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Battery Pack Requirements and Targets Validation FY 2009 DOE Vehicle Technologies Program

Annual Merit Review

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Sponsor:
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Project ID: es_01_santini

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Overview

Timeline

- Start: Oct. 2006
- Completion: summer 2009
- 90% complete

Budget

- Total project funding
  - 100% DOE funding
- FY09 funding $600K

Barriers

- Initial costs of providing both power and energy in plug-in hybrid batteries
- Establishing a cost effective balance/mix of mechanical and electric drive
- Achieving battery life cycle net benefits, given low U.S. gasoline prices

Partners

- Electric Power Research Institute

  Project lead: Argonne
- IEA HEV and EV Implementing Agreement

Objectives of this Study

- Examine li-ion as a plug-in hybrid (PHEV) battery chemistry
- Evaluate 3 PHEV powertrain configurations
  - Parallel, split and series powertrains
- Evaluate PHEVs designed for blended vs. all-electric charge depletion
- Determine cell power and energy cost trade-offs, by chemistry (4)
- Determine best charge depletion distance for high PHEV market share
- Determine real world fuel and electricity consumption of PHEVs
- Determine most likely early U.S. market for PHEVs
- Estimate life cycle emissions and energy use of PHEVs

Milestones: PHEV Evaluations

- FY2007
  - Select promising battery chemistries — Summer 2007
  - Specify probable PHEV powertrain designs to study — Summer 2007
  - Characterize most probable "glider" (vehicle body) — Summer 2007
  - Collect information on markets, driving behavior — Winter 2007
  - PHEV chapter of IEA "Annex VII" HEV Report — Dec. 2007
  - Early market assessment paper (EVS-23, WEVJ, 2009) — Dec. 2007
  - Cost-benefit and oil use reduction paper (EVS-23, WEVJ '09) — Dec. 2007
  - Life cycle analysis paper (EVS-23, WEVJ 2009) — Dec. 2007
- FY2008
  - AABC 2008 paper on urban vs. highway gas saved/hr — May 2008
  - Findings on 2007 presentations at conferences (several) — All year
- FY2009
  - TRB paper on estimation of oil use reduction by PHEVs — Jan. 2009
  - TRR version of Jan. TRB paper — late 2009
  - EVS-24 paper on battery costs — May 2009
  - Argonne/EPRI Report on PHEVs and City EVs — Sept. 2009

Approach:

- Net present value benefit estimates
- Driving – dense urban to intra-city limited access highways
- Examine design of PHEVs to fit existing infrastructure
  - Overnight charging @ 110 V standard plugs, some 220 V
  - Distribution of existing garages and carports
  - Evolution of dwelling units – garages per new dwelling unit
- Examine design of PHEVs to match pattern of driving
  - Fully deplete on nearly all days after overnight charge, best 2/day charge options
  - Engine downsizing in cars vs. constant peak engine power in trucks
- Interaction of charging strategy with generating unit type
  - Current generation mix (utilize excess natural gas generation capacity)
  - Future generation options (particularly - compatibility with wind)

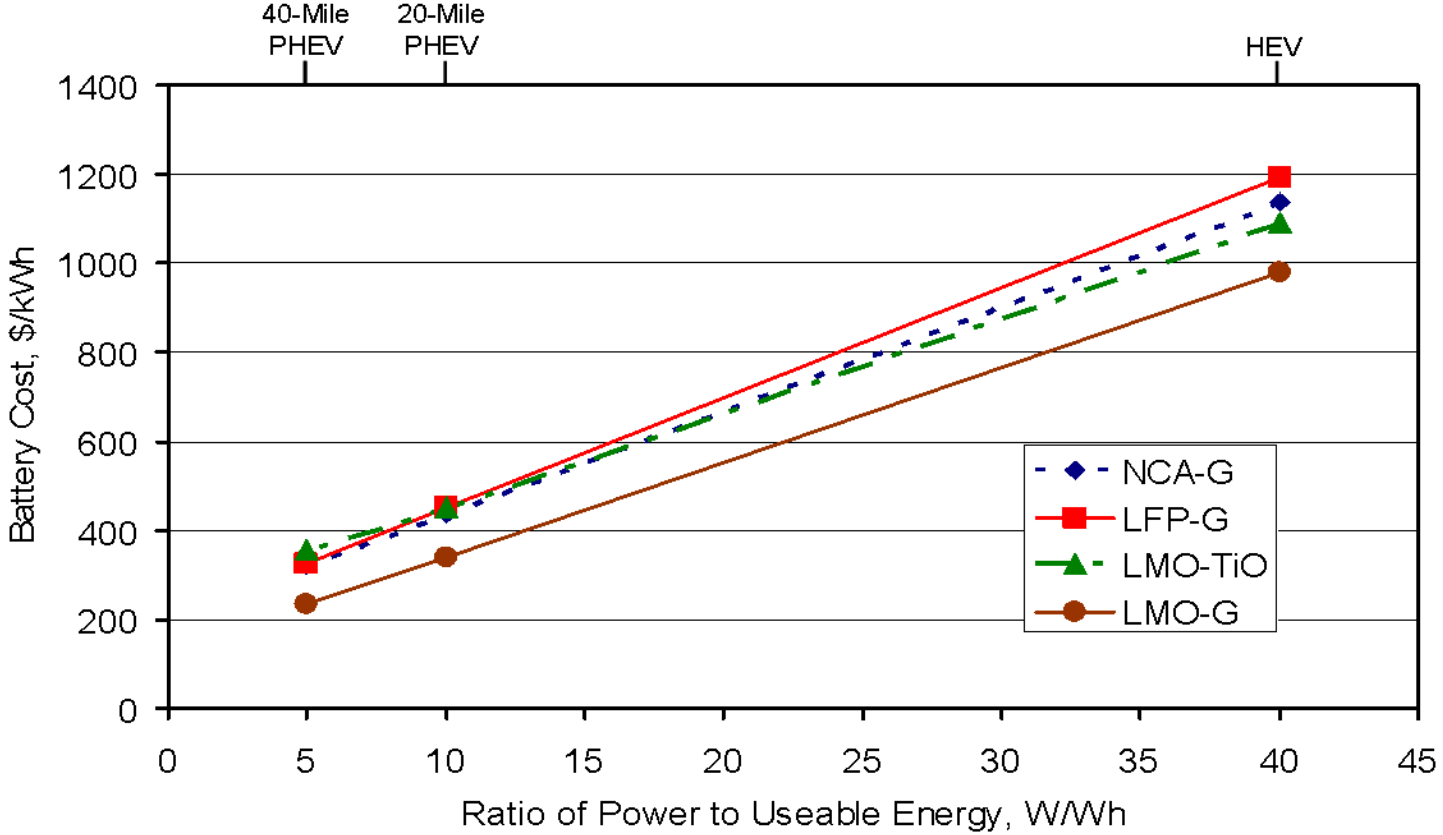
Some Technical Accomplishments

Evaluate four battery chemistries

System → Electrodes ↓	NCA Graphite	LFP (phosphate) Graphite	MS (spinel) Graphite	MS TiO
Positive (cathode)	$LiNi_{0.8}Co_{0.15}Al_{0.05}O_2$	$LiFePO_4$	$LiMn_2O_4$	$LiMn_2O_4$
Negative (anode)	Graphite	Graphite	Graphite	$Li_4Ti_5O_{12}$

- All contain lithium in cathode
- One uses lithium in anode as well
- Electrolyte contains lithium salt ($LiPF_6$) in solution

