Broad Overview of Plug-in Hybrids and Analytical Studies

Presented at:

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Danilo J. Santini

Section Leader, Technology Analysis

Center for Transportation Research

Sponsor: Office of Freedom Car and Vehicle Technologies

U.S. Department of Energy

E. Wall, Program Manager, Office of Freedom Car and Vehicle Technologies

T. Duong, Team Leader, Vehicle Systems Technologies

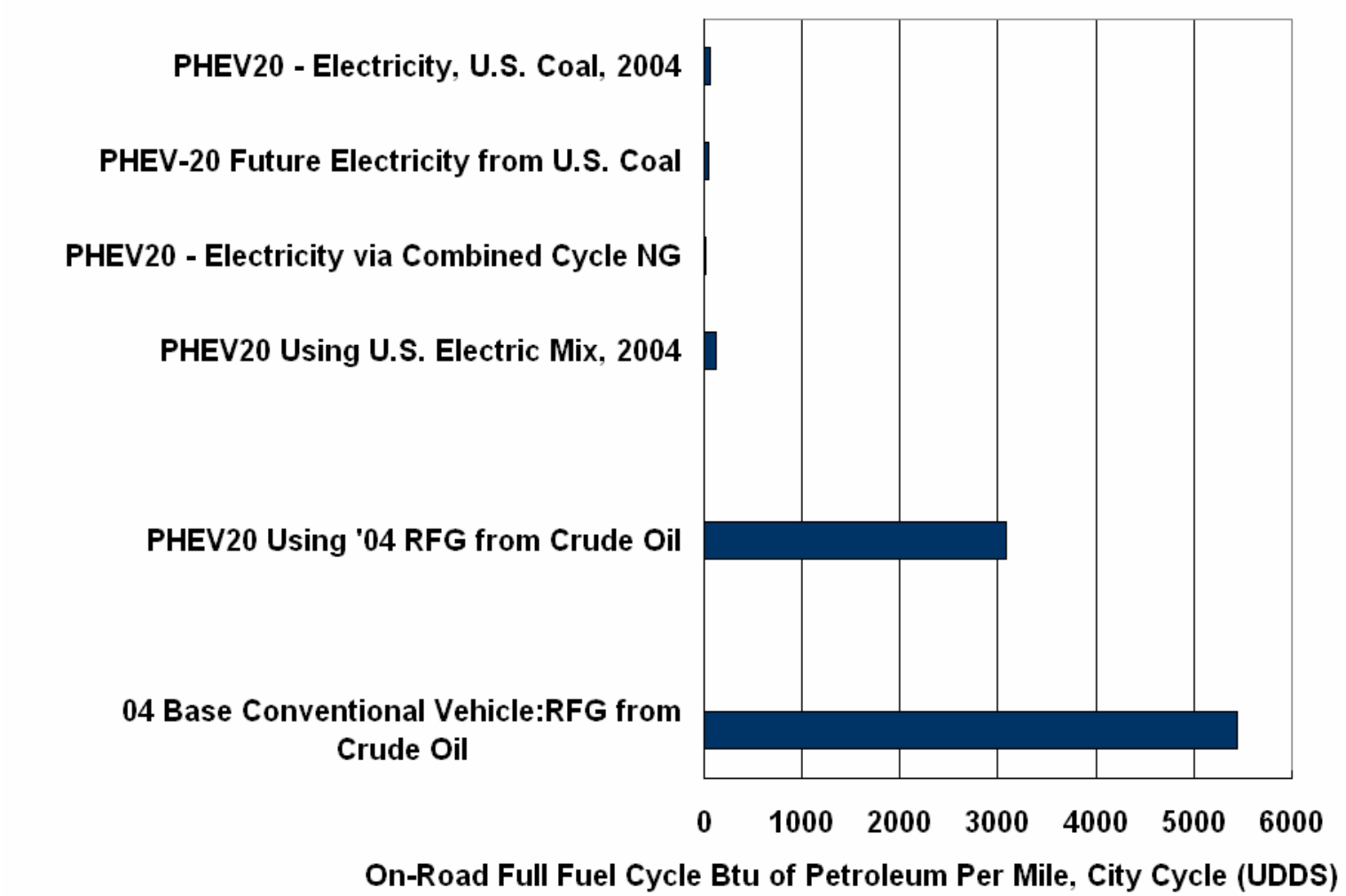
Topics

- Why the expanding interest in PHEVs?
- Would massive success with PHEVs stress power generation?
- Would massive success stress the grid?
- What new sources of power would be favored for expansion?
- How does the pattern of driving interact with PHEV design?
- How would successful R&D, achieving cost reduction, affect patterns of PHEV preference?
- Is a shift of preferred HEV/PHEV battery chemistry underway?
- Illustrations of some of the technical problems to address
- Have PHEVs jumped into public consciousness?
- Provide a closing list of important questions to discuss

