# Battery Choices for Different Plug-in HEV Configurations

*Plug-in HEV Forum and Technical Roundtable*
*South Coast Air Quality Management District*
*Diamond Bar, CA*

July 12, 2006

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**National Renewable Energy Laboratory**

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

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# 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

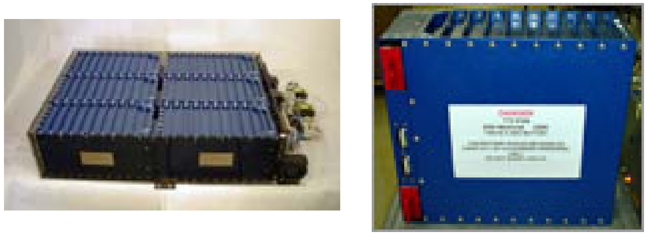
# Key Messages

- 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

**NiMH**

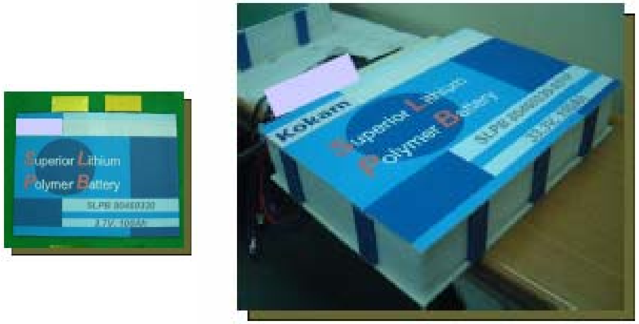
Varta



Electro Energy Inc.

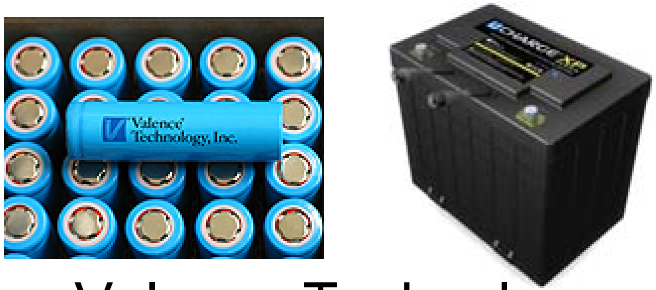
**Co/Ni based Li-Ion**

Johnson Controls/SAFT



Kokam

**Iron phosphate based Li-Ion**



Valence Technology

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** | | | | |
| **23ºC, 50% SOC** | 400 | 1300 | 3000 | >3000 |
| **-20ºC, 50% SOC** | 250 | 250 | 400 | >500 |
| **Charge acceptance, 10 sec. W/kg** | | | | |
| **23ºC, 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 |

Source: M. Anderman, AABC-04 Tutorial, San Francisco, CA June 2004

# Qualitative Comparison of Large-Format Battery Technologies for PHEVS

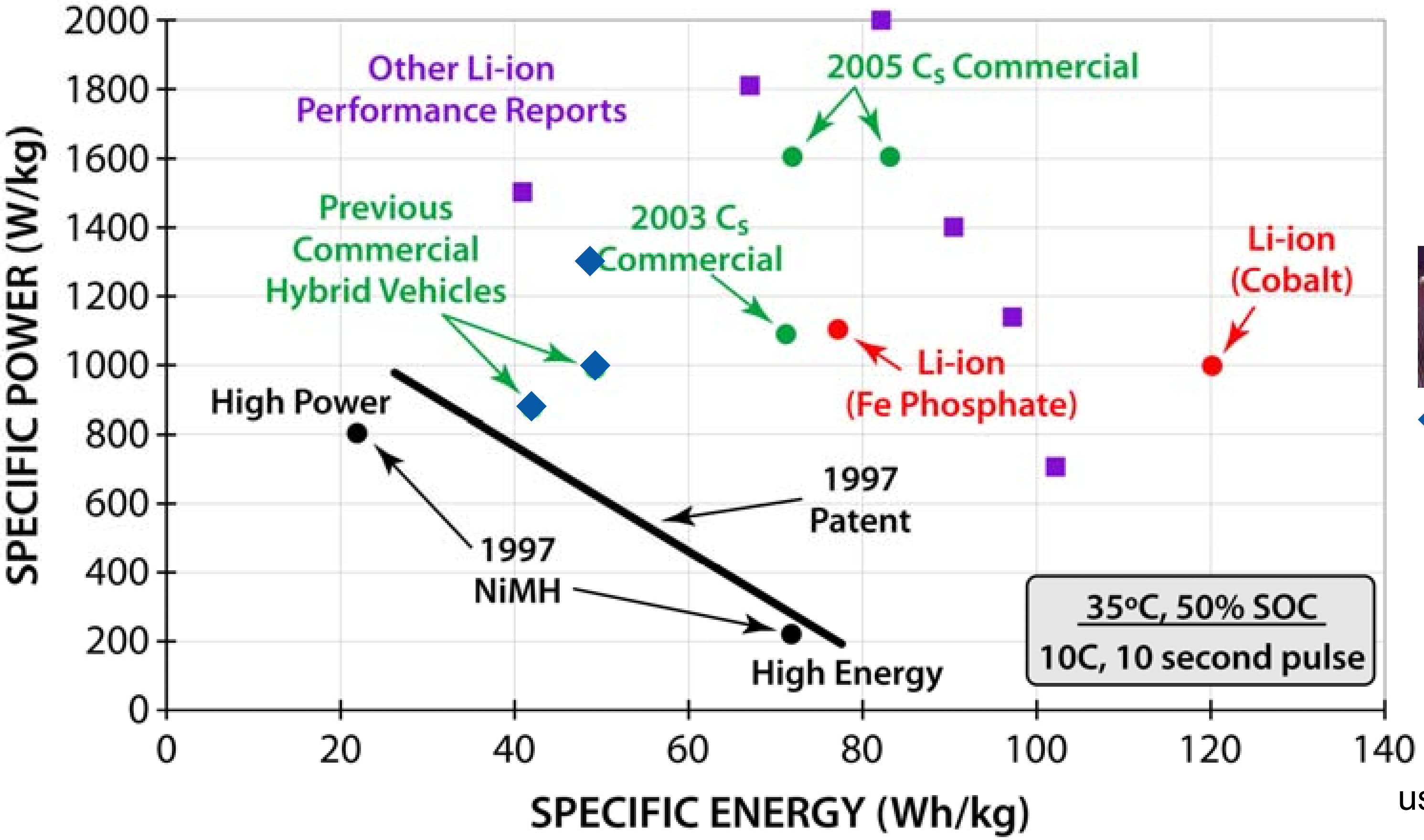
Key
(relative to each other)

- 🟥 Poor
- 🟨 Fair
- 🟩 Good

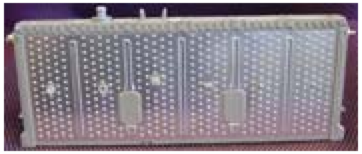
| Attribute | Lead Acid | NiMH | Li-Ion |
|---|---|---|---|
| Weight (kg) | 🟥 | 🟨 | 🟩 |
| Volume (lit) | 🟥 | 🟩 | 🟩 |
| Capacity/Energy (kWh) | 🟥 | 🟨 | 🟩 |
| Discharge Power (kW) | 🟩 | 🟨 | 🟩 |
| Regen Power (kW) | 🟥 | 🟨 | 🟩 |
| Cold-Temperature (kWh & kW) | 🟩 | 🟨 | 🟥 |
| Shallow Cycle Life (number) |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

# 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

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

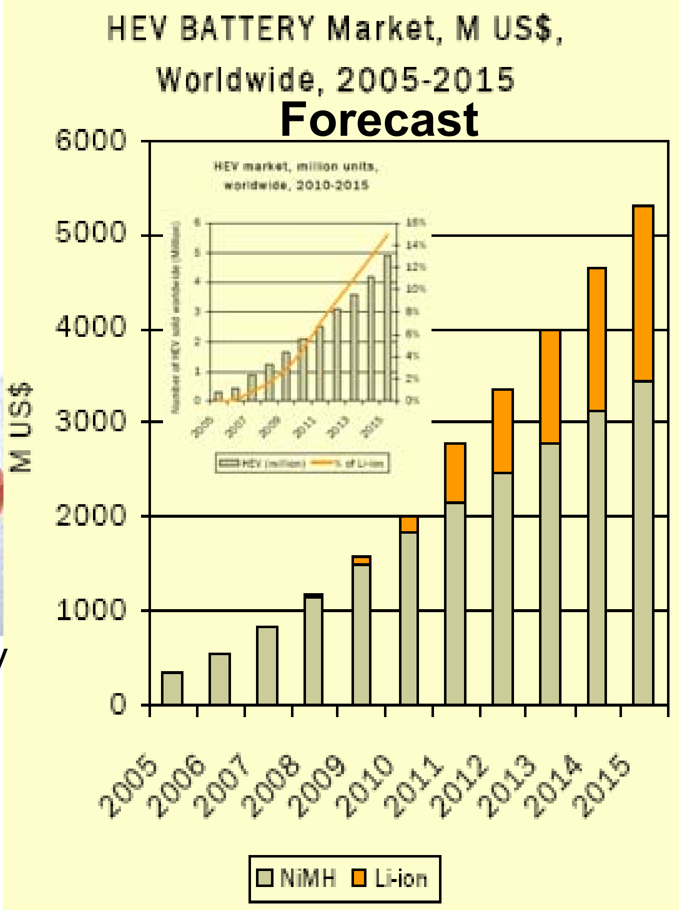
**Sanyo**

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.