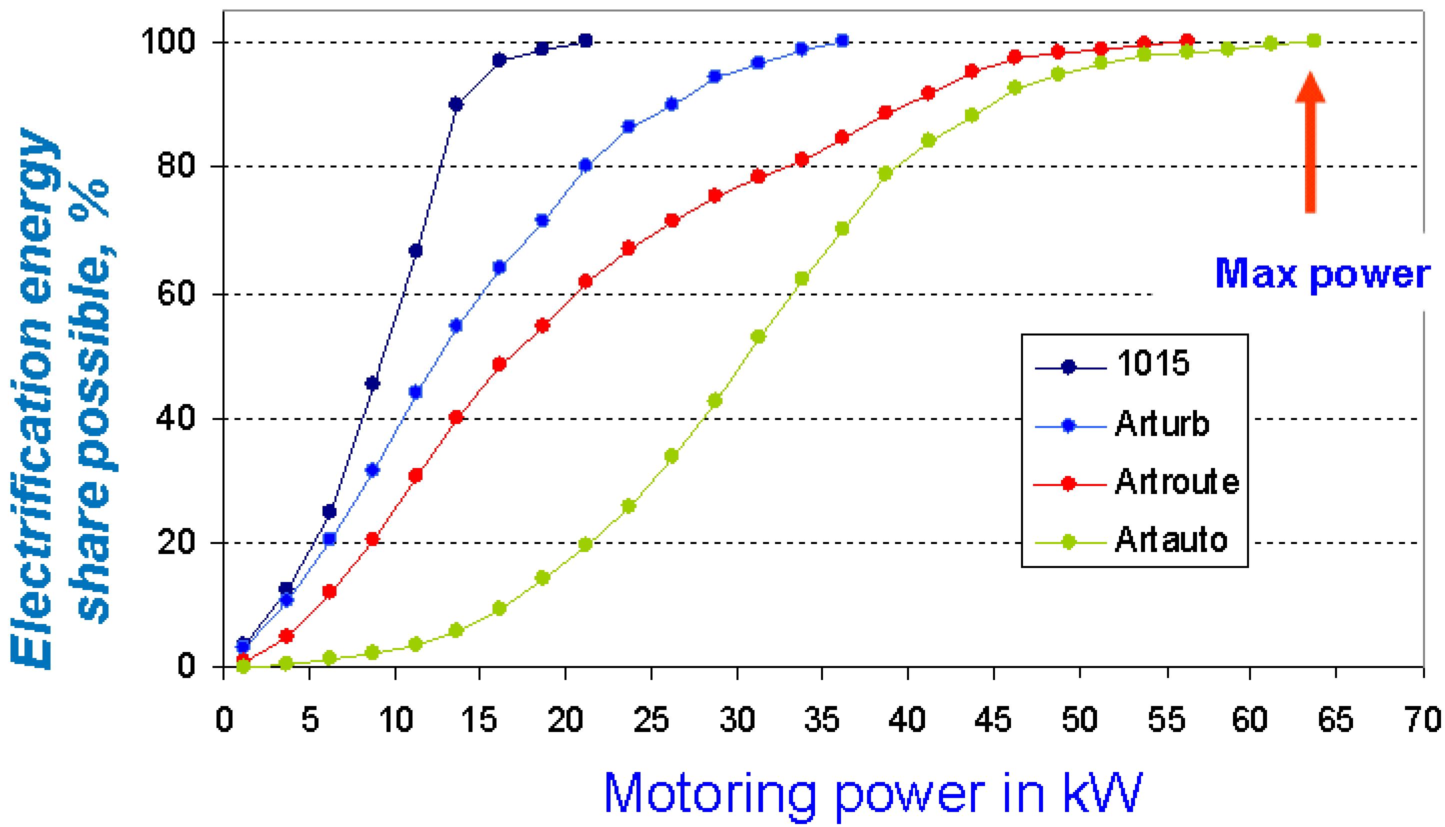
A ***fundamental*** *benefit for a PHEV vs. a HEV is a sharp drop in battery pack cost/kwh, regardless of chemistry. $/kWh reductions are far bigger from HEV to PHEV20 than PHEV20 to PHEV40. Corollary – less battery pack power means lower $/kWh*



Estimated $/kWh battery pack cost by vehicle type and resulting W/Wh rating

(March 2009 estimates in current draft of forthcoming EVS-24 paper by Santini, Nelson, and Barnes – revisions may affect relative positions of chemistries, but not the major point)

All electric operation requires higher and higher peak power as average roadway network speed increases



Share of specified driving cycle that can be driven electrically, vs. motor/battery net power

(European "Artemis" cycle simulations, <u>small</u> car: urb = dense urban; route = countryside; auto = limited access highway)

Desire for early PHEV utilization – always fully discharge in same day charge is completed

Point – use maximum battery capacity as often as possible

- Cycle life is more important than calendar life (@ ~ 7 yrs) – use the battery as intensively as possible
- Battery replacement is fine if you get your money back before the battery dies, and “death” is well predicted
- Long cycle life with consistent deep discharge is most important attribute
- Small changes in power vs. SOC are desirable
- Expand SOC window used from 30% for HEV to 70% and higher for PHEVs

Economics of PHEV ownership and the dictates of PHEV design are <u>far</u> different than for EVs!

- For the EV, range must exceed the *upper values* of daily driving distance.
- For a PHEV charge depletion (CD) range should be less than *lower values* of daily driving distance! PHEV evaluators have failed to recognize that daily driving distance of PHEVs should <u>exceed</u> CD range.

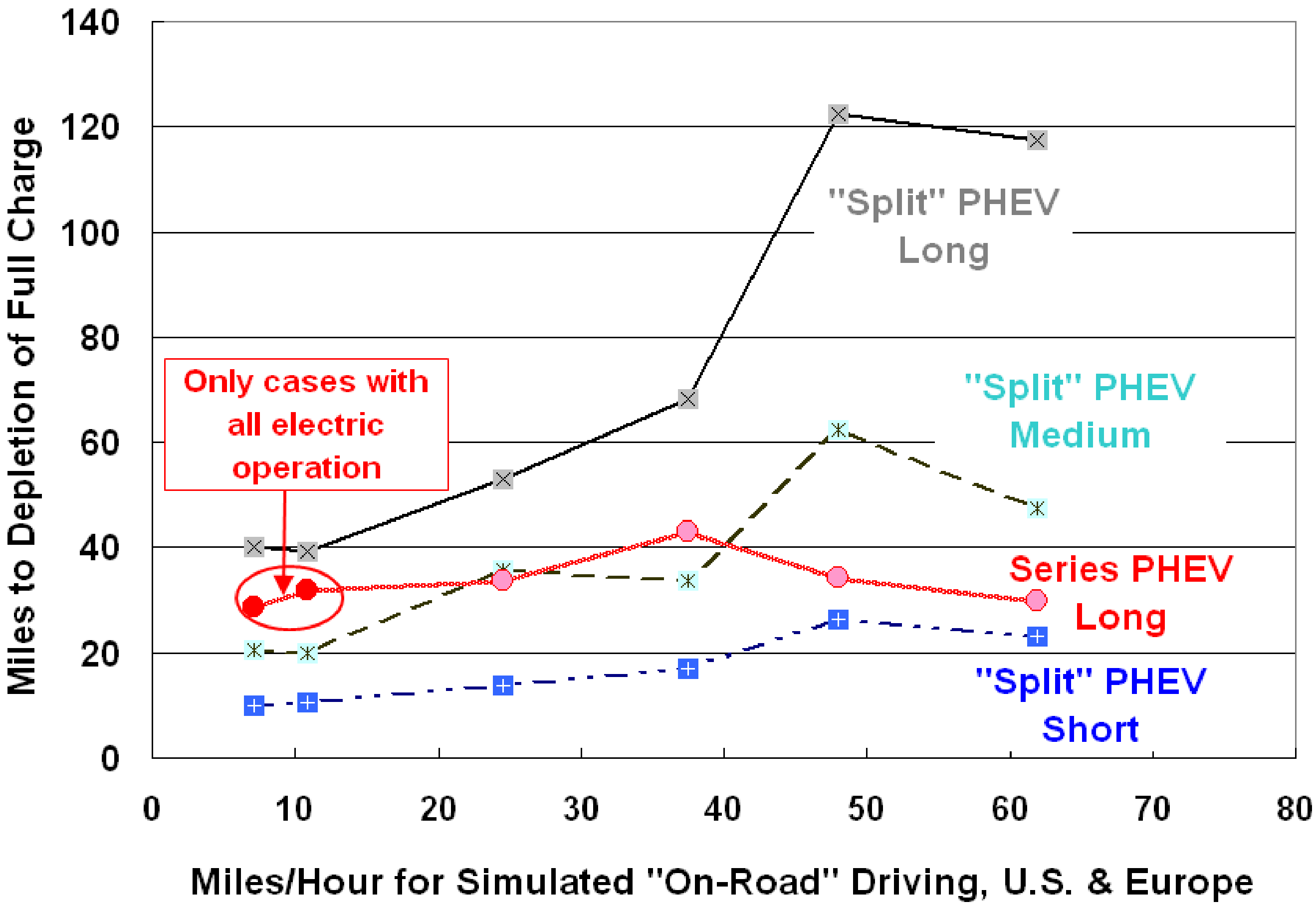
  Traditional: "< 50 km/day driving = > 60% of vehicle km" (example from Samaris and Meisterling, ES&T, 2007).

