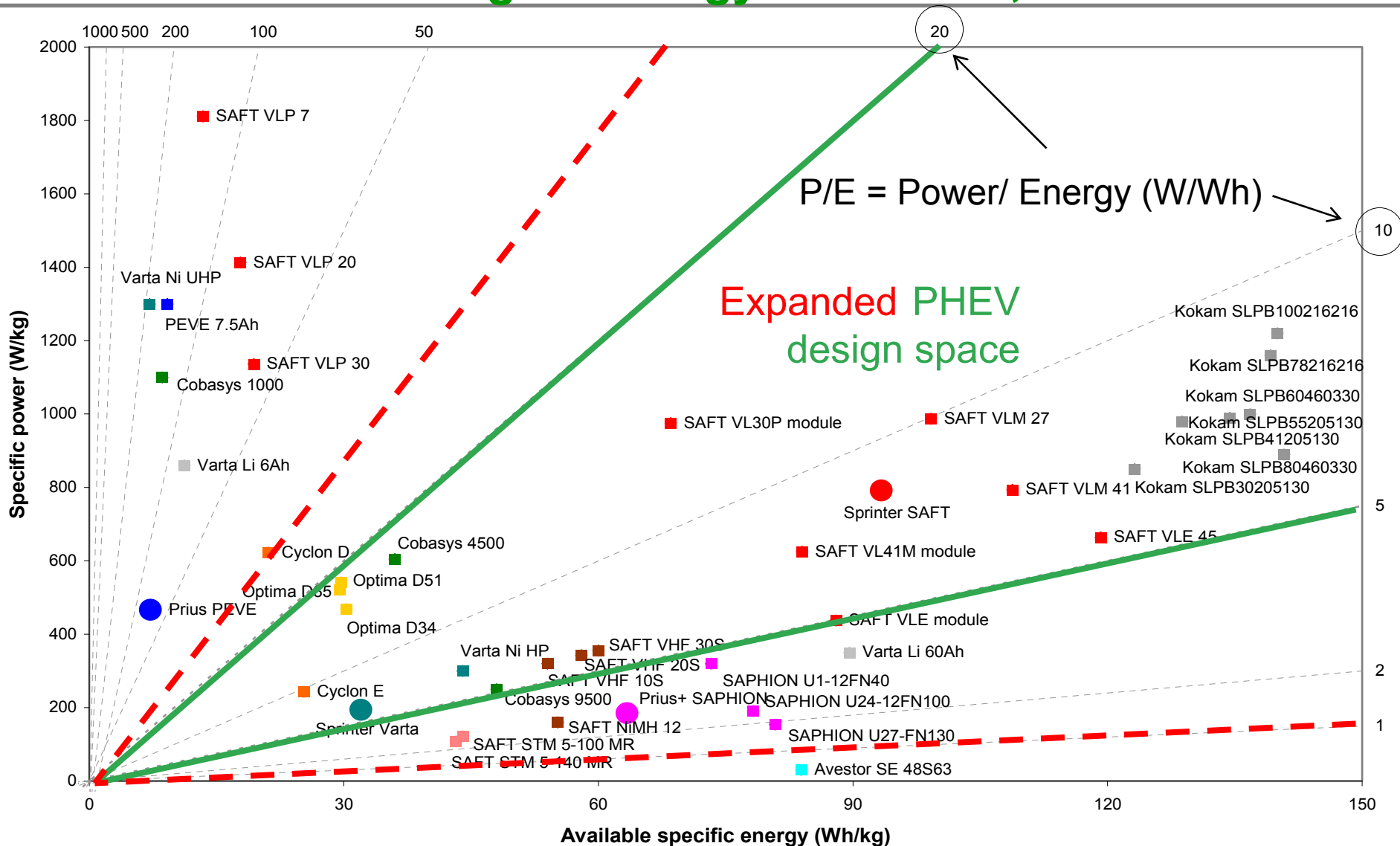
- Improved low temperature performance
- Faster charge acceptance
- Longer cycle life
- 80-100 Wh/kg
- 2000-4000 W/kg



Source: E. House (Altair Nanotechnologies) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

PHEV Battery Options

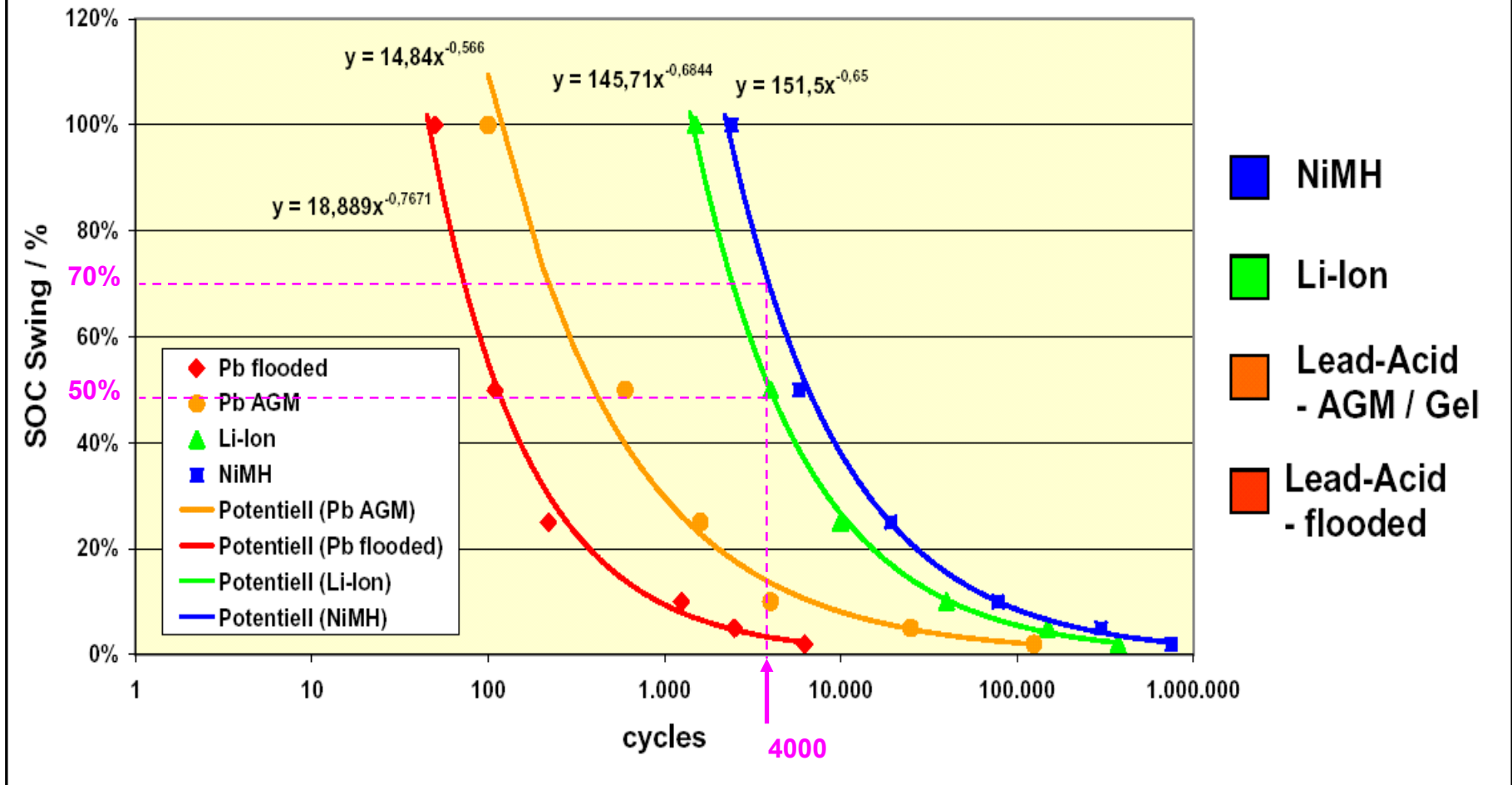
Need for higher energy than HEVs, so P/E lower