Why more interest in plug-in hybrids with new EPACT legislation authorizing new government/industry programs?

- **Oil savings** (heightened interest due to oil price increases)
  - "our nation is addicted to oil" President Bush
  - EERE priority – improve energy security by reducing oil imports
- Focus of 2001 studies: CA desire for zero tailpipe emissions
- Greenhouse gas reductions (cumulative climate change science)
- Electric utility efficiency (load leveling)
- Emergency services (hurricanes, power failures, spot gasoline shortages)
- Improvements in li-ion battery technology
  - (li-ion eclipses NiMH in consumer electronics)

Oil Savings: Each PHEV (Full HEV) Sharply Reduces Oil Use Even If No Electricity is Used, Far More if Electricity is Used



Oil Use, Electric Generation Expansion, Change in Power Plant Mix and Greenhouse Gases With PHEVs in Future Decades:

2 Current National Lab PHEV Initial Scenario Analyses

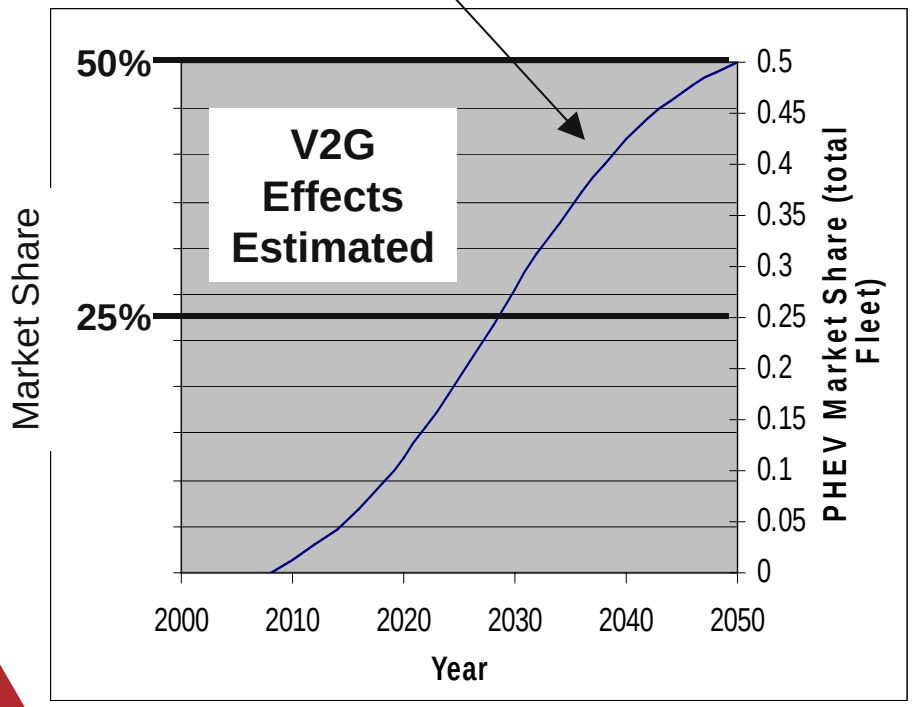
(Others coming from EPRI, more from National Labs)

What Could The Effect on Oil Use, Electric Generation, and Carbon Emissions Be if Massive Success of PHEVs Were Achieved?