  Correct: "> 32 km/day driving = > 72% of vehicle km"

- An EV must have a powerful electric motor and battery pack. A PHEV can have a much less powerful motor and pack, not drive all electrically, still save a lot of gasoline.

Source: Santini and Vyas, The Influence of Cost-Benefit Analysis on the Conduct of Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains. Advanced Automotive Battery and Ultracapacitor Conference. May 12-16, 2008, Tampa, FL

As driving speed rises, initial simulations imply that U.S. PHEVs with ~ 60 kW of battery power must go further before depleting



Note: "Prius like" mid-size car, simulated with "split" and series powertrains. Split has ~ 60 kW electric power, series ~ 90 kW

Those who reliably exceed 20 miles of driving per day average from 29 to 41 mph. This might push CARB-rated PHEV20 actual depletion distance > 30 miles (see prior slide)

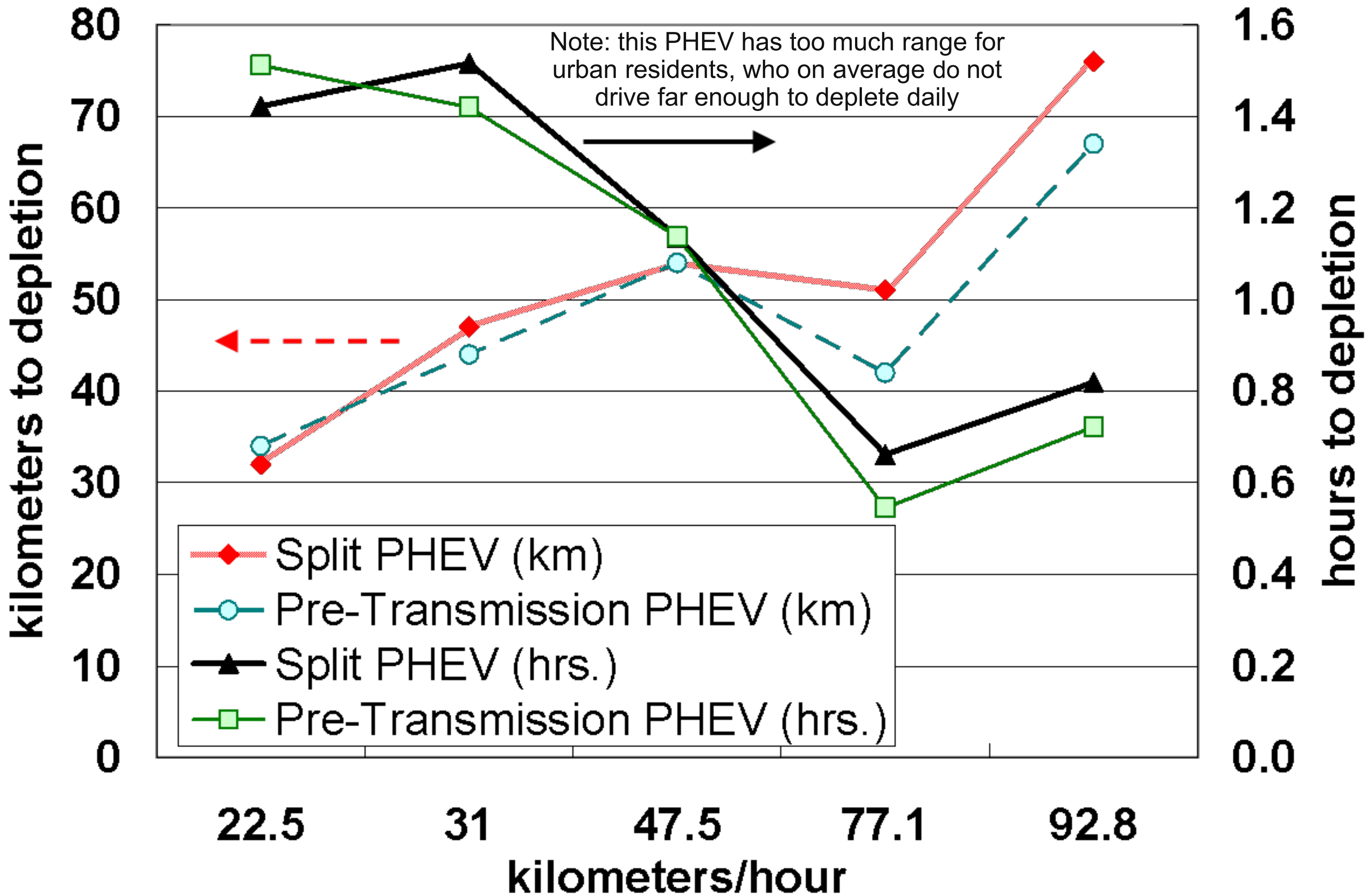
Speed, Share of Time, Miles and Fuel Use, by Distance Traveled from Day's Start

Distance from day's starting point (miles)	First 0–20§	Next 20–40#	Remainder >40	All
Mph of portion traveling up to the distance	17.2	25.7	Not applicable	19.7
Mph of portion traveling beyond the distance	29.4	30.9	41.3	34.7
Mph total (average) for category	24.8	28.2	41.3	30.4

§ Includes travel up to 20miles and first 20 miles of travel of vehicles traveling >20 miles.
# Includes 20+ mile portion of days of travel > 20 mi. but < 40, and for days of travel > 40, includes 20 - 40 mile portion

See Vyas, Santini and Johnson, Plug-In Hybrid Electric Vehicles' Potential for Petroleum Use Reduction: Issues Involved in Developing Reliable Estimates. Transportation Research Board Annual Meeting Paper TRB 09-3009, Washington DC. Jan. 2009