Source: Tony Markel and Andrew Simpson, Milestone Report, National Renewable Energy Laboratory, Golden, CO, September 2005.

Battery Cycle Life Depends on State of Charge Swing

- PHEV battery likely to deep-cycle each day driven: 15 yrs equates to 4000-5000 deep cycles
- Also need to consider combination of high and low frequency cycling



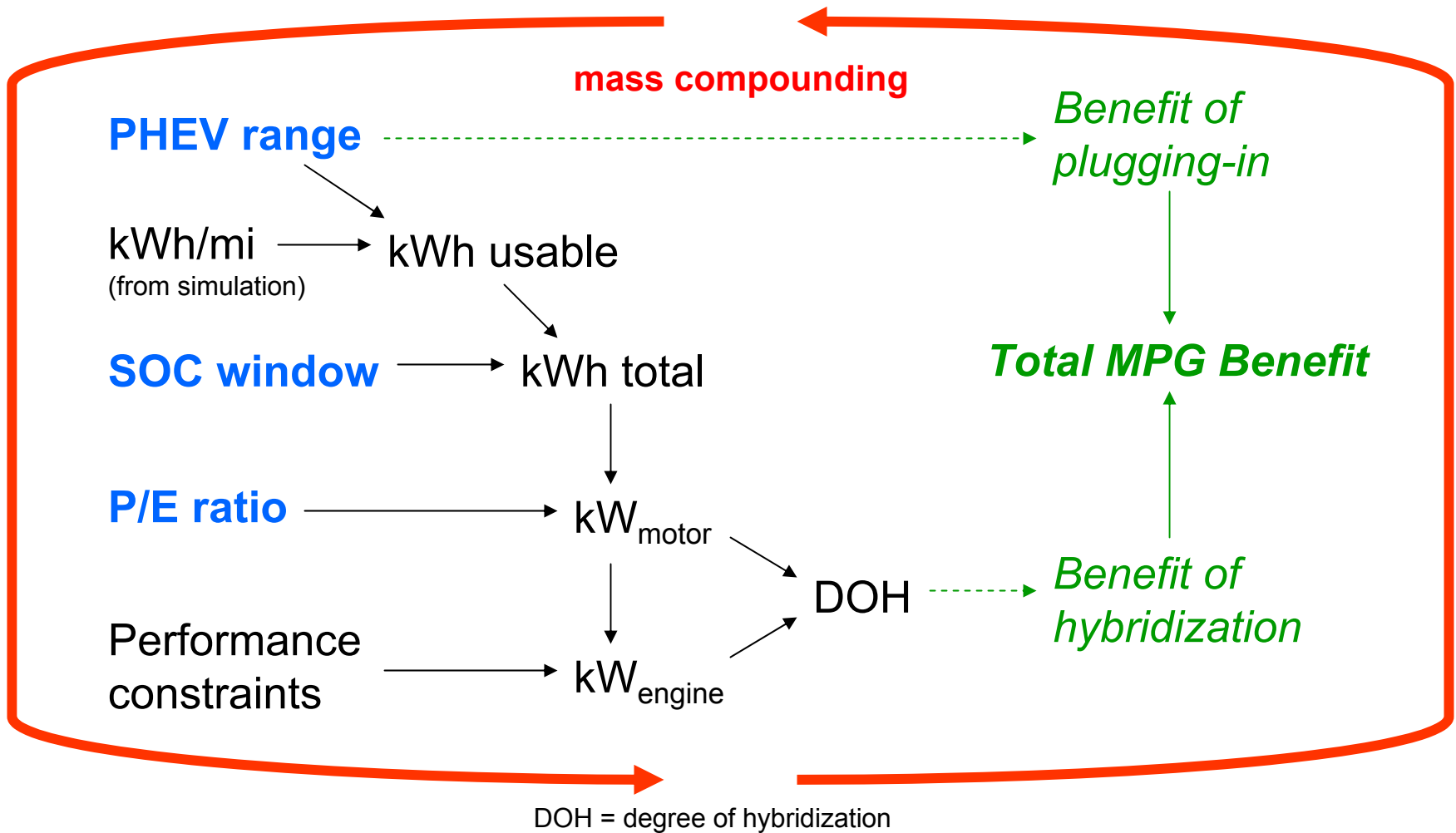
Source: Christian Rosenkranz (Johnson Controls) at EVS 20, Long Beach, CA, November 15-19, 2003

Summary: Exciting Times for Li-Ion Batteries

- New Cathodes
 - Lower cost
 - Higher power
 - Better safety
 - Improved life
- New Anodes
 - Faster charge rate
 - Improved life
- New Electrolyte
 - Improved safety
 - Improved low temperature performance
- New Separator
 - Lower cost
 - Improved safety