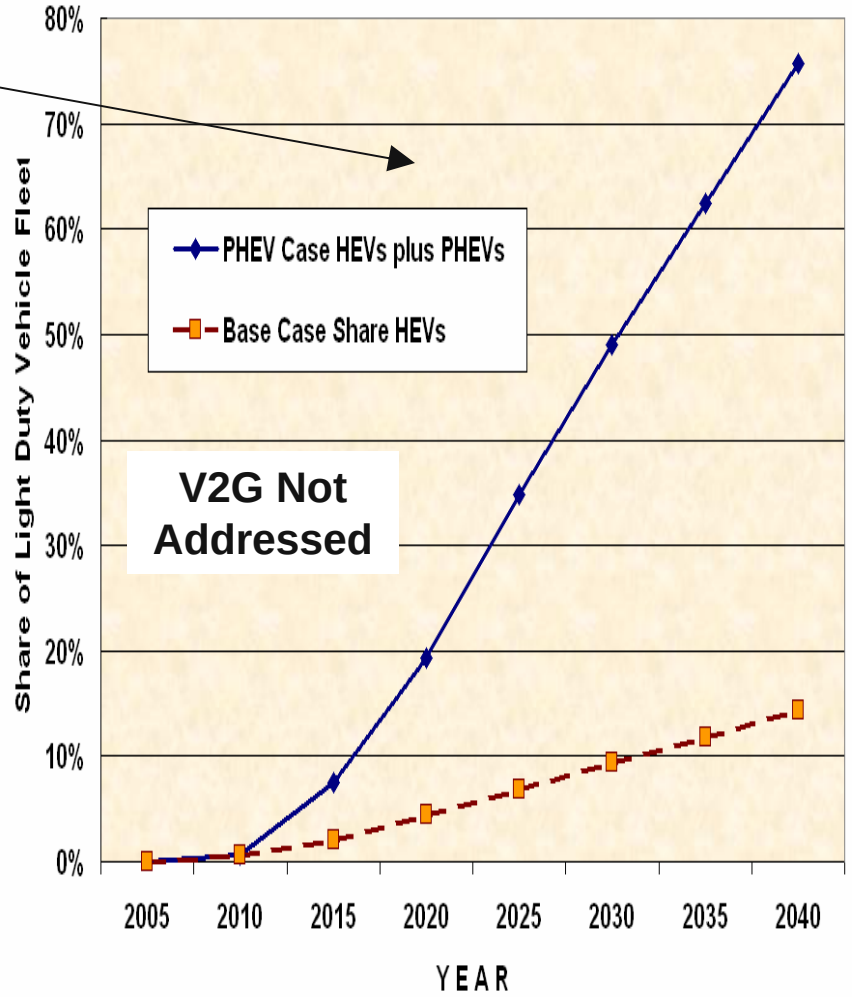
"What If" scenarios

AMIGA Scenario by Argonne

WinDS Scenario by NREL



Courtesy of W. Short, NREL



Courtesy of D. Hanson, Argonne

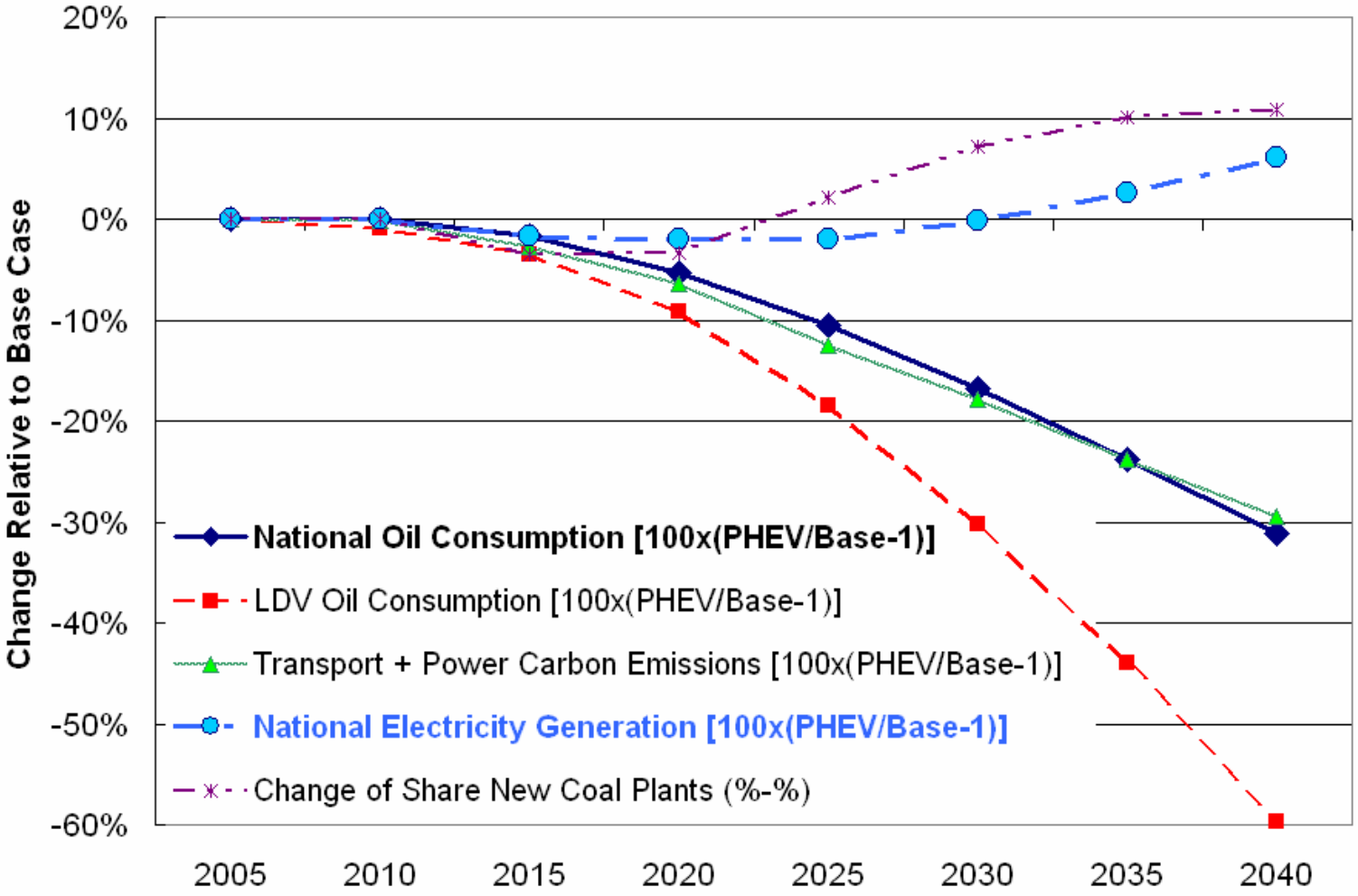
Massive Success Requires a Few Percent Increase in Total Generation, Leads to Significant Use of Wind Power

Summary of 2050 WinDS/PHEV Results – PHEV Cases Compared to Base Case

2050 Projected Values	Base Case (no PHEVs)	PHEV-20 Case	PHEV-60 Case
Gasoline use (Billions of Gallons)	368	255 (31% decrease)	212 (43% decrease)
Wind Generation (TWh/year)	757	853 (13% increase)	1554 (105% increase)
Total Load (TWh/year)	9392	9808 (4.4% increase due to PHEV load)	10082 (7.3% increase due to PHEV load)
Increase of Wind Electricity vs. Base Case	-	0.6%	7.5%
Total Installed Generation Capacity (GW)	2161	2092	1972
Generation from Coal (TWh/year)	8272	8597 (3.9% increase)	8169 (1% decrease)
Electric and Light Duty Transport Sector CO2 (Million Tons CO2/year)	10956	9910 (9.5% decrease)	9346 (14.7% decrease)

Courtesy of W. Short, NREL

With A Higher PHEV Penetration Scenario Than in WinDS, AMIGA Obtains Higher Oil Savings (also by Including Coal-to-Liquids for Co-Production of Diesel Fuel and Electricity)



What Should be Assumed to be the Long Term Marginal (Incremental) Source of PHEV Electricity?