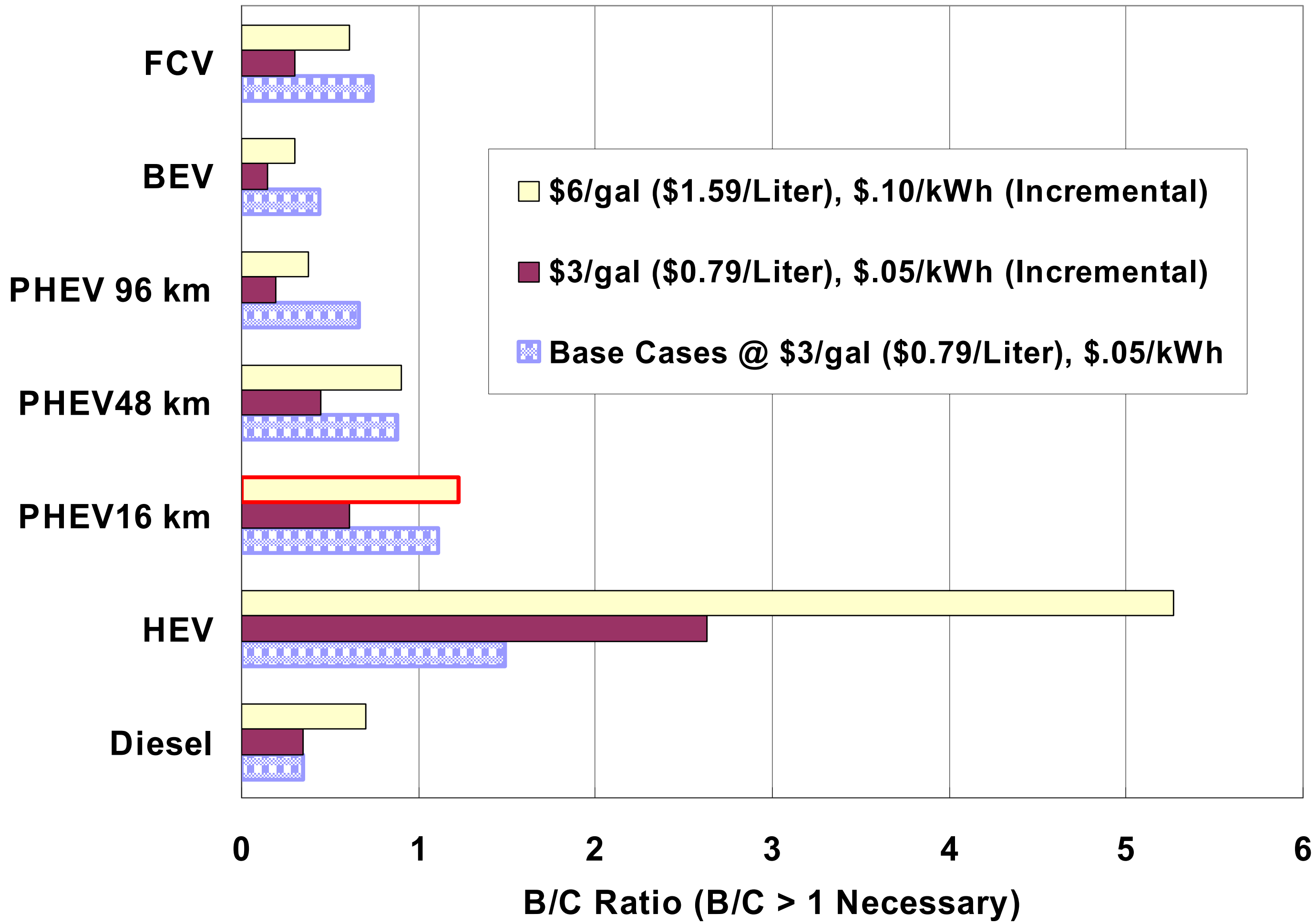
Though requiring longer depletion distance, 60 kW blended mode PHEVs take less time to deplete at higher speed



Estimated distance and time to depletion for PHEVs designed to go 32 km all electrically in urban driving, five driving cycles

Source: Santini and Vyas, The Influence of Cost-Benefit Analysis on the Conduct of Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains. Advanced Automotive Battery and Ultracapacitor Conference. May 12-16, 2008, Tampa, FL

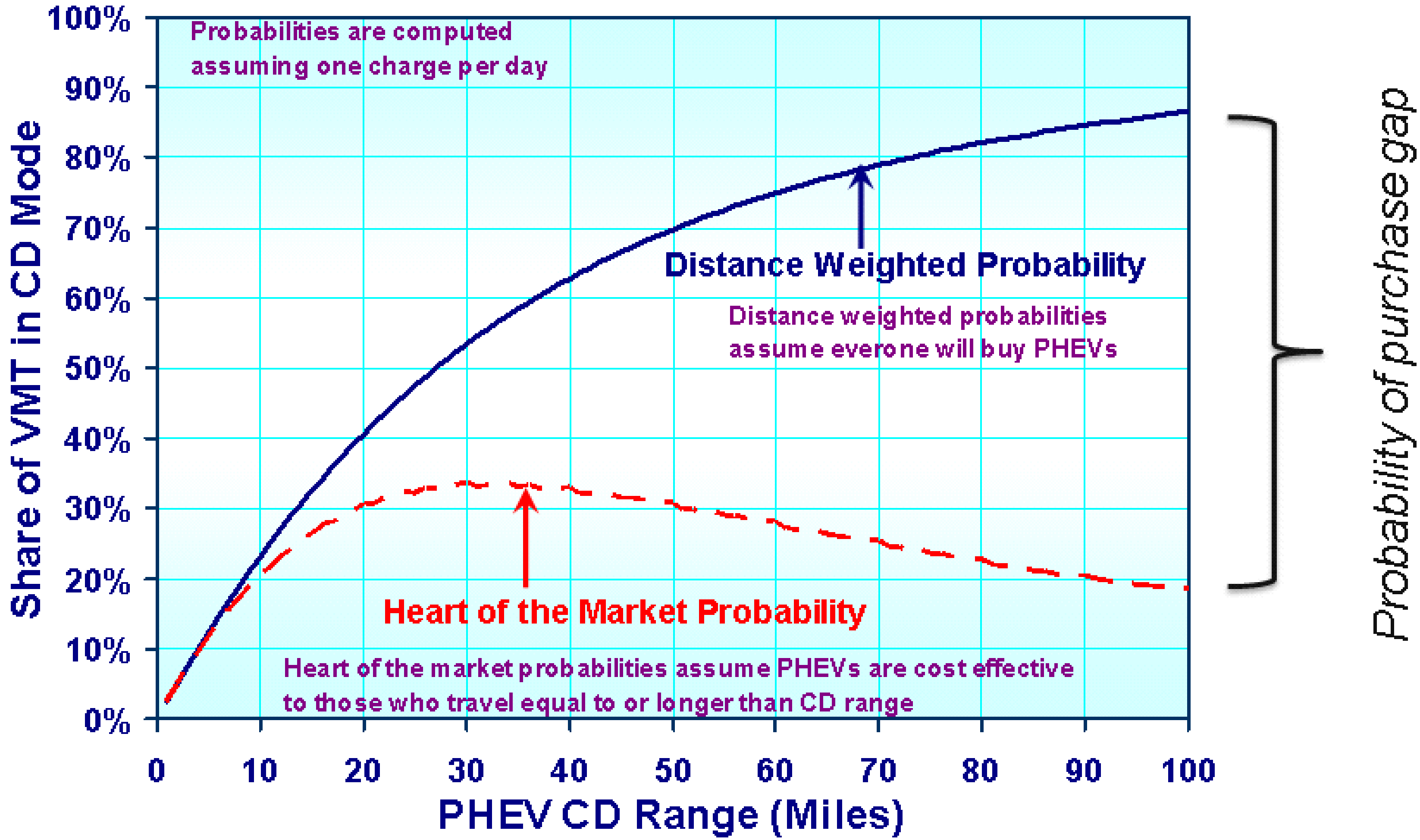
To achieve positive NPV via drivetrain electrification, PHEVs are far superior to BEVs, & gas prices must be "European"