Battery Definition as Key Input to Simulation

Input parameters that define the battery in BLUE

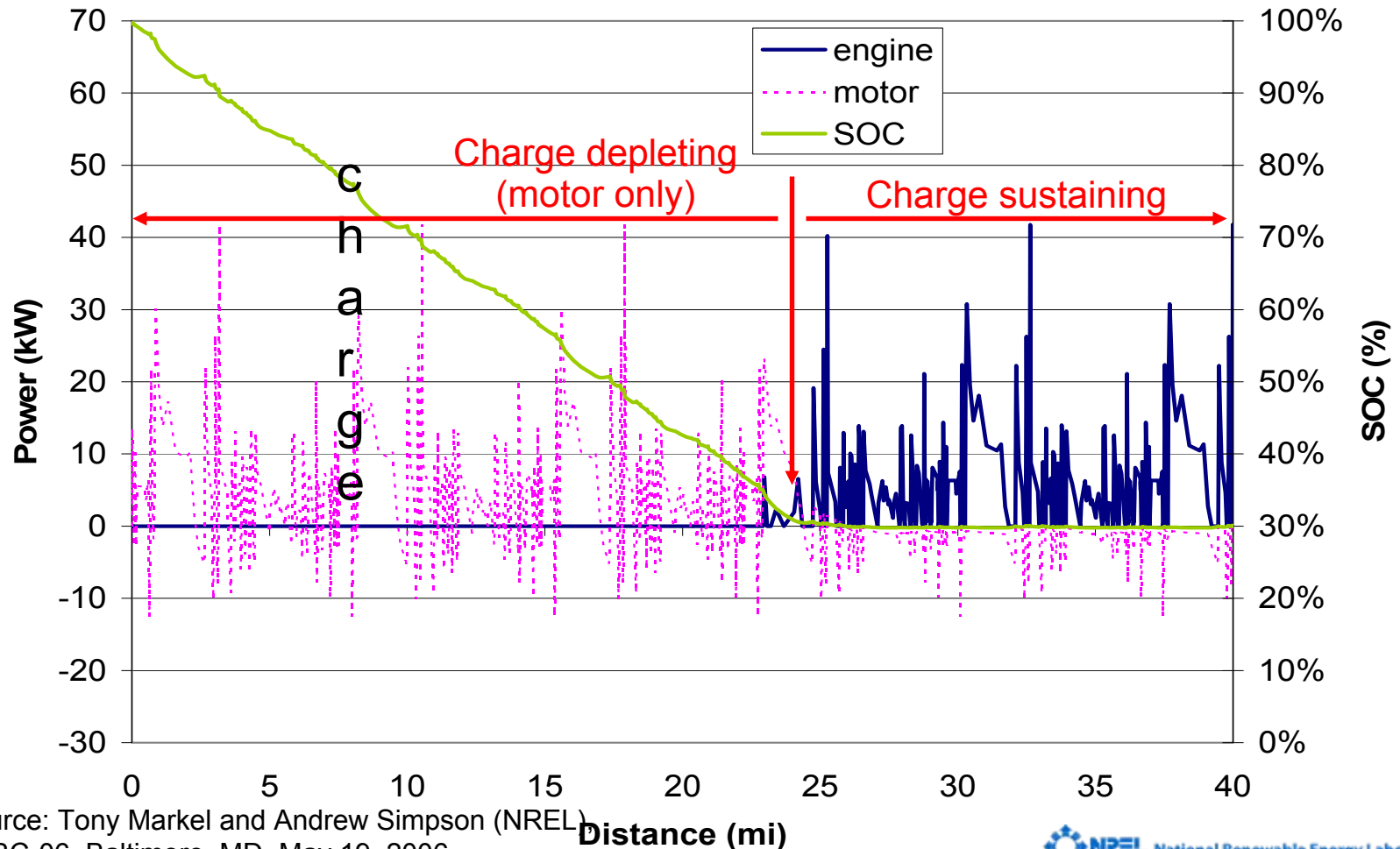


Source: Tony Markel and Andrew Simpson, Milestone Report, National Renewable Energy Laboratory, Golden, CO, September 2005.

Alternative PHEV Design Strategies: All-Electric vs Blended

- Engine turns on when battery reaches low state of charge
- Requires high power battery and motor

All-Electric (Pure EV or ZEV)