PREDICTED CONTRACTING & STABLE SHARES IF PHEVs SUCCEED

- **Coal: AMIGA and WinDS PHEV60 cases predict reduced coal use**
- **Nuclear: WinDS decline, AMIGA steady production share**
- **Oil and Gas: WinDS uses AEO declines for "oil-gas-steam" power plants, and assumed a high gas price, shrinking other natural gas**

PREDICTED INCREASING SHARES

- **Wind**
  - **Both AMIGA and WinDS predict more expansion of wind than natural gas or "other" (renewable) power generation**
- **Other (hydro, biomass, geothermal, waste to electricity, solar)**
  - **AMIGA predicts an increase**
- **Natural Gas**
  - **AMIGA predicts some expansion of natural gas**

PNNL Electric Infrastructure Capability Study Early Findings Show >> National Reserve Capacity to Serve PHEVs Than Needed, But …

Preliminary conclusions:

- Idle grid capacity (generation, T&D) is adequate to supply ~50% - 65% (or more) of energy for U.S. cars and light trucks at hybrid performance levels
- There are significant regional differences based on varying reserve margins across regions
- Todays' CO_2 impacts approximately neutral for today's baseload and intermediate plants (10% above or below current emissions depending on region)
- Significant issues for coordinating vehicle charging with grid peak loads, reliability needs, and market and other signals

Prior EPRI and/or Argonne Studies (2001) Examined the Following Questions

- **Ni-MH batteries (too pessimistic on power)**
- **20 and 60 mi. of EV range (CARB credit kink points)**
- **CAFE MPG assumptions (too optimistic on electric miles?)**
- **Variation in battery cost as function of kW/kWh ratio**
- **Charge depletion to achieve ZEV range operating as EV**
- **Consumer preferences, given education about HEVs**
- **Effects of requiring a range of 0-60 times (12, 10, 8 sec.)**
- **Effects of varying powertrain costs on marketability**
- As EV, approximate capability to match US06 driving schedule
- Automated manual transmissions in HEVs
- Minimum sustainable top speed, PNGV gradeability minimum
- Economics of series vs. parallel HEV (parallel superior)
- Effects of a reduced load glider on mpg of HEV vs. CV (like the Prius)
- Total fuel cycle pathway emissions

Average National Miles Per Day ~ 30 Miles, Typically Composed of Several Short Trips

- Instrumented vehicle results
  - Baltimore 4.0-5.9 mi.- average of 4.9
  - Spokane 3.6 mi.
  - Atlanta 6.0 mi.
- EPA MOVES 2004 assumptions
  - Passenger cars: 4.4 mi., 7 starts/ average day
  - Light trucks < 6000 lb: 4.8 mi., 7 starts/ average day
  - Light trucks > 6000 lb: 4.6 mi., 7 starts/ average day