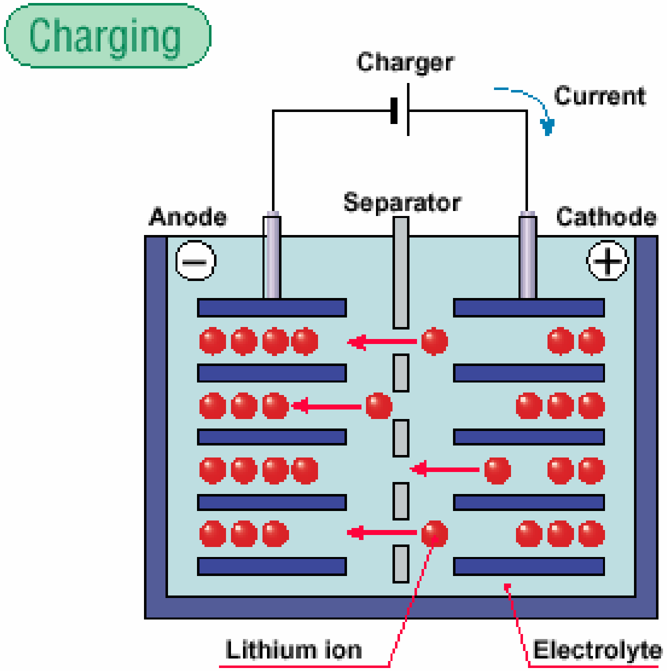
**Electro Energy**

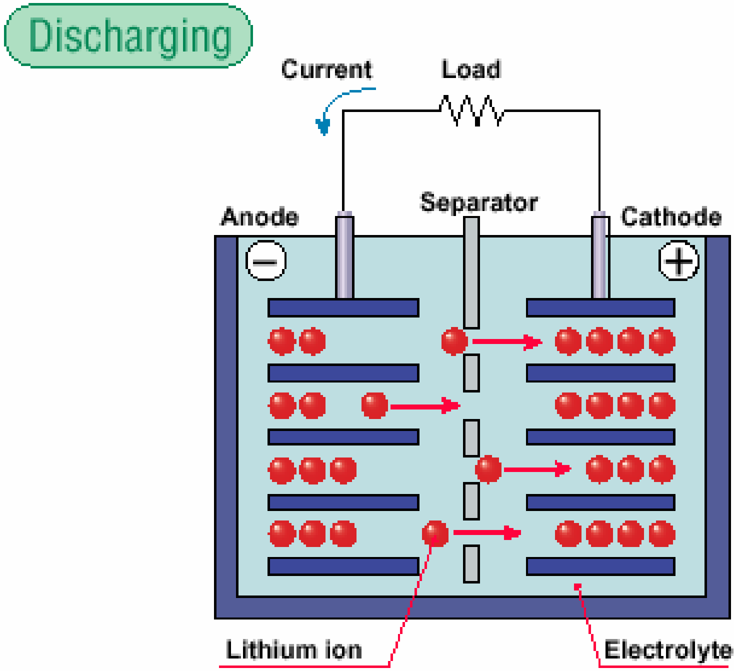
Pack with bipolar Cells/Modules

Bipolar pack in a Plug-In Prius

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

# Li Ion Technology – Diverse Chemistry & Opportunity





**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** | **Many electrolytes are possible** | **Many cathodes are possible** |
|---|---|---|
| Carbon/Graphite | $LiPF_6$ based | Cobalt oxide |
| Titanate ($Li_4Ti_5O_{12}$) | $LiBF_4$ based | Manganese oxide |
| Titanium oxide based | Various solid electrolytes | Mixed oxides with Nickel |
| Thin Oxide based | Polymer electrolytes | Iron phosphate |
| Tungsten oxide | | Vanadium oxide based |

Source: Robert M. Spotnitz, Battery Design LLC, “Advanced EV and HEV Batteries,” 2005 IEEE Vehicle Power and Propulsion Conference, September 7-9, 2005, IIT, Chicago, IL

# Characteristics of Cathode Materials

**Theoretical values** for a battery system relative to graphite anode and $LiPF_6$ electrolyte

| Material | $\Delta x$ | 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 |
| $LiMn_2O_4$ | 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
$LiMn_{1/3}Co_{1/3}Ni_{1/3}O_2$ newer than $LiNiCoO_2$
$Mn_2O_4$ around for many years – not competitive for consumer – good for high power
$LiFePO_4$ – 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

Source: Robert M. Spotnitz, Battery Design LLC, “Advanced EV and HEV Batteries,” 2005 IEEE Vehicle Power and Propulsion Conference, September 7-9, 2005, IIT, Chicago, IL

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

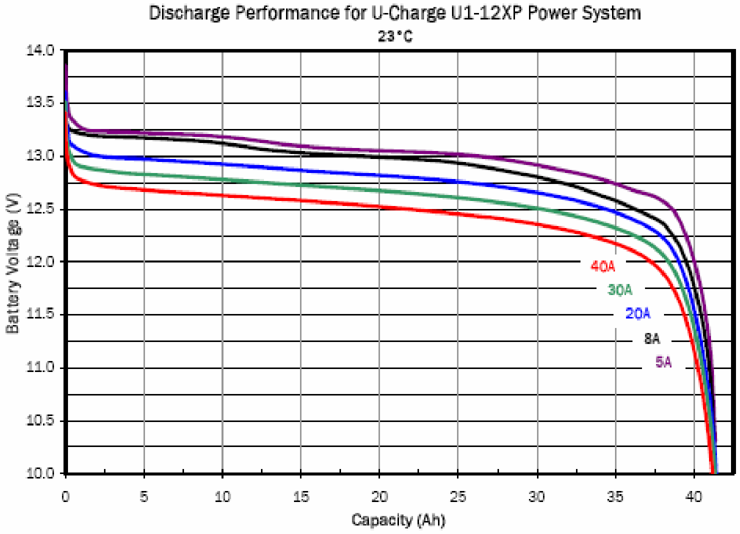
- Easier diffusion of Li-ion into and out of the host
  - High specific capacity at high rate
- Increased electrode surface area and thus higher rates
- Stable 3 dimensional host materials
- Small dimensional change as Li-ions are cycled in and out
  - Improved cycling life due to less structural change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

Source: Excepts 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



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

+ 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 ($D_{Li}$~ $10^{-13}$ $cm^2$/Sec)
– Poor electronic conductivity (~ $10^{-8}$ S/cm)

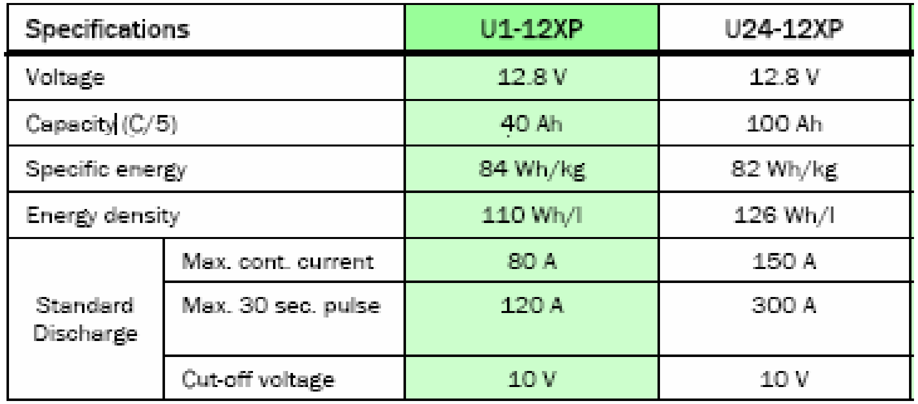
- Approach many use to overcome poor characteristics
  - Use nano $LiFePO_4$ – carbon composite
  - Use larger number of cells
  - Nano structured materials

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

# Improvements in Iron Phosphate Li-Ion Batteries

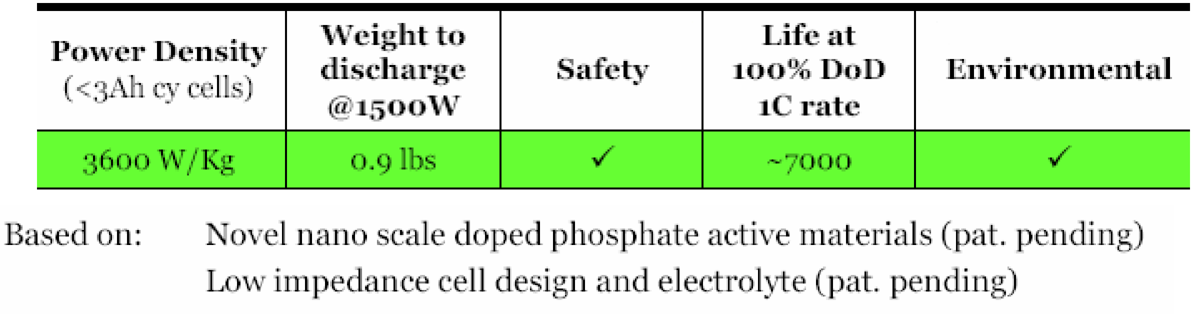
**Valence Technology 18650 Cells**
**100 Wh/kg in cell 84 Wh/kg in U Charge module**