Base is vs. CV; Incremental is vs. powertrain immediately below

From Kromer and Heywood 2007 Projections for 2030 – average driving

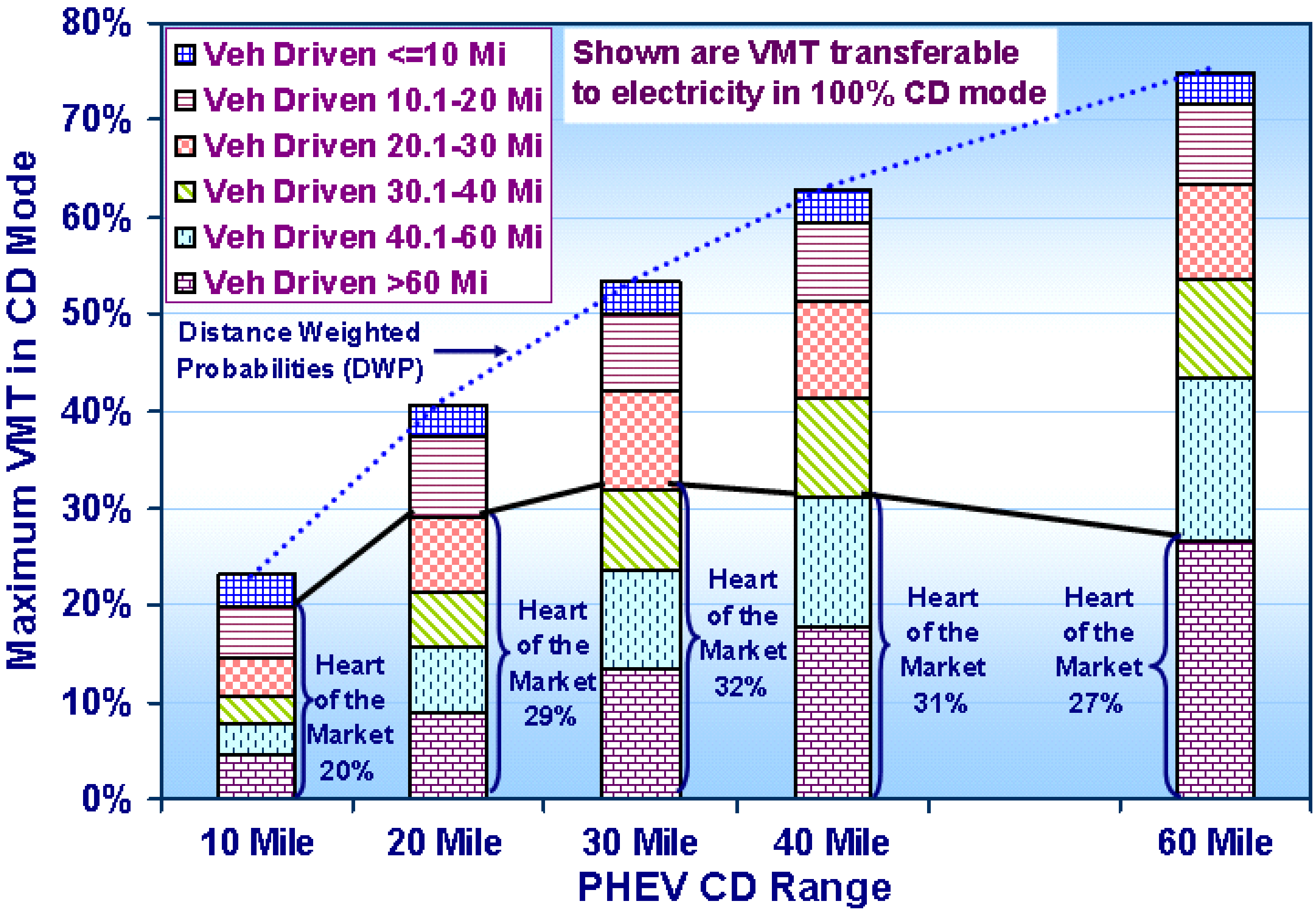
Distance weighted probability estimation of VMT electrifiable incorrectly assumes all consumers will switch to a PHEVxx



Two alternative estimates of vehicle miles of travel (VMT) electrifiable if all available PHEVs have only the specified charge depletion range

Note: The conceptual structure for the red line is roughly based on NPV logic . It assumes that due to costs of energy storage in batteries, consumers will not purchase PHEVs with range in excess of what they use daily. See Vyas, Santini and Johnson, TRB 09-3009, Jan. 2009

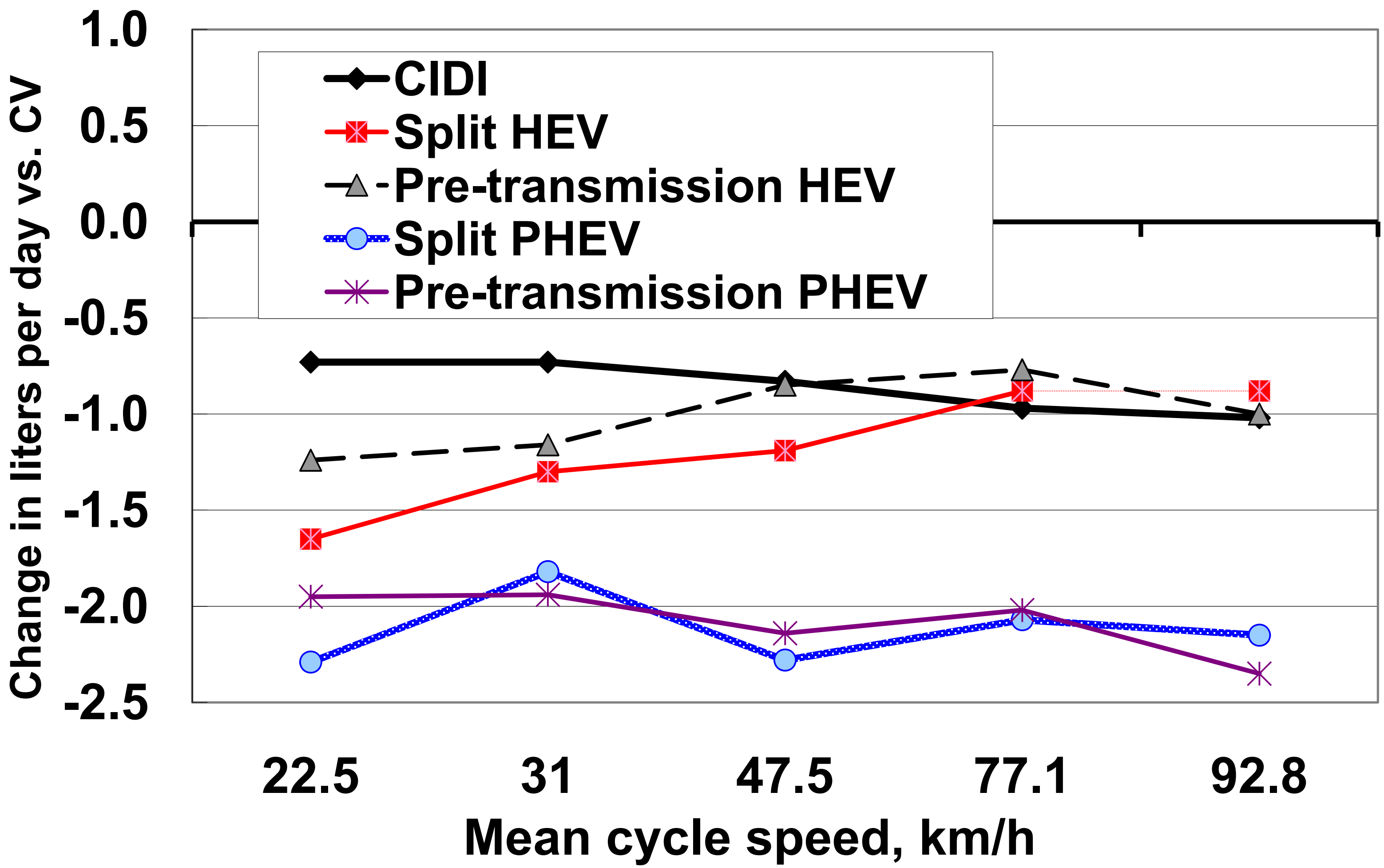
If only one charge depletion range were chosen for PHEV R&D, ~ 20-30 Mi. seems best (avoid too many kWh per PHEV)