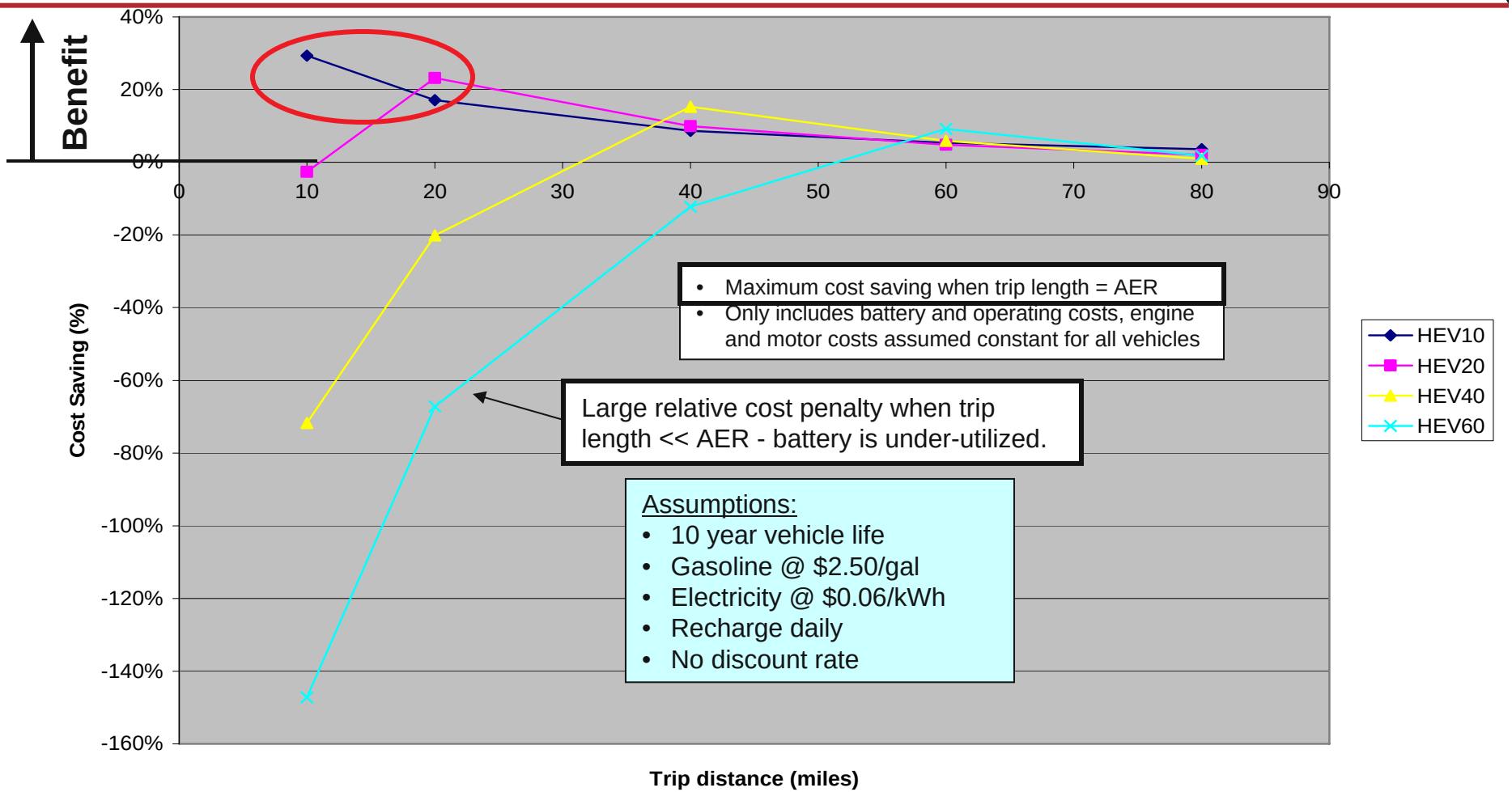
Derivative questions relating to PHEV design, benefits:

How many of the 7 starts are “cold”?

How many of the trips could be in EV mode?

What is top speed of short trips?