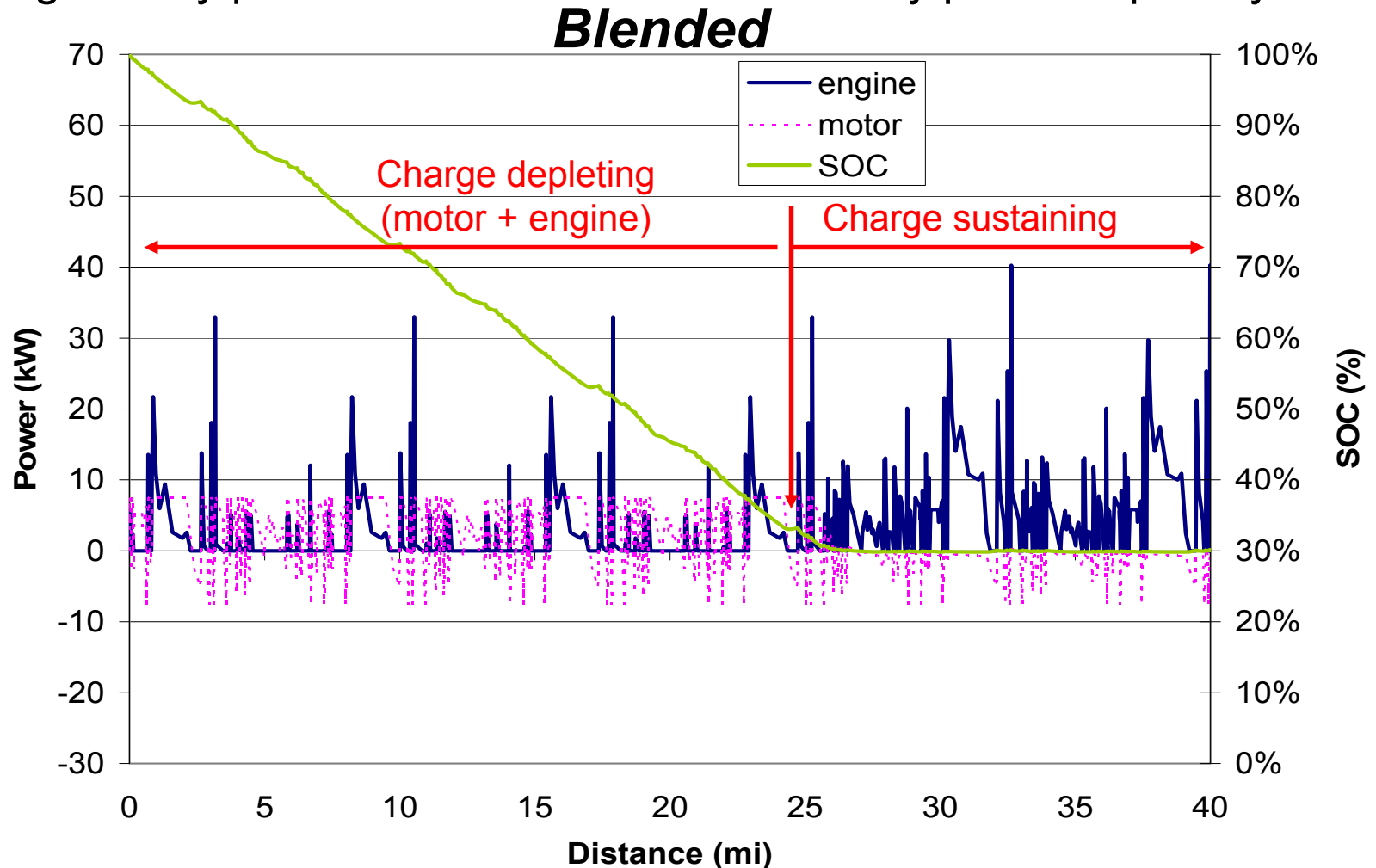


Source: Tony Markel and Andrew Simpson (NREL)

AABC-06, Baltimore, MD, May 19, 2006

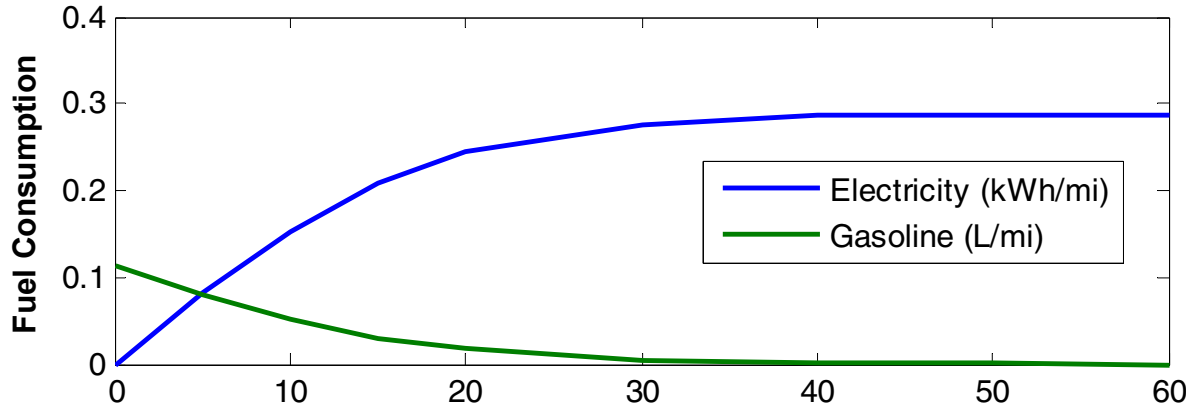
Alternative PHEV Design Strategies: All-Electric vs Blended

- Engine turns on when power exceeds battery power capability
- Engine only provides load that exceeds battery power capability

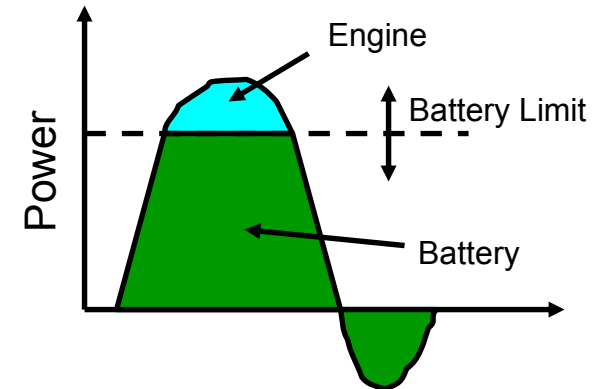
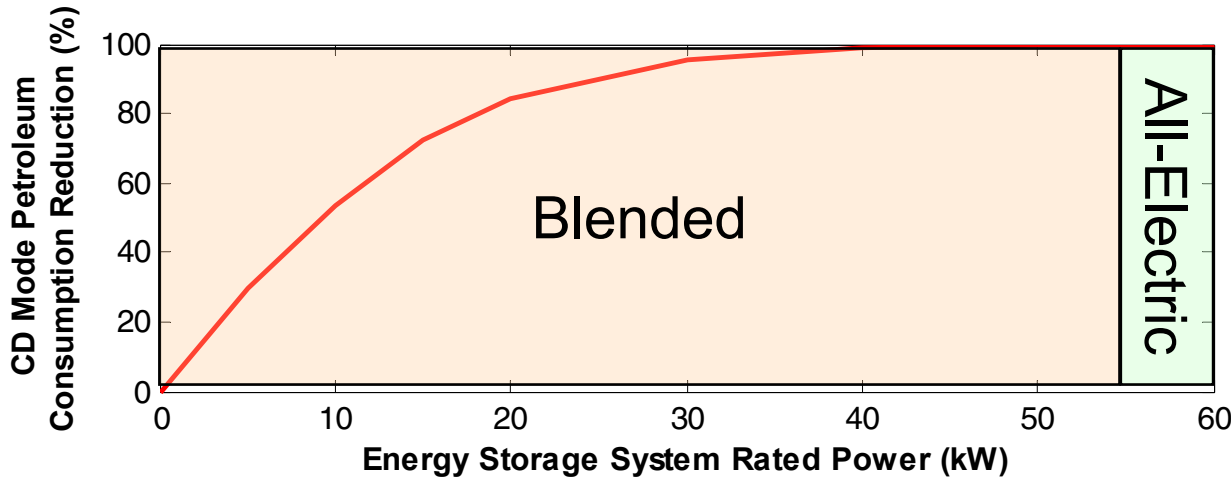