Estimate of cost effective national market potential (black line) to electrify VMT if only one charge depleting range is in all PHEVs

Note: The conceptual structure - based on NPV logic - assumes that due to costs of energy storage in batteries, consumers will not purchase PHEVs with range in excess of what they use daily. See Vyas, Santini and Johnson, TRB 09-3009, Jan. 2009

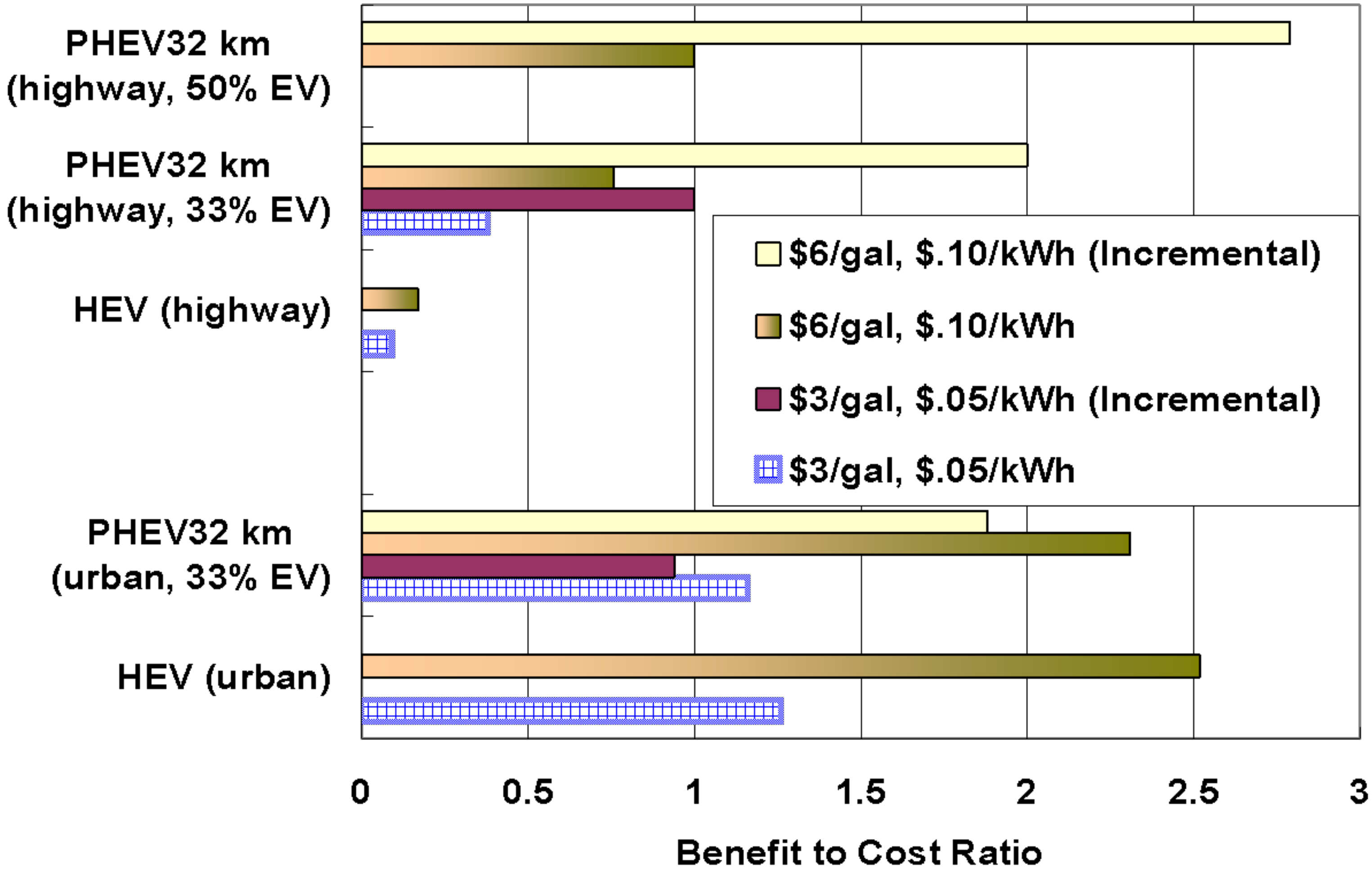
Estimated fuel savings/day via PHEVs increased vs. HEVs as simulated mean driving speed rose. HEV benefit vs. ICE dropped.



Estimated reduction in refined oil product use per day with one charge, compared to conventional gasoline fueled ICE (for PHEV"20")

Source: Santini and Vyas, The Influence of Cost-Benefit Analysis on the Conduct of Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains. Advanced Automotive Battery and Ultracapacitor Conference. May 12-16, 2008, Tampa, FL

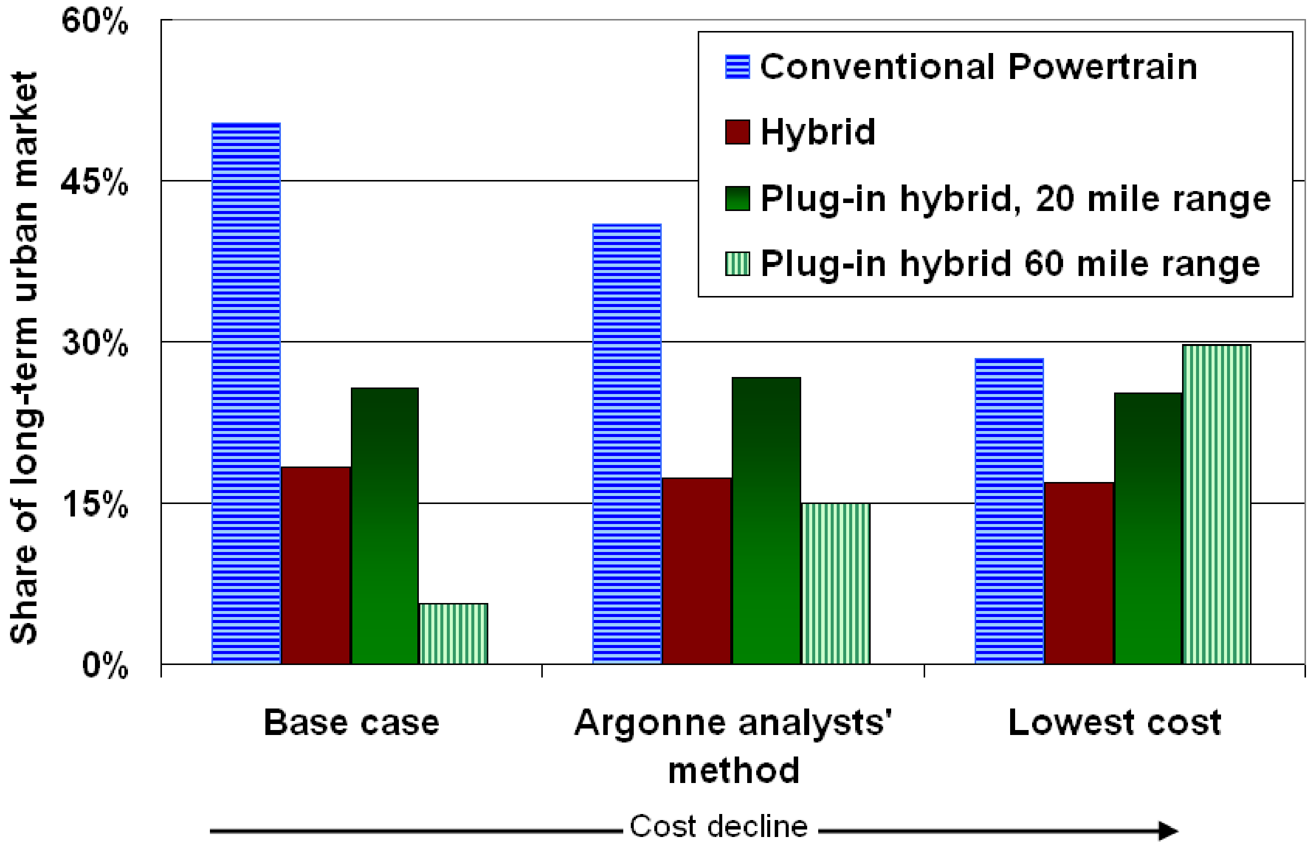
A HEV is a bit more cost effective than a PHEV in city (20 mph) driving; the PHEV is far superior in highway (48 mph) driving