NREL Investigation of Cumulative Costs Indicates Shorter Ranges Offer More Consistent Benefits. Customer Needs For Range Will Differ Significantly

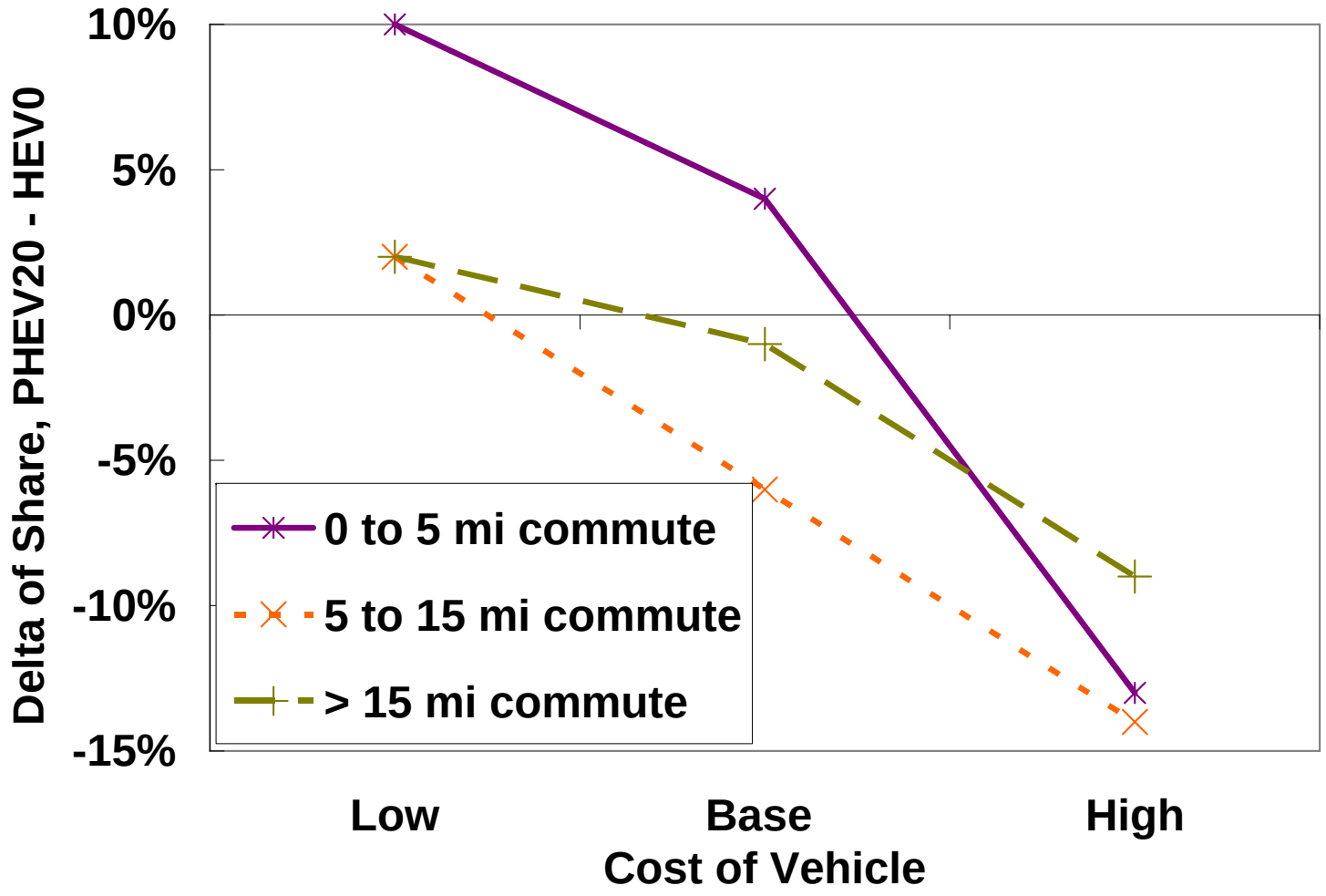


Plug-in HEV Annual Cost savings relative to HEV0 vs. Trip Distance (73% DOD window) as a percentage of HEV0 Annual Costs

EPRI Surveyed Consumers in Major Urban Areas About Preferences for HEVs, PHEV20s, and PHEV60s