Blended vs. AER Consumption Tradeoff

PHEV20 on LA92



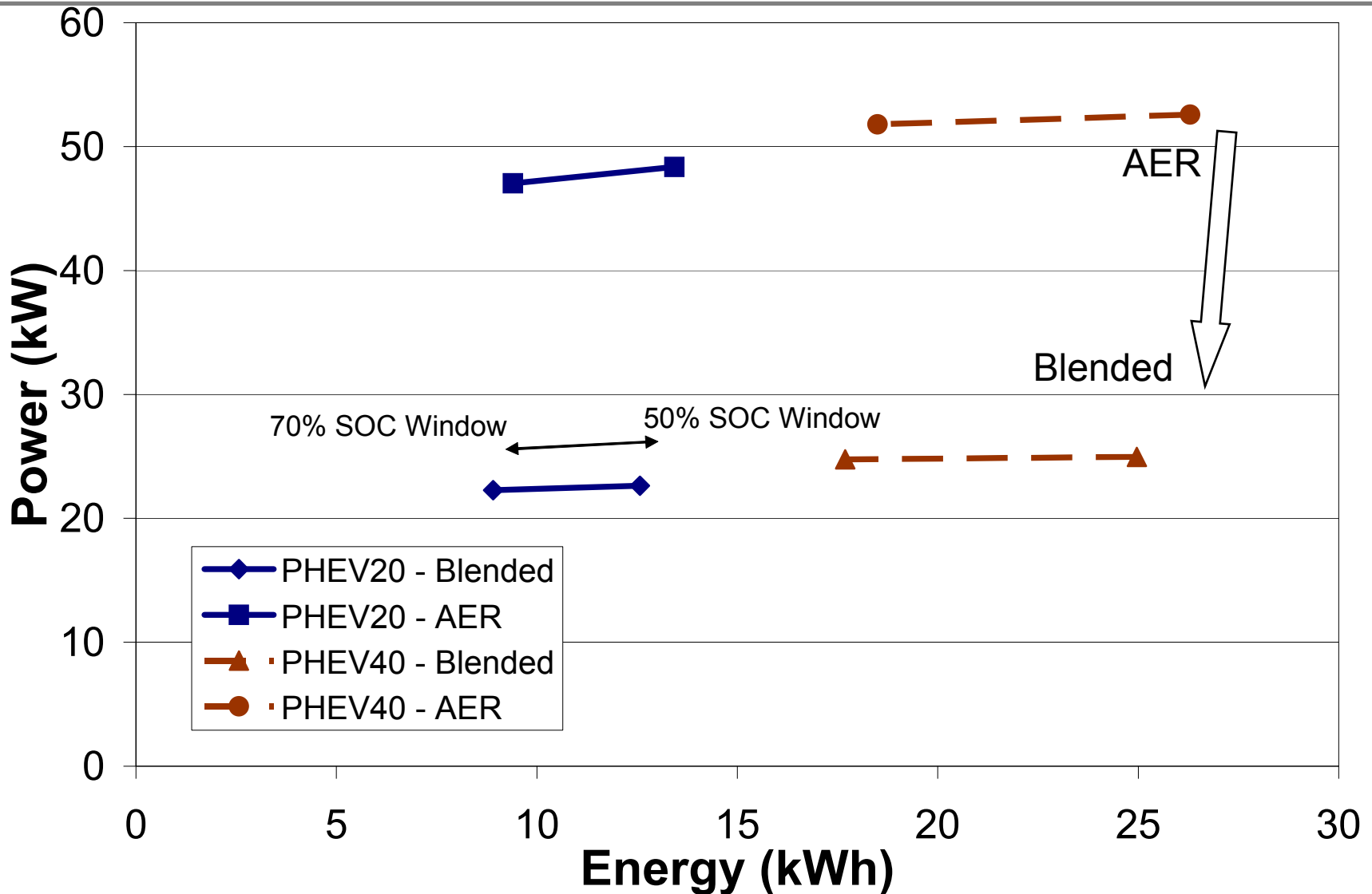
- Reducing ESS power should reduce cost, mass, volume
- 50% reduction in power still provides almost all of the fuel consumption benefit