Relative B/C ratio for HEV vs. PHEV options, both compared to ICE (using EPRI's '01 study – results to be re-verified, are not expected to change)

Source: Santini and Vyas, The Influence of Cost-Benefit Analysis on the Conduct of Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains. Advanced Automotive Battery and Ultracapacitor Conference. May 12-16, 2008, Tampa, FL

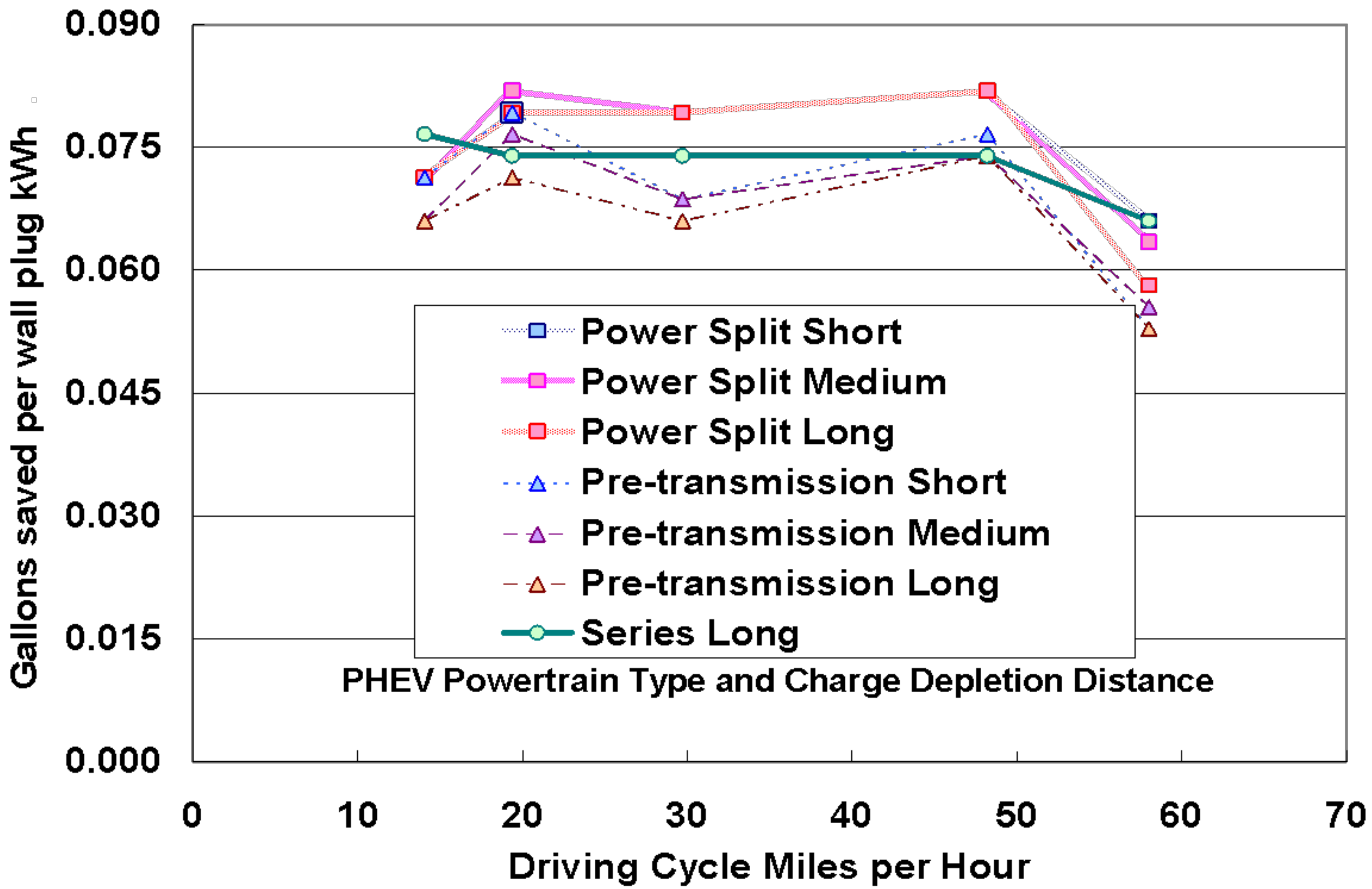
EPRI's 2001 market share assessment implied that widespread drivetrain electrification requires PHEVs and low cost batteries. It is expected that our NPV analysis will have the same implication.



Attainable shares, midsize car, as electric drive costs drop

Market share predictions from EPRI Report 1000349, 2001

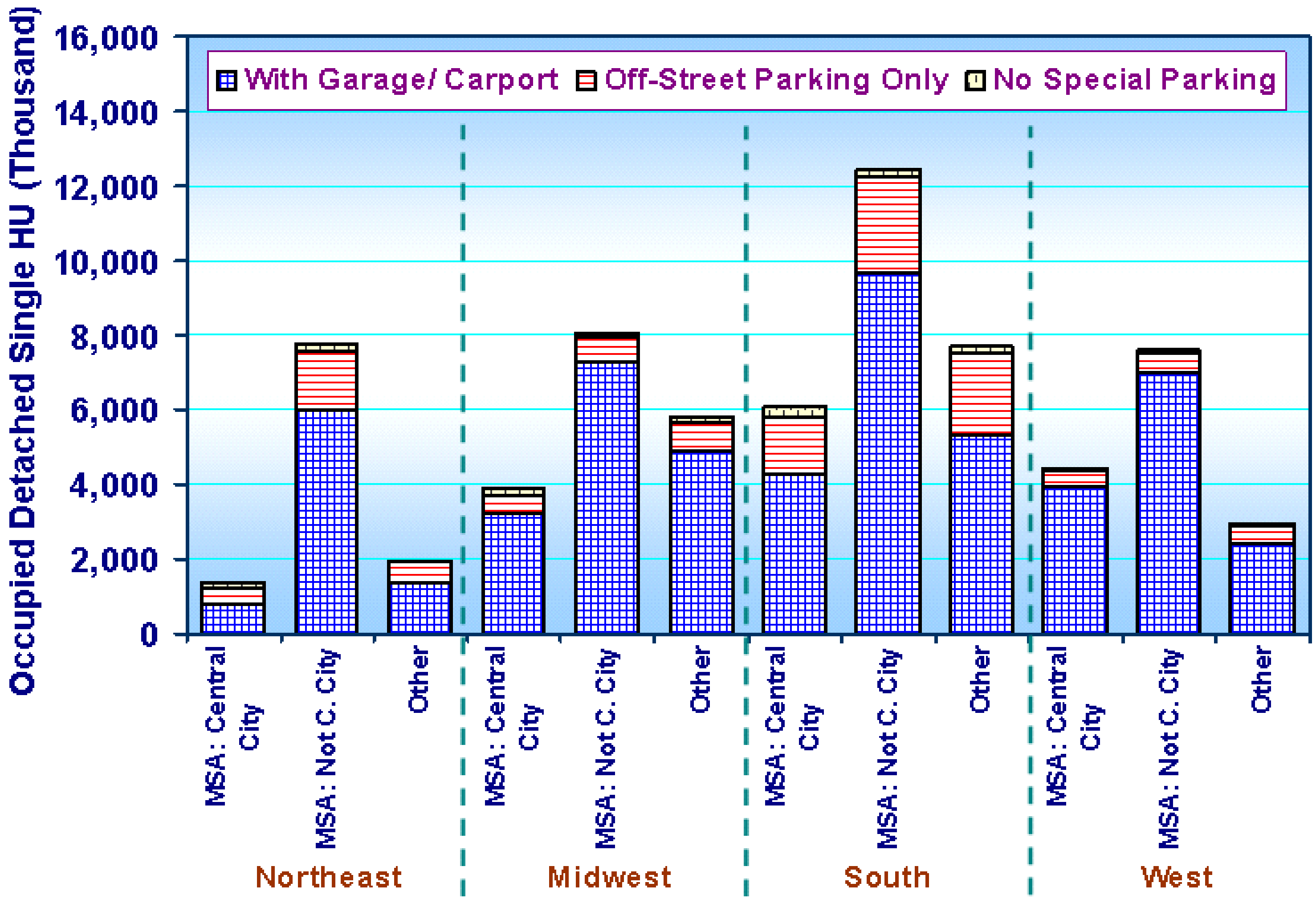
PHEV oil savings vs. HEVs may be relatively constant per kWh of grid electricity used, over a wide range of driving patterns.