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 |

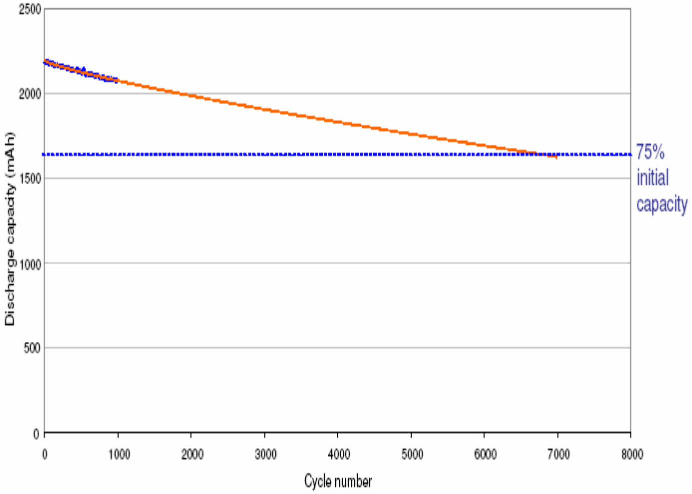
Source: On line brochures from Valence Technology, http://www.valence.com/ucharge.asp



| 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**

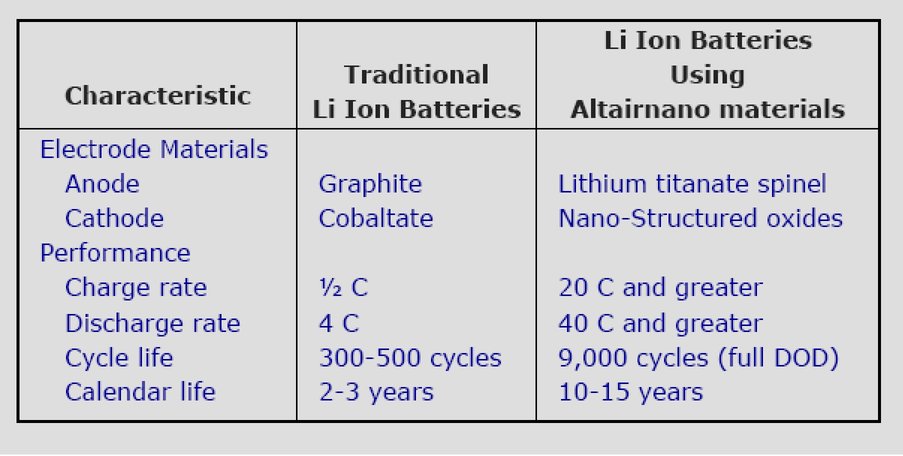


100%DOD 1C charge, 1C discharge cycling data.
Using first 1000 cycles, extrapolated cycle life: ~7000 cycles.

National Renewable Energy Laboratory

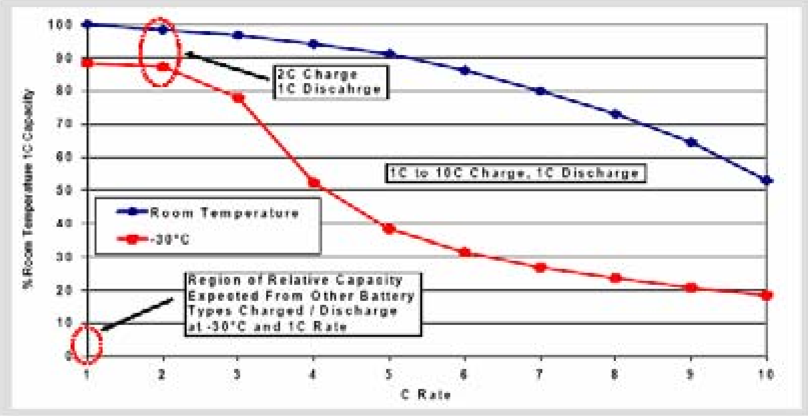
Source: Andrew Chu (A123 Systems) from the 23rd International Battery Seminar & Exhibit, March 13-16, Ft. Lauderdale, FL.

# 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 | ½ 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 |

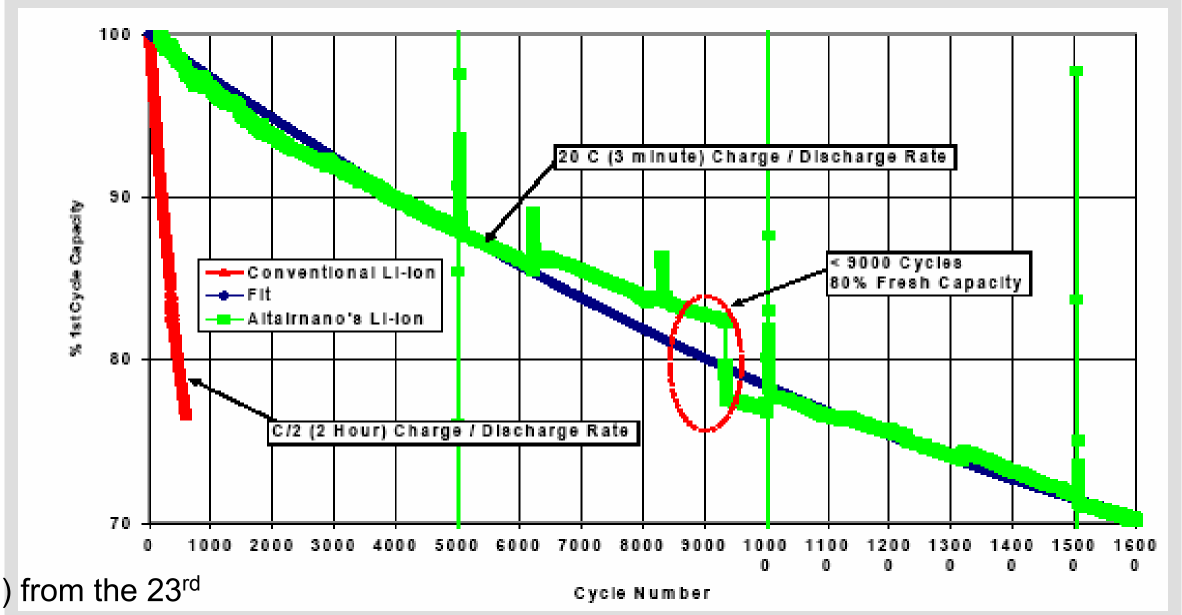
Long Life, POWER Lithium Ion Batteries



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

Altaire Nanotechnologies Inc.

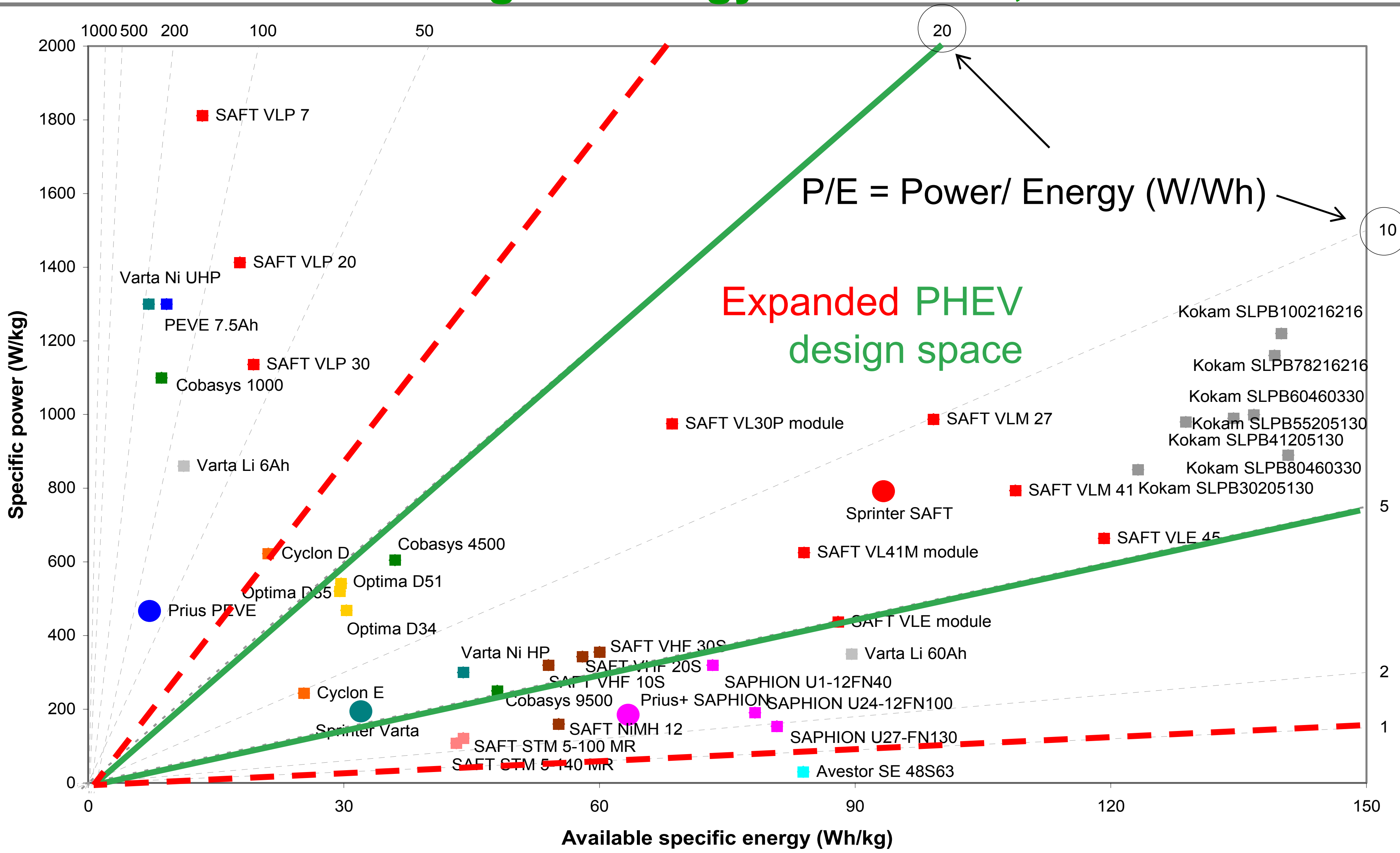
- Improved low temperature performance
- Faster charge acceptance
- Longer cycle life
- 80-100 Wh/kg
- 2000-4000 W/kg