* CD = Charge Depleting

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006

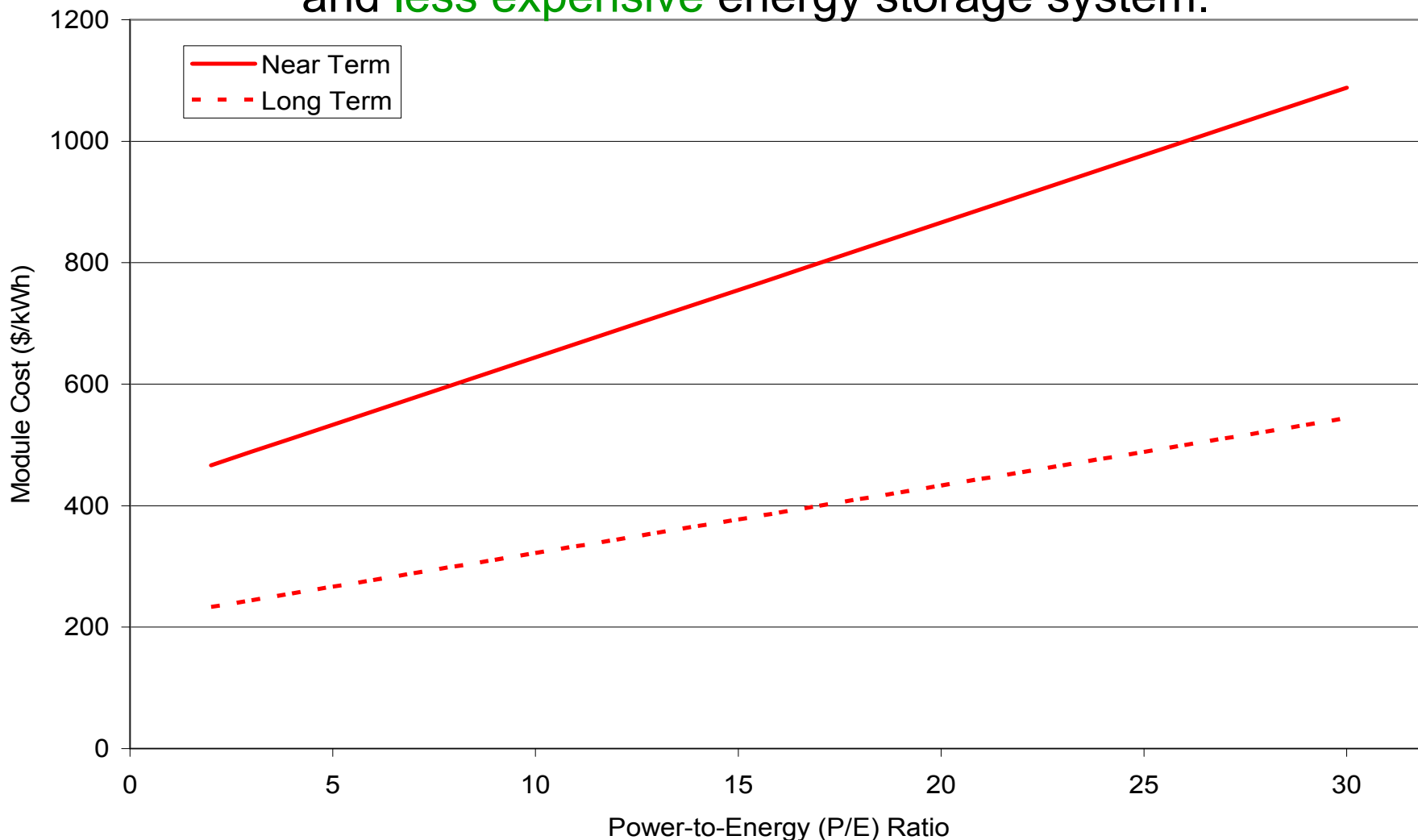
PHEV Battery Sizing Alternatives



Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006

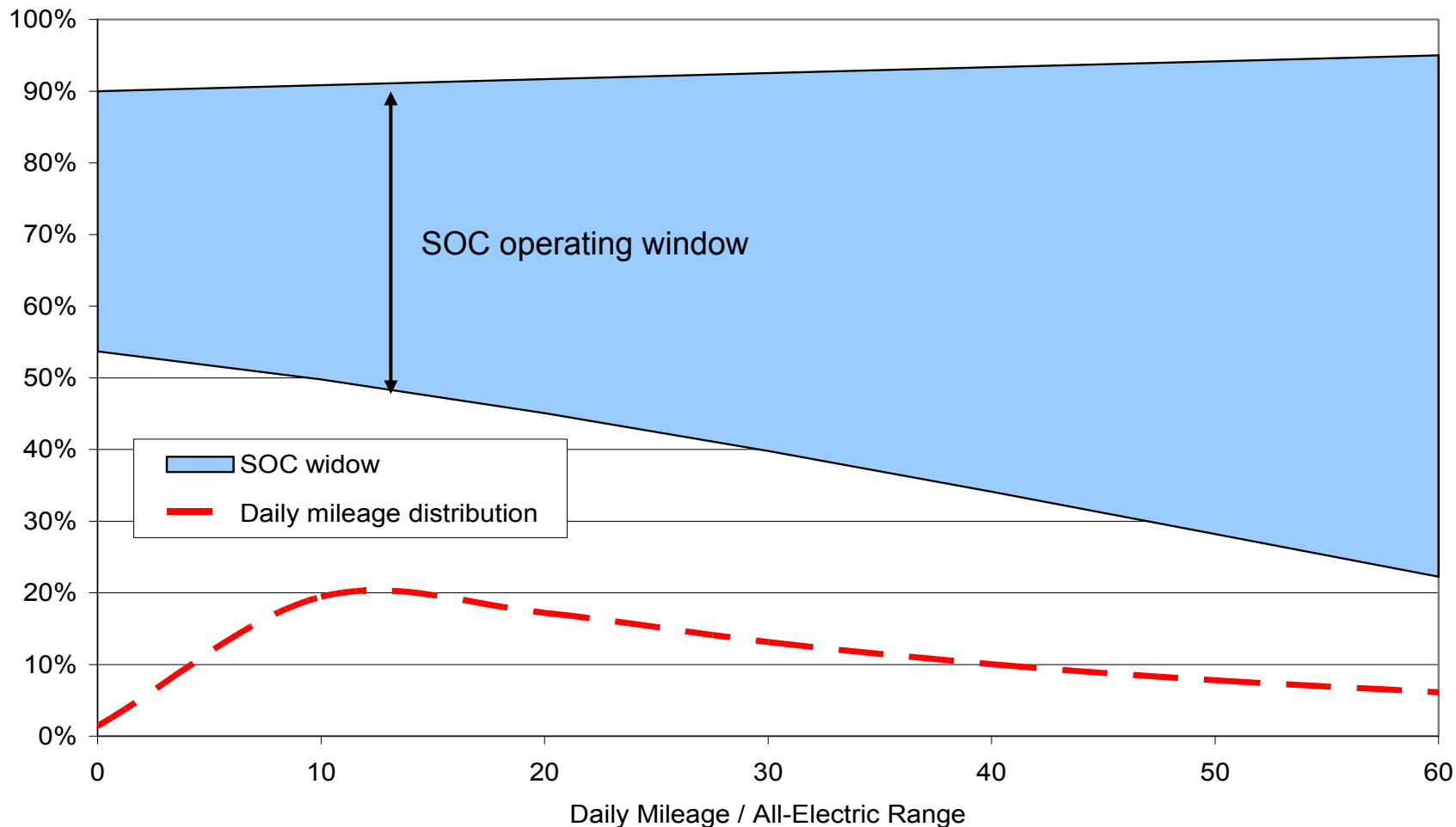
Battery Cost Model based on P/E Ratio

Lower power to energy ratio leads to lighter, smaller, and less expensive energy storage system.



Battery Model (cont.) – SOC Window

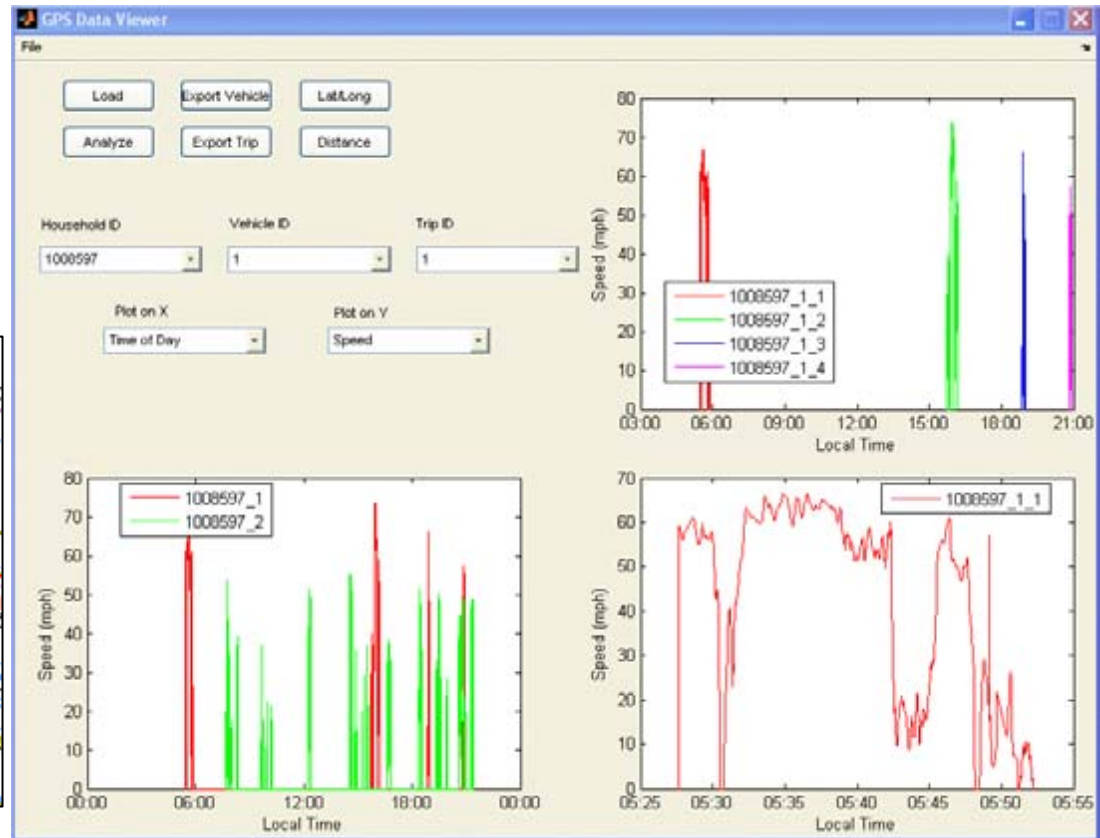
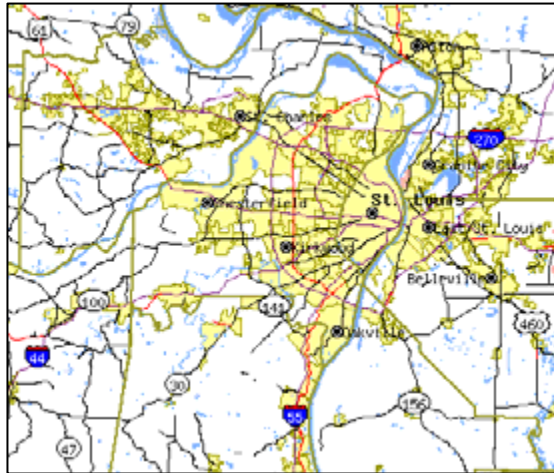
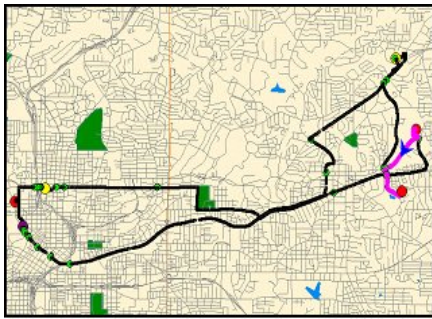
Battery SOC Operating Window vs. Specified All-Electric Range