Initial estimates of charge depleting fuel saved / kWh, vs. charge sustaining (HEV) fuel use

Source: Santini and Vyas, The Influence of Cost-Benefit Analysis on the Conduct of Life Cycle Analysis Comparisons of PHEVs to Competing Powertrains. Advanced Automotive Battery and Ultracapacitor Conference. May 12-16, 2008, Tampa, FL

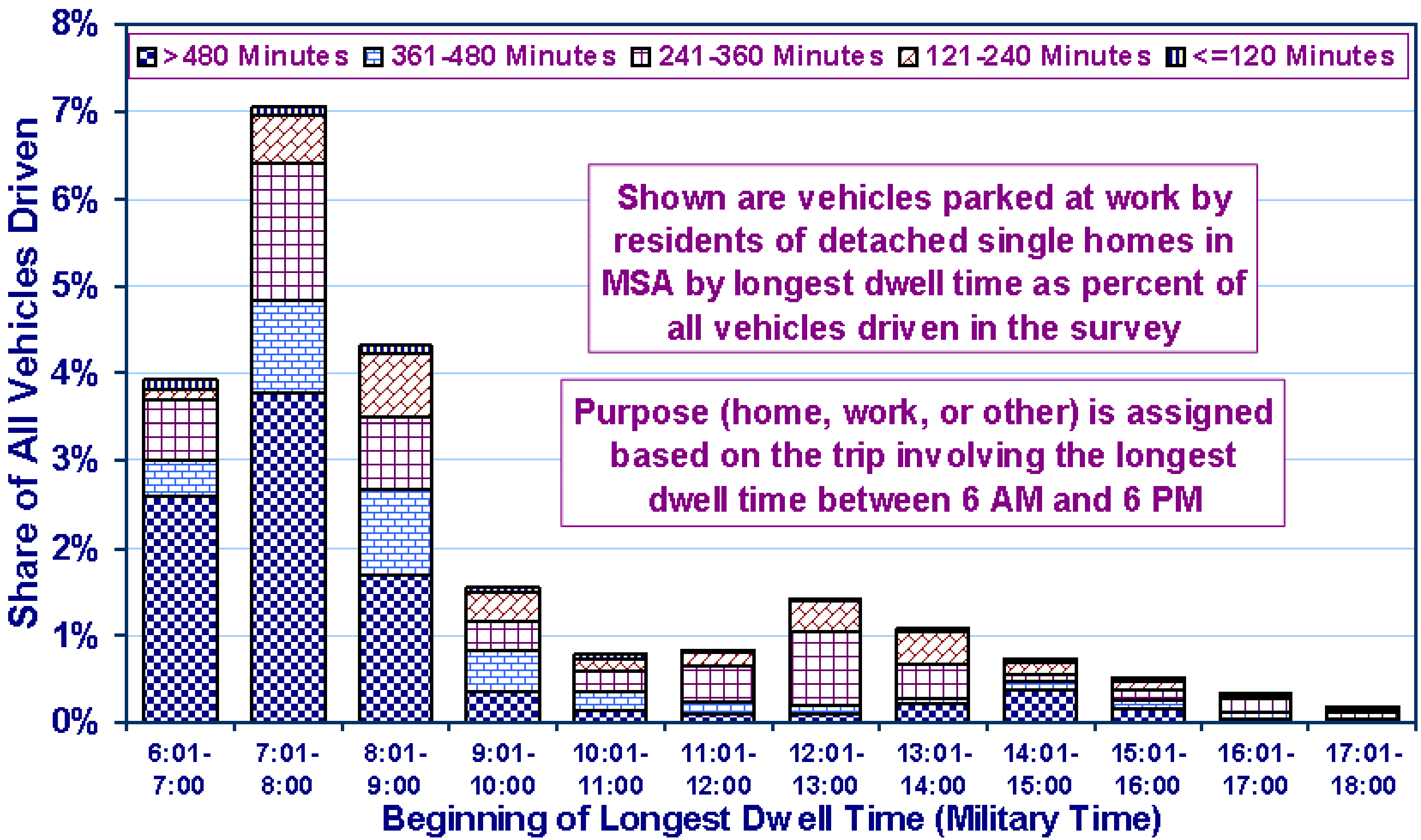
Suburbs are the target market for PHEVs



Note: In addition to higher incomes and garages in suburbs, favorable driving patterns are also a factor favoring suburbs

Source: Vyas and Santini, "Use of National Surveys For Estimating "Full" PHEV Potential For Oil Use Reduction", Plug-in 2008, July 21-24, San Jose, CA

PHEVs used for work trips have the greatest potential for twice a day charging, thus fast payback of battery kWh



Arrival Time vs. Parking Dwell Times For Vehicles Driven to Work

Planned future work:

- FY09: Comprehensive Argonne and EPRI report on trade-offs examined from 2007 thru early 2009
- FY10: Examine interactions of highway network attributes vs. PHEV oil and GHG savings vs. competing technologies on:
  - Neighborhood streets
  - Urban, suburban, rural streets and arterials
  - Urban, suburban and rural interstates
- FY 09-11: Conduct IEA PHEV study “subtask” on policy issues and marketability

Possible Summary for 2009 Study Findings (1):

- To successfully market electrification of drivetrains, PHEVs are <u>far</u> superior to EVs.
- Car (or small crossover)-based series or split PHEVs with moderate power (50-70 kW) and energy (~ 6-10 kWh) are most cost effective
- Suburbs are the target market for PHEVs
- HEV and PHEV powertrains are complements, not competitors (HEV for urban street driving, PHEV for urban/suburban arterial driving).
- PHEVs should be compared to conventional drivetrains in suburban driving conditions, not to HEVs
- Drivetrain electrification via PHEVs can most cost effectively reduce GHGs and extend fuel resources (enhance sustainability)
- PHEVs may never be a universal powertrain, will take time to cut oil use
- Best li-ion chemistries for PHEVs are probably different than for HEVs

Possible Summary for 2009 Study Findings (2):

- Traditional ICE, HEV and PHEV options in the same vehicle platform may diminish manufacturer risk and maximize national VMT electrification
- Considering demands of interstate driving, universal all-electric drive capability for PHEVs is too expensive for initial markets
- Due to demands of interstate driving, city electric vehicles are very limited in market share, will not save the nation a lot of oil
- Short to medium range blended mode PHEVs are very effective in miles electrifiable potential. Addition of workplace charging could enhance their effectiveness.
- Ultimately, corporate and/or regulatory decisions on target markets for HEV, PHEV, and EV powertrains determines the balance of power and energy to be sought in battery cell designs in DOE R&D programs, as well as the degree of emphasis on cycle life (kWh throughput) vs. calendar life.