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

# PHEV Battery Options

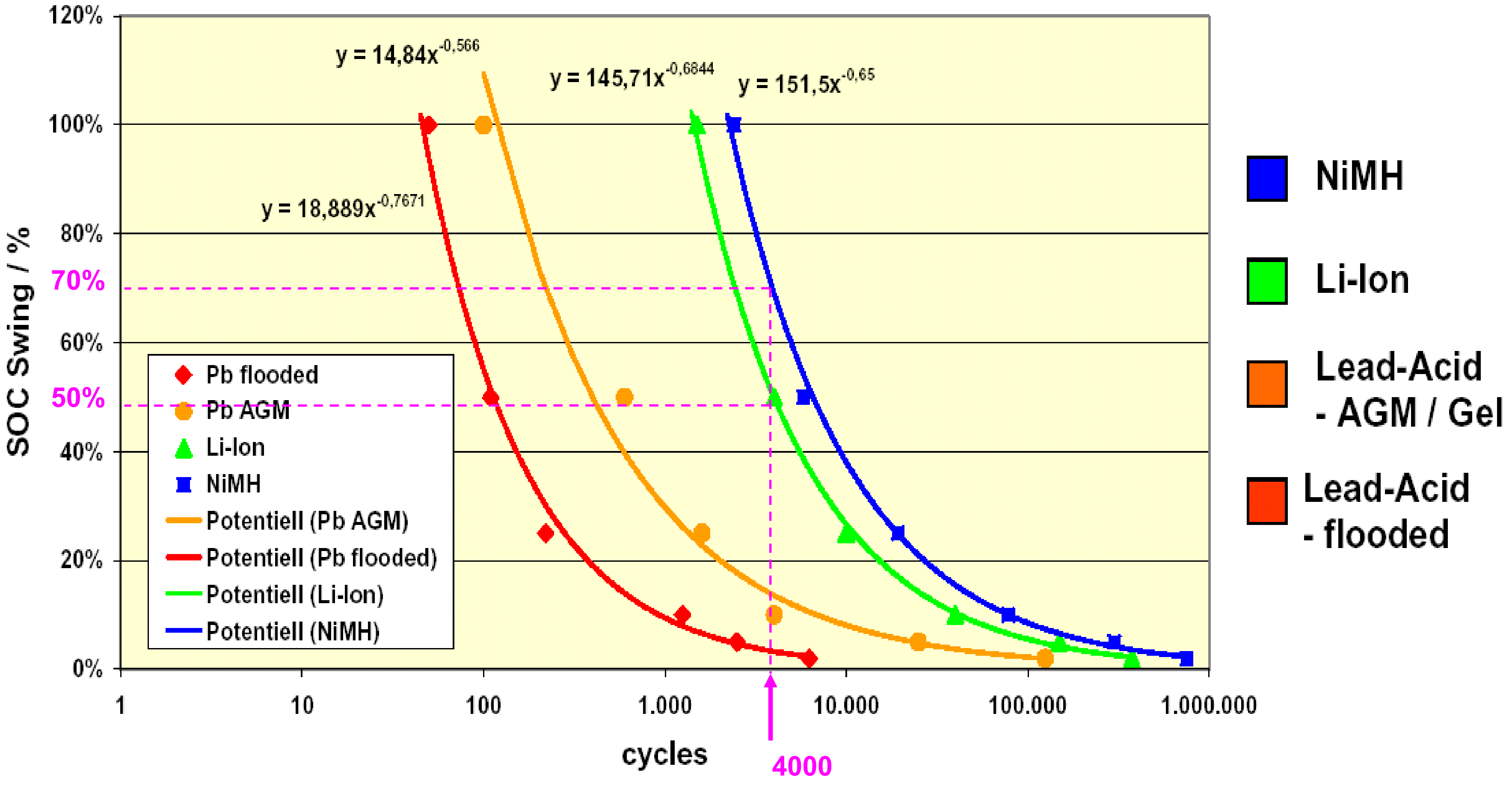
## Need for higher energy than HEVs, so P/E lower



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



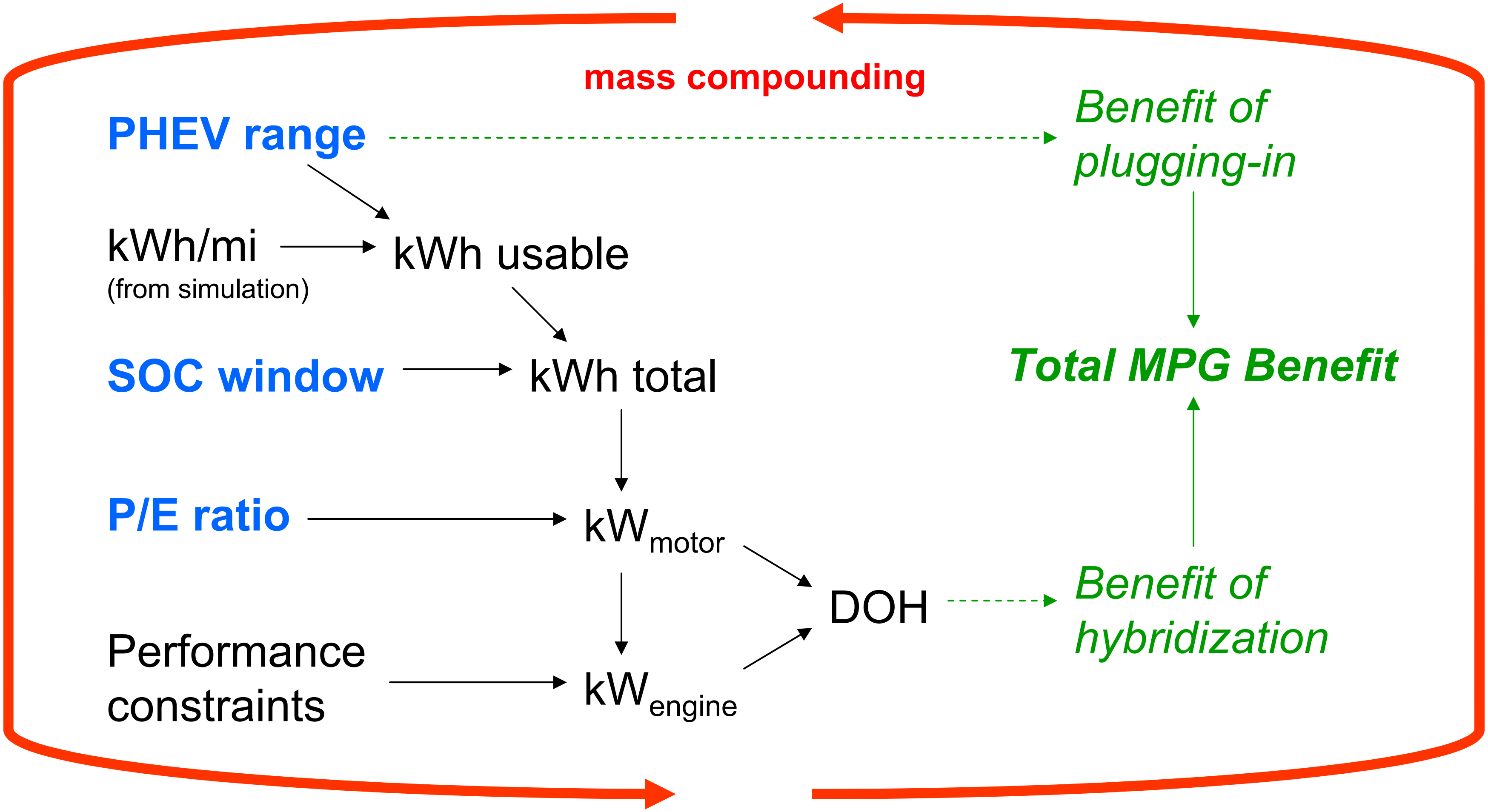
Source: Christian Rosenkranz (Johnson Controls) at EVS 20, Long Beach, CA, November 15-19, 2003