Source: Andrew Simpson (NREL), Presented to FreedomCAR Vehicle System Analysis Team, March 1 2006

Real Driving Survey Data

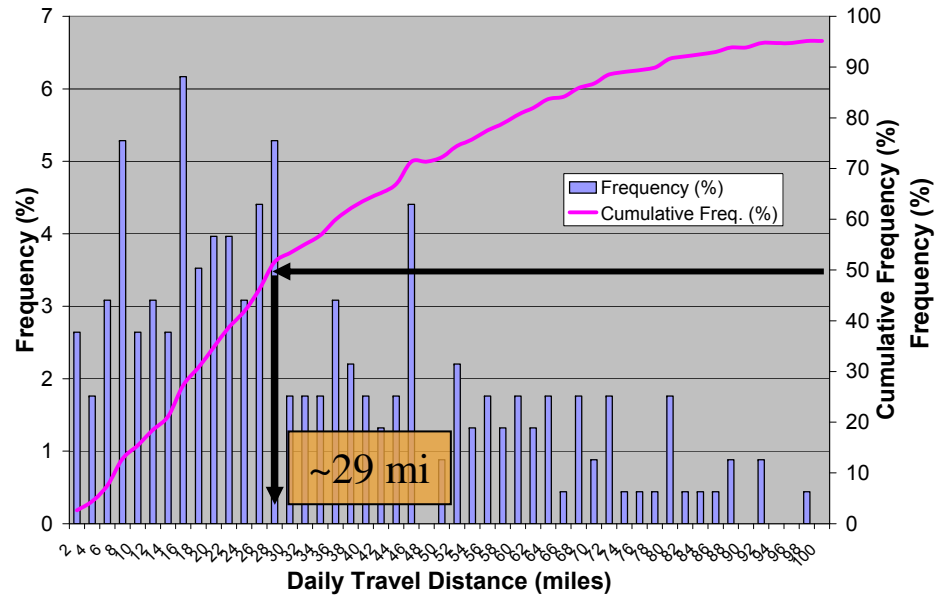
- Provides valuable insight into travel behavior
- GPS augmented surveys supply details needed for vehicle simulation