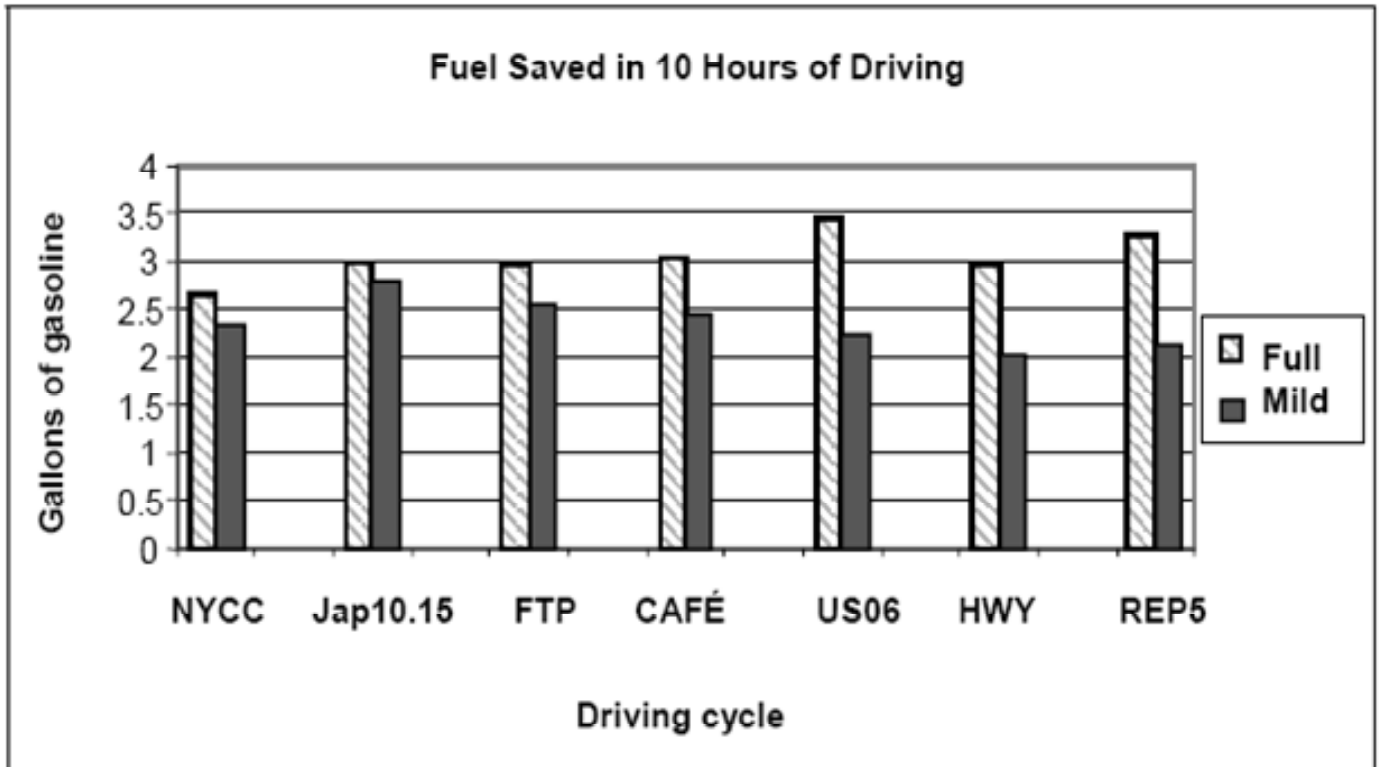
- Boston, Atlanta, Phoenix, Los Angeles
- 60 trade off questions for nine attributes of HEVs
- Respondents were separated into “commute bins”
  - 0-5 miles (28% of sample) 7700 miles/yr
  - 5-15 miles (30% of sample) 11900 miles/yr
  - >15 miles (42% of sample) 17975 miles/yr

Those With Short Commutes in the EPRI 2001 Survey Had Most Interest in a PHEV20



Think Differently About HEV/PHEV Fuel Advantage: Hrs/Driving are Key, Not the Miles