# 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**



mass compounding

**PHEV range**

kWh/mi
(from simulation)

kWh usable

**SOC window**

kWh total

**P/E ratio**

$kW_{motor}$

Performance constraints

$kW_{engine}$

DOH

*Benefit of plugging-in*

***Total MPG Benefit***

*Benefit of hybridization*

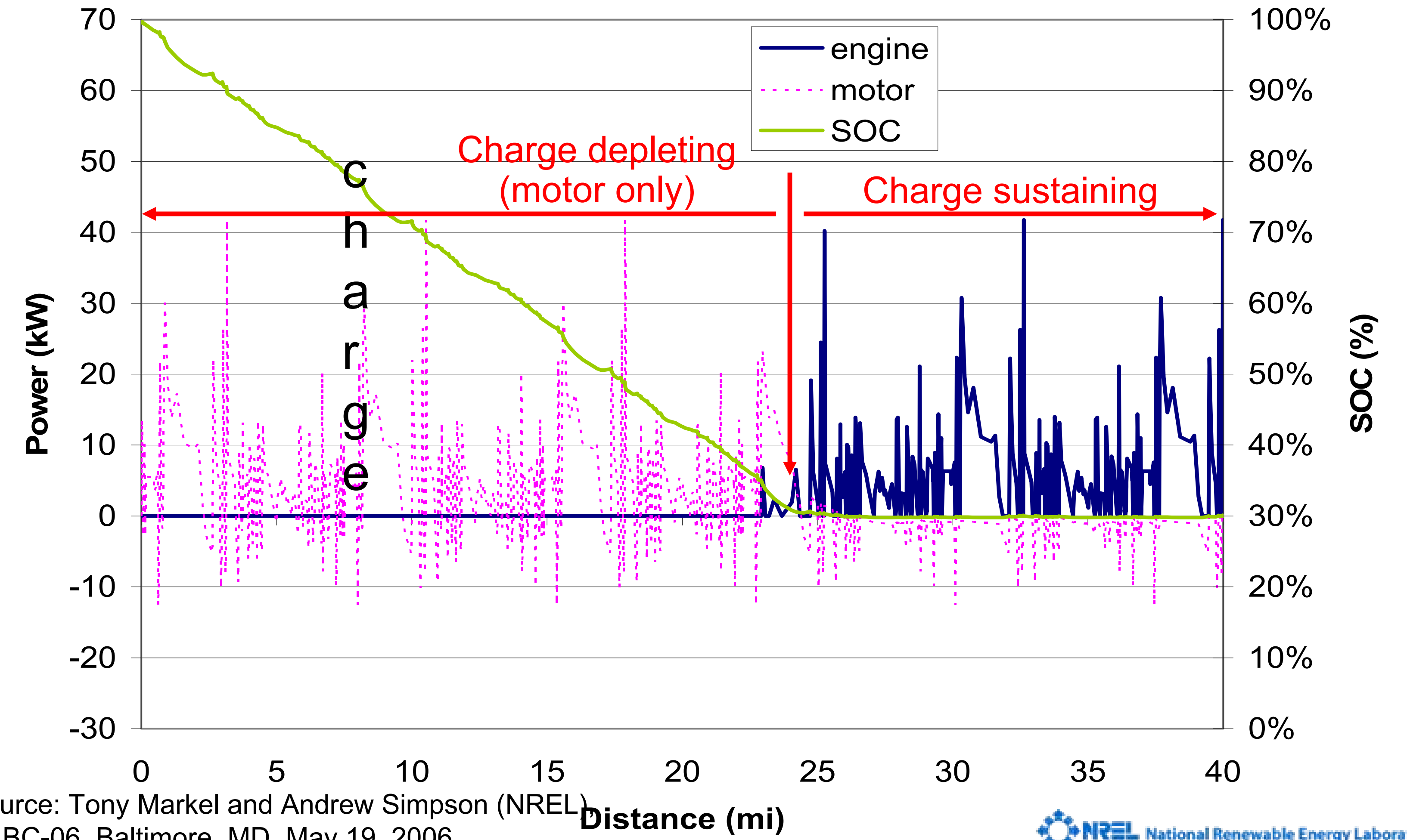
DOH = degree of hybridization

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

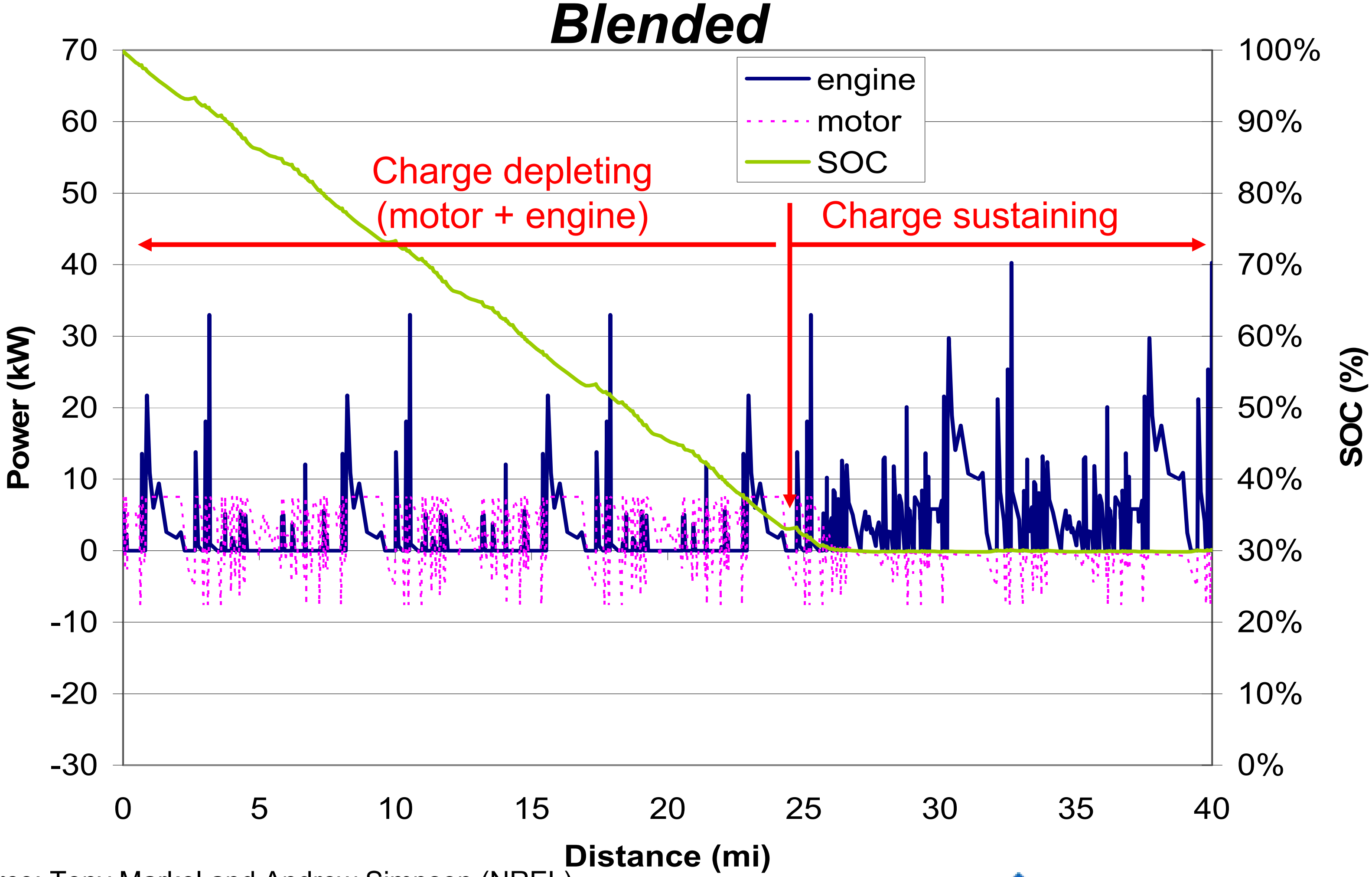
## *All-Electric (Pure EV or ZEV)*



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