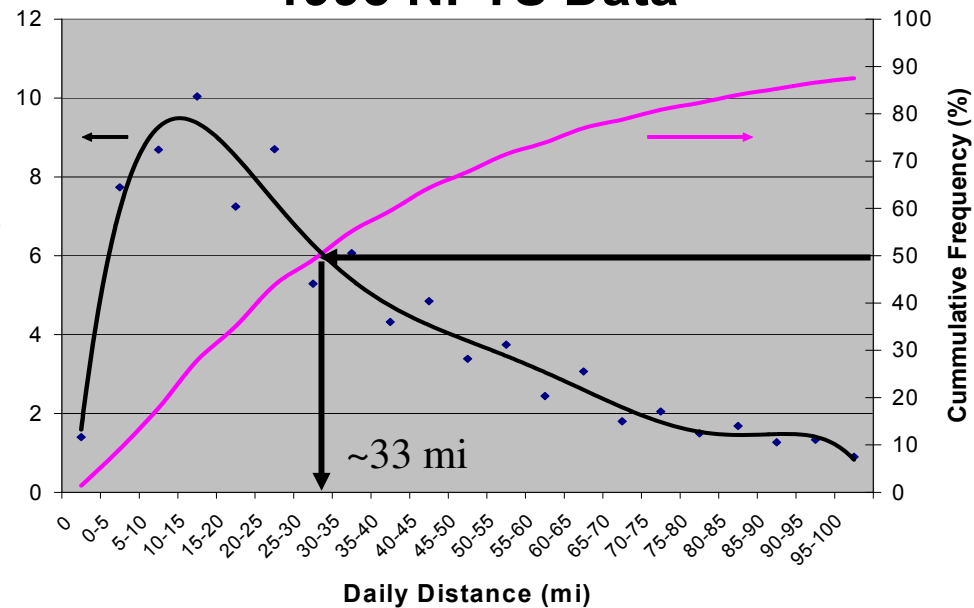
St. Louis Travel Data Analysis

Daily Driving Distance Similar to 1995 NPTS Data

St. Louis HHTS Data



1995 NPTS Data

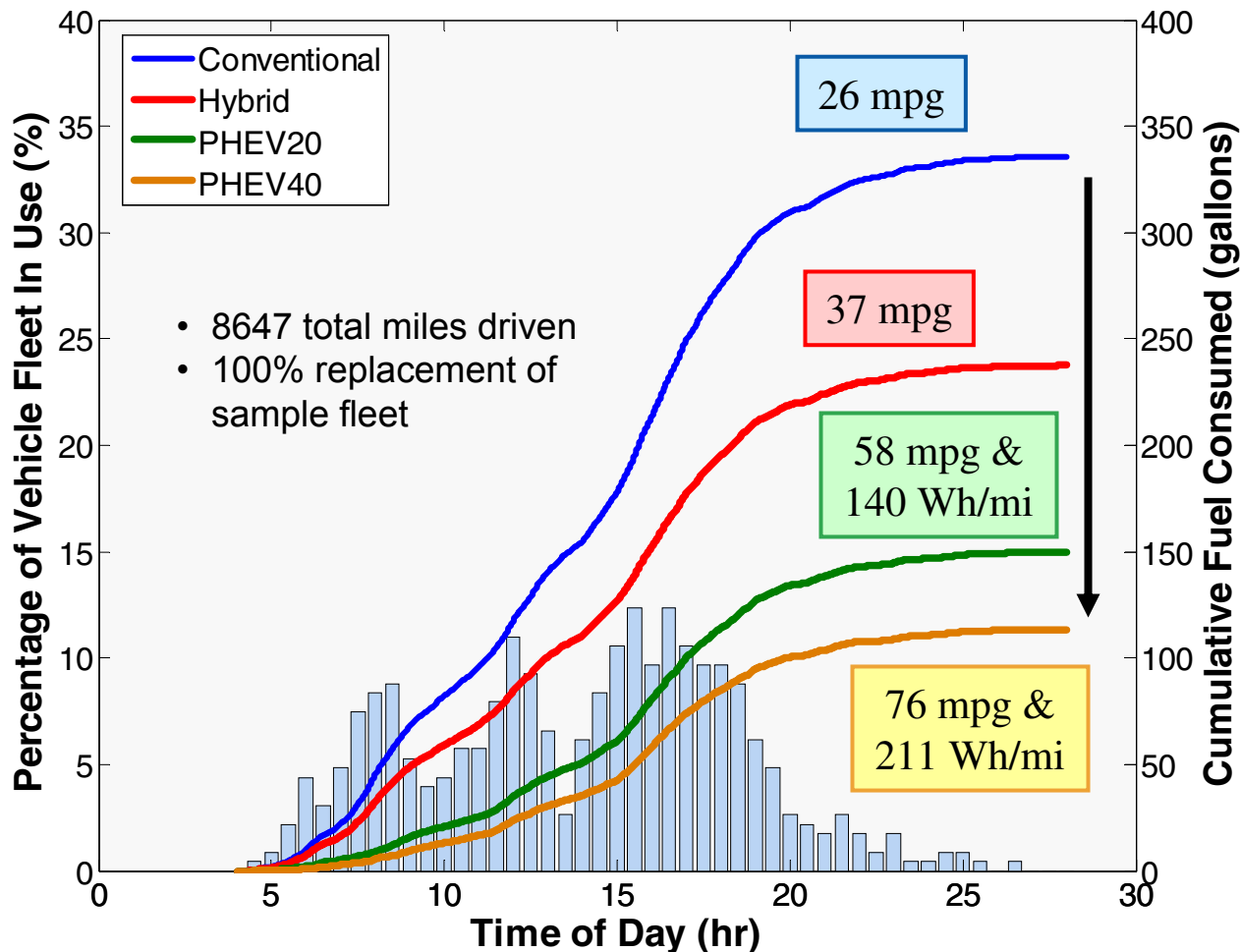


- St. Louis data set includes 227 vehicles from 147 households
- Complete second by second driving profile for one day
- 8650 miles of travel
- St. Louis data set is a small sample of real data
- NPTS data is generated from mileage estimates

Source: Tony Markel, Jeff Gondor, and Andrew Simpson (NREL), Presented to FreedomCAR Vehicle System Analysis Team, June 14 2006

PHEVs Reduce Fuel Consumption By >50% On Real-World Driving Cycles

227 vehicles from St. Louis each modeled as a conventional, hybrid and PHEV



	Average Daily Costs		
	Gas.	Elec.	¢/mi
CV	\$3.45	---	9.1
HEV	\$2.48	---	6.5
PHEV20	\$1.58	\$0.48	5.4
PHEV40	\$1.21	\$0.72	5.1

Assumes \$2.41/gal and 9¢/kWh

PHEVs:
>40% reduction in energy costs
>\$500 annual savings

Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006

Fuel Economy and All Electric Range Comparison

- Difference between rated (EPA drive cycles) and Real median values are significant for the PHEVs
 - Consumers likely to observe fuel economy higher than rated value in typical driving
 - Vehicles designed with all electric range likely to operate in a blended mode to meet driver demands

	<i>Fuel Economy (mpg) **</i>		<i>All Electric Range (mi)</i>	
	Rated	Median	Rated	Median
Conventional	26	24.4	n/a	n/a
HEV	39.2	35.8	n/a	n/a
PHEV20	54	70.2	22.3	5.6
PHEV40	67.4	133.6	35.8	3.8

** Fuel economy values do not include electrical energy consumption

Concluding Remarks – Vehicle Simulations

- Simulations on sample real-world drive cycles suggests PHEV technology can dramatically reduce petroleum consumption.
- Benefits of a PHEV over a conventional vehicle or HEV are tied to travel behavior.
- A vehicle designed for all electric range in urban driving will likely provide only limited electric operation in real world applications
 - Still provides significant fuel displacement
- Plug-in hybrid technology can reduce petroleum consumption beyond that of HEV technology.

Concluding Remarks - Battery

- Batteries with low power to energy ratios would be needed for PHEVs
- Expansion of the energy storage system usable state of charge window while maintaining life will be critical for reducing system cost and volume
- A blended operating strategy as opposed to an all electric range focused strategy may provide some benefit in reducing cost and volume while maintaining petroleum consumption benefits
- The key remaining barriers to commercial PHEVs are battery life, packaging and cost.

Some Final Thoughts

- PHEVs reduce emissions and displace petroleum
 - Is there a need to require ZEV (pure EV) range?
 - Does blended EV range achieve both objectives?
- Does AER or ZEV need to be over a “standard” drive cycle or “real” drive cycles?
- DOE and others are focusing R&D to reduce battery cost and to improve performance and life.
- Incentives for PHEVs with larger EV range (larger battery pack) may be needed.
- Learning demonstrations are key in the short term – a good role for AQMD.

- DOE Program Support
 - Dave Howell
 - Tien Duong

- NREL Technical Support
 - Tony Markel
 - Andrew Simpson
 - Jeff Gonder