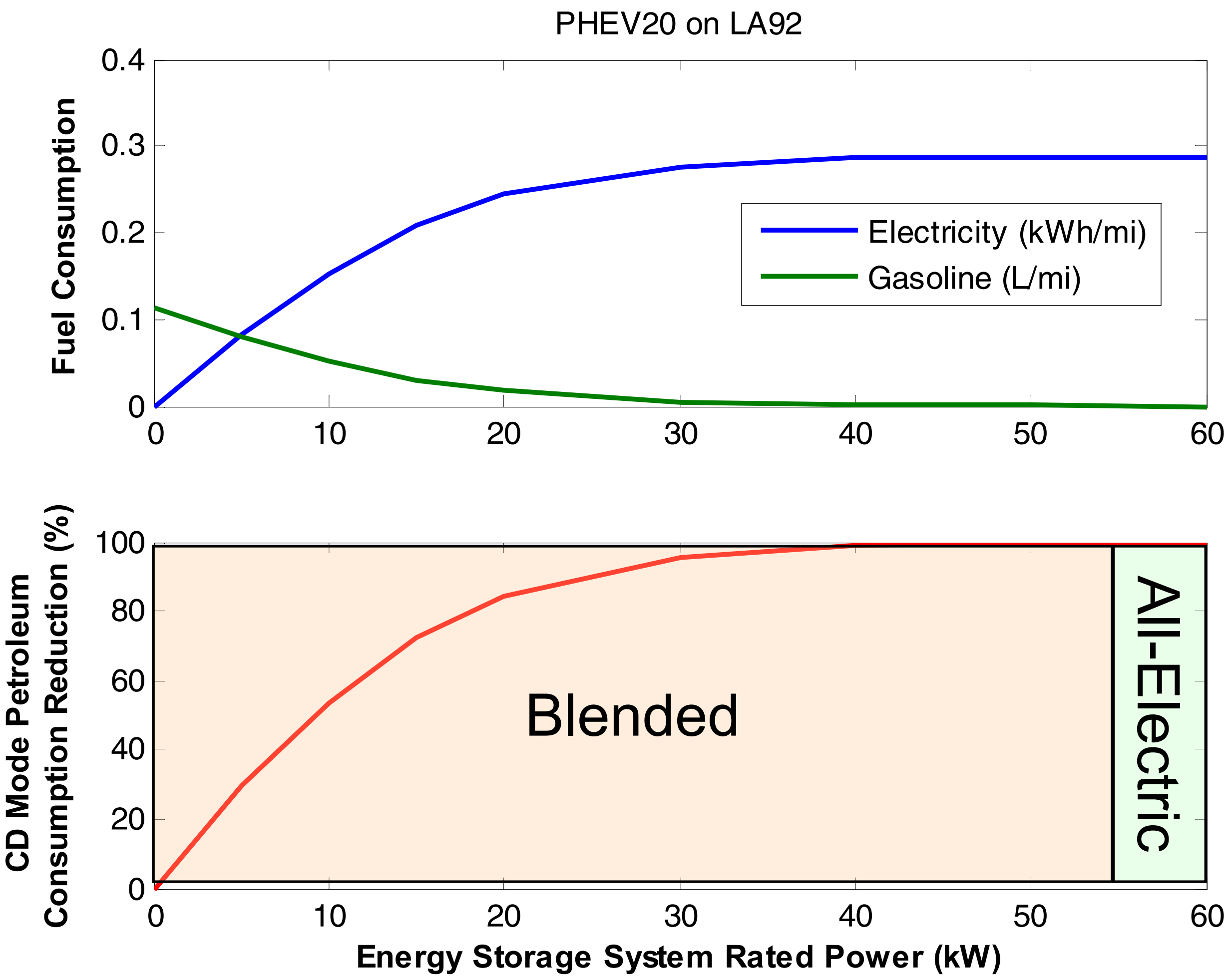
# Alternative PHEV Design Strategies: All-Electric vs Blended

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



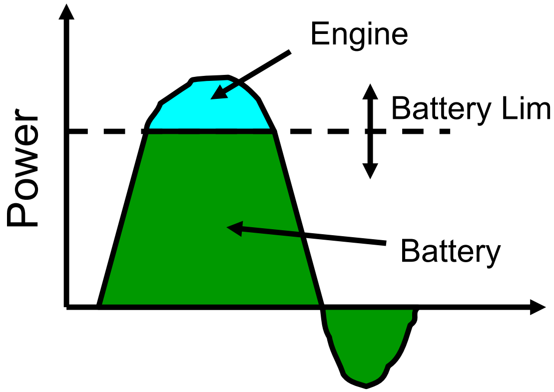
Source: Tony Markel and Andrew Simpson (NREL), AABC-06, Baltimore, MD, May 19, 2006

# Blended vs. AER Consumption Tradeoff



- Reducing ESS power should reduce cost, mass, volume

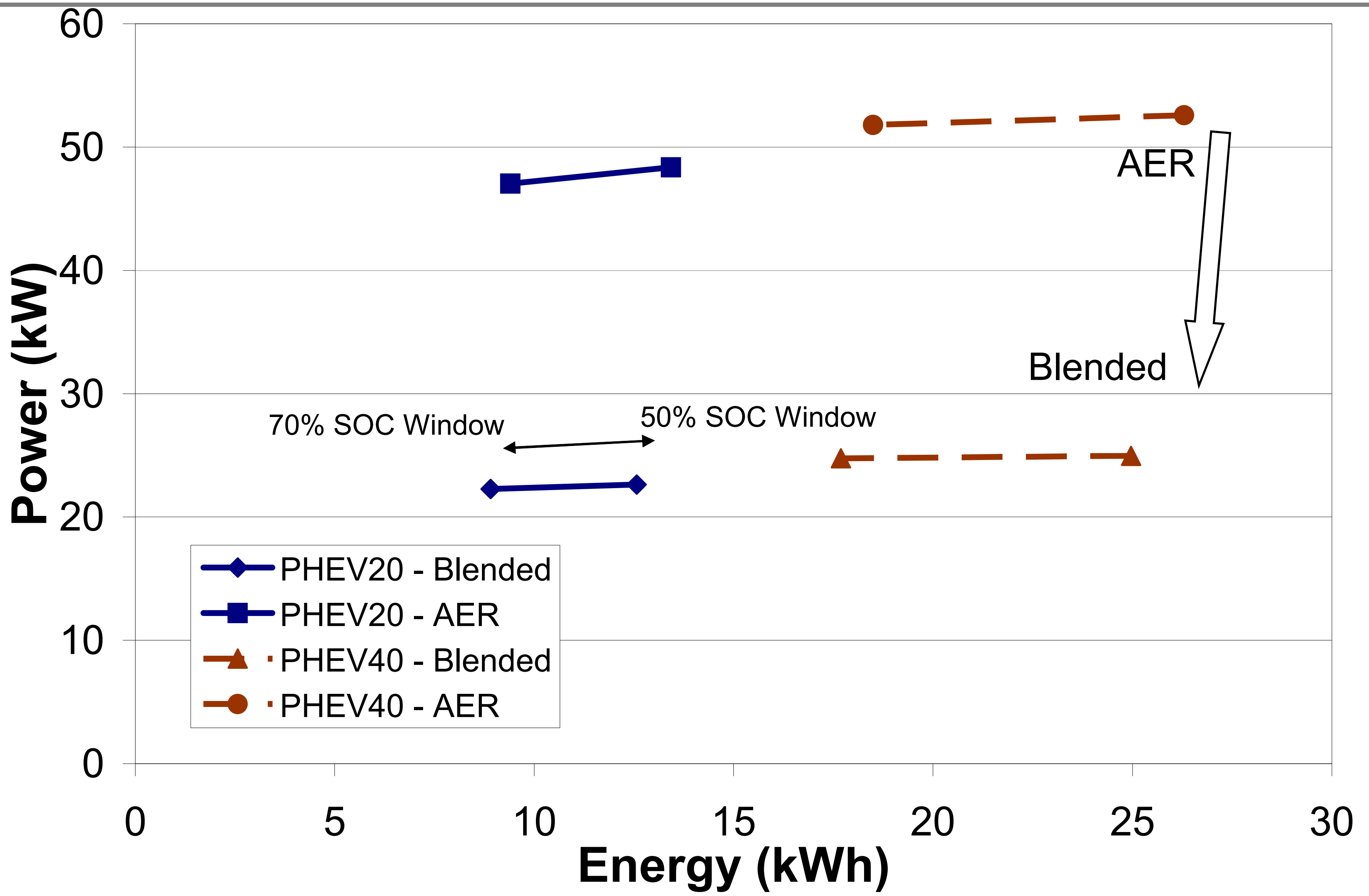
- 50% reduction in power still provides almost all of the fuel consumption benefit



* CD = Charge Depleting

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

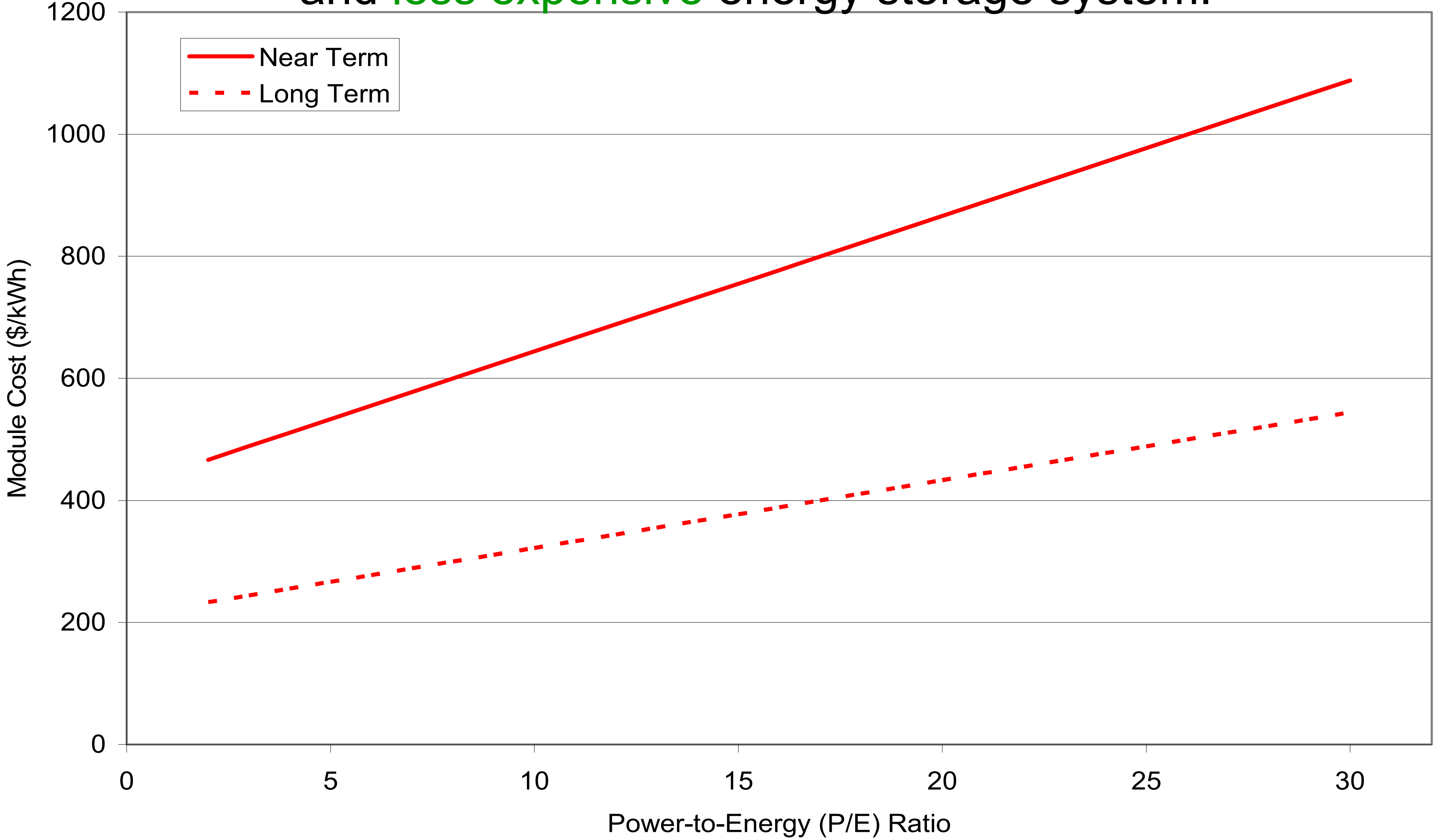
# PHEV Battery Sizing Alternatives



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

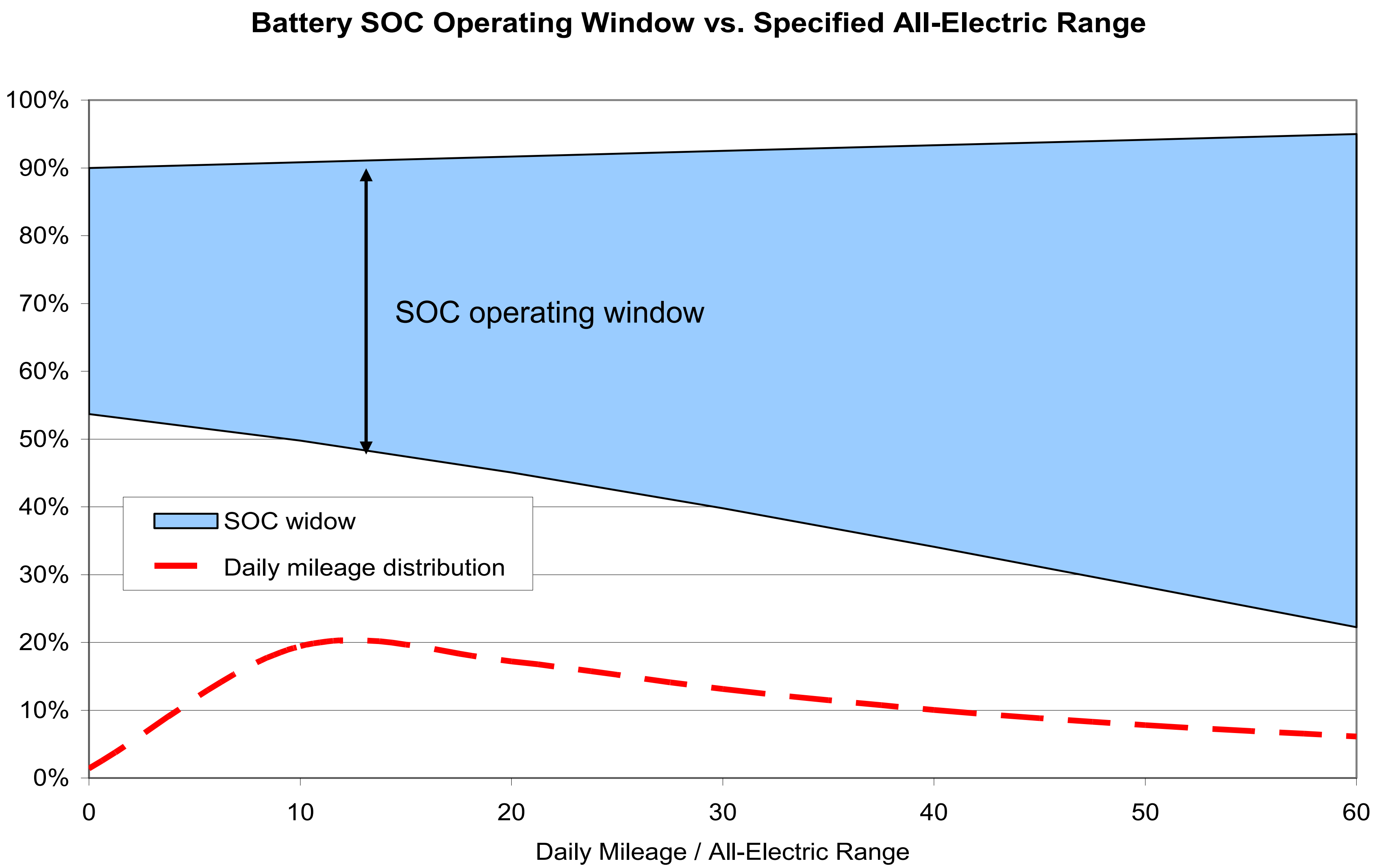
# Battery Cost Model based on P/E Ratio

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



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

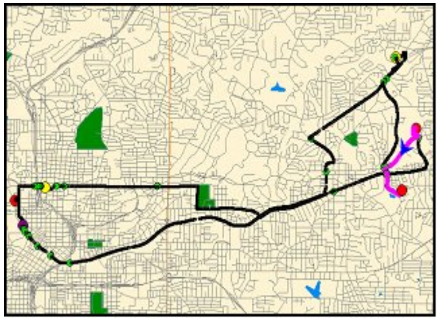
# Battery Model (cont.) – SOC Window

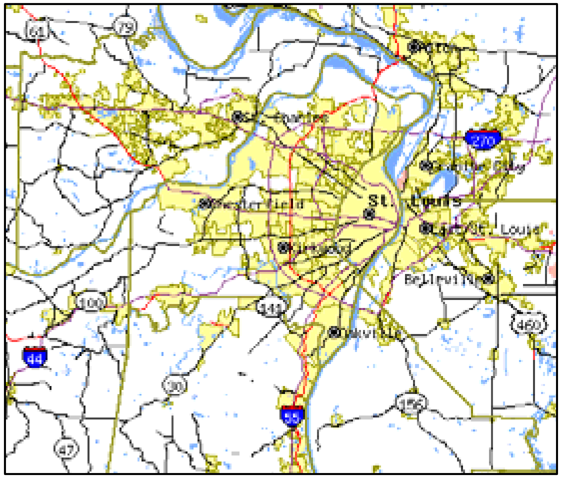


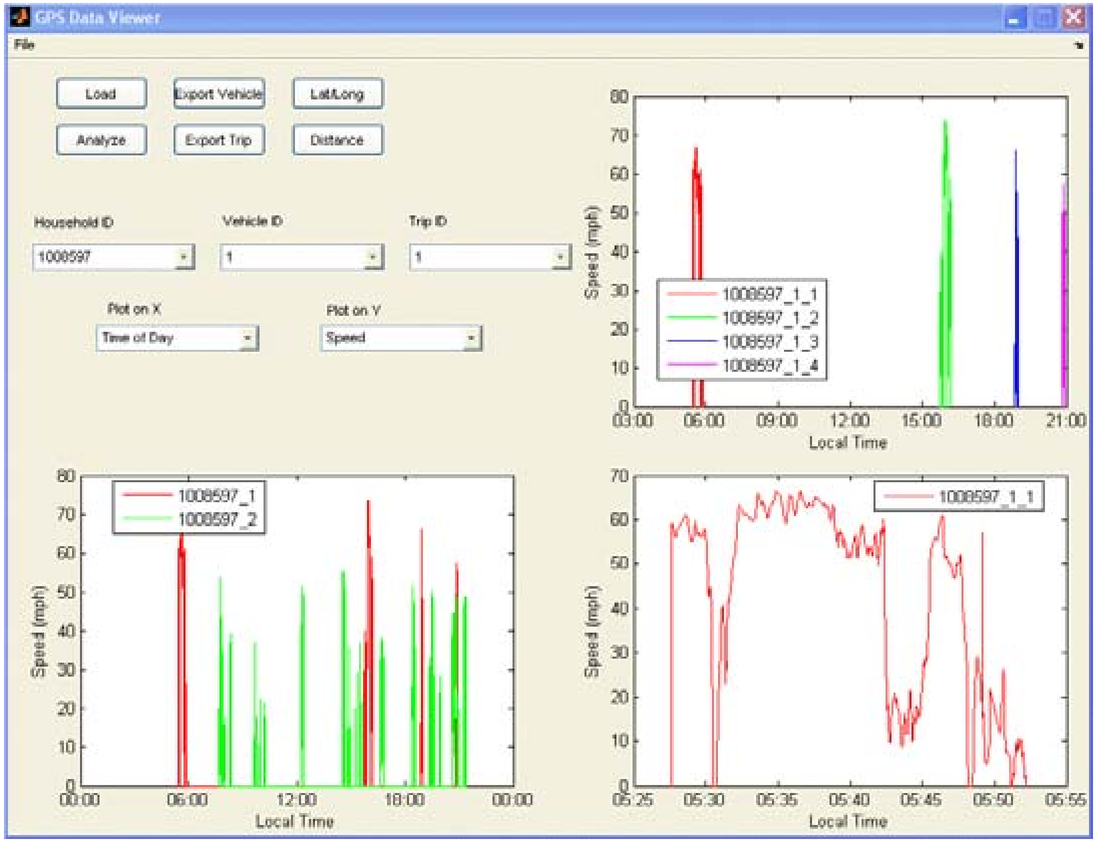
Source: Andrew Simpson (NREL), Presented to FreedomCAR Vehicle System Analysis Team, March 1 2006

# Real Driving Survey Data

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







Household ID: 1008597

Vehicle ID: 1

Trip ID: 1

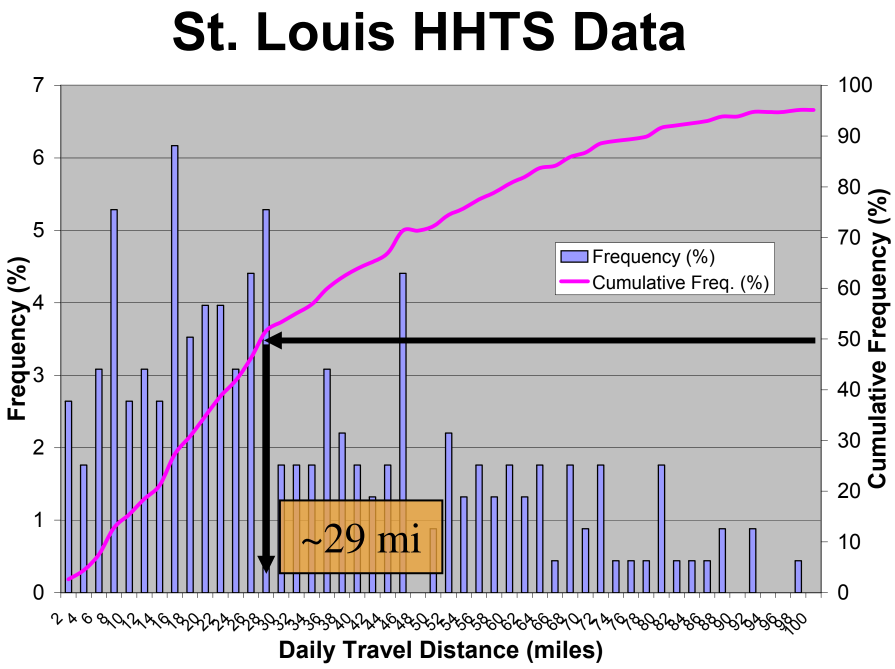
Plot on X: Time of Day

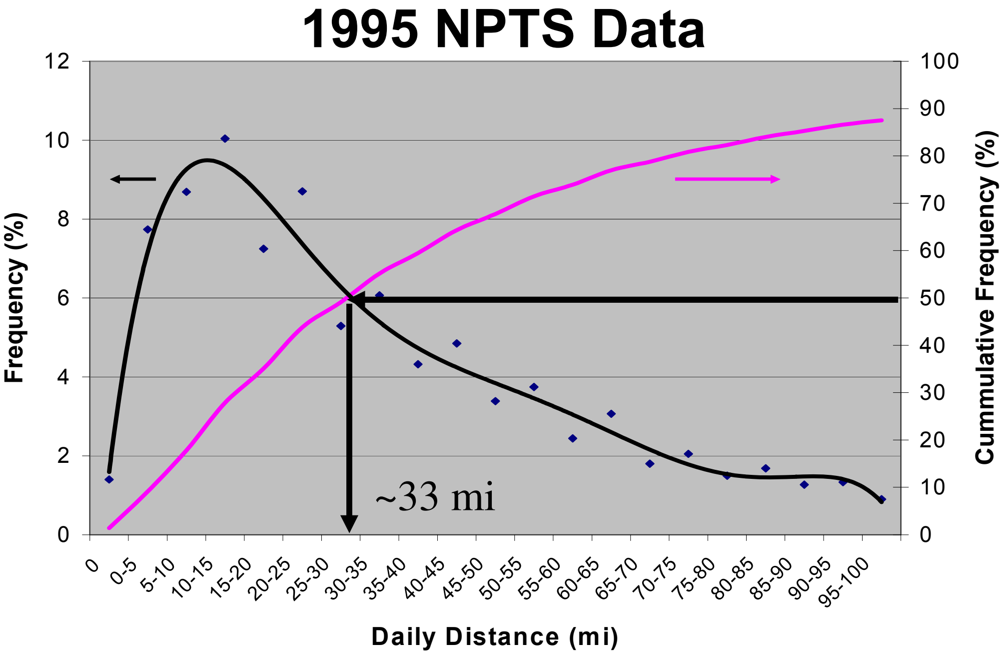
Plot on Y: Speed

Source: Tony Markel, Presentation at Clean City Congress and Expo, (NREL), Phenoix, AZ, May 8, 2006

# St. Louis Travel Data Analysis

## Daily Driving Distance Similar to 1995 NPTS Data



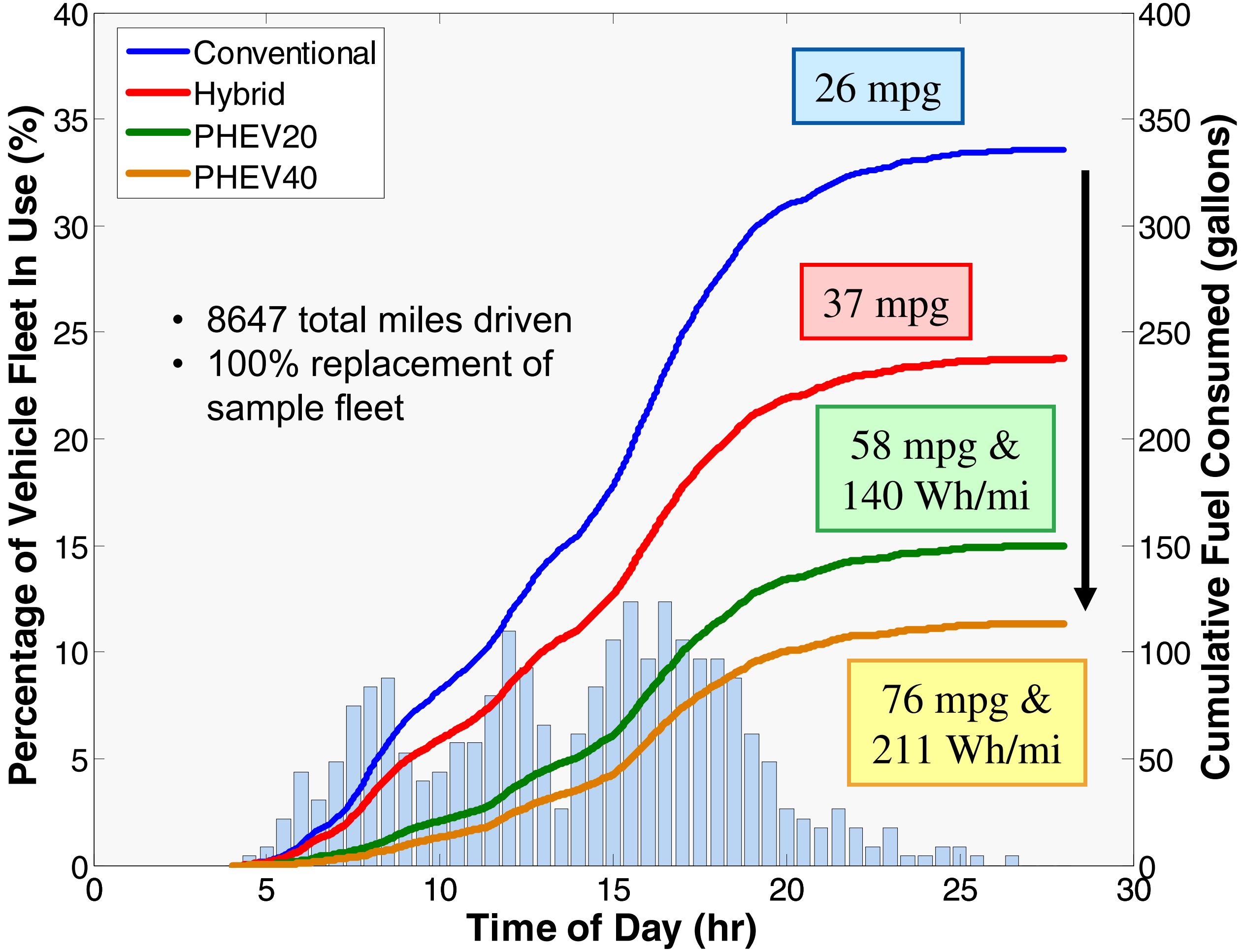


- St. Louis data set includes 227 vehicles from 147 households
- Complete second by second driving profile for one day
- 8650 miles of travel
- St. Louis data set is a small sample of real data
- NPTS data is generated from mileage estimates

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



26 mpg

37 mpg

58 mpg &
140 Wh/mi

76 mpg &
211 Wh/mi

- 8647 total miles driven
- 100% replacement of sample fleet

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

| | 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

# 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

| | *Fuel Economy (mpg) *** | | *All Electric Range (mi)* | |
|---|---|---|---|---|
| | **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

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

# 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.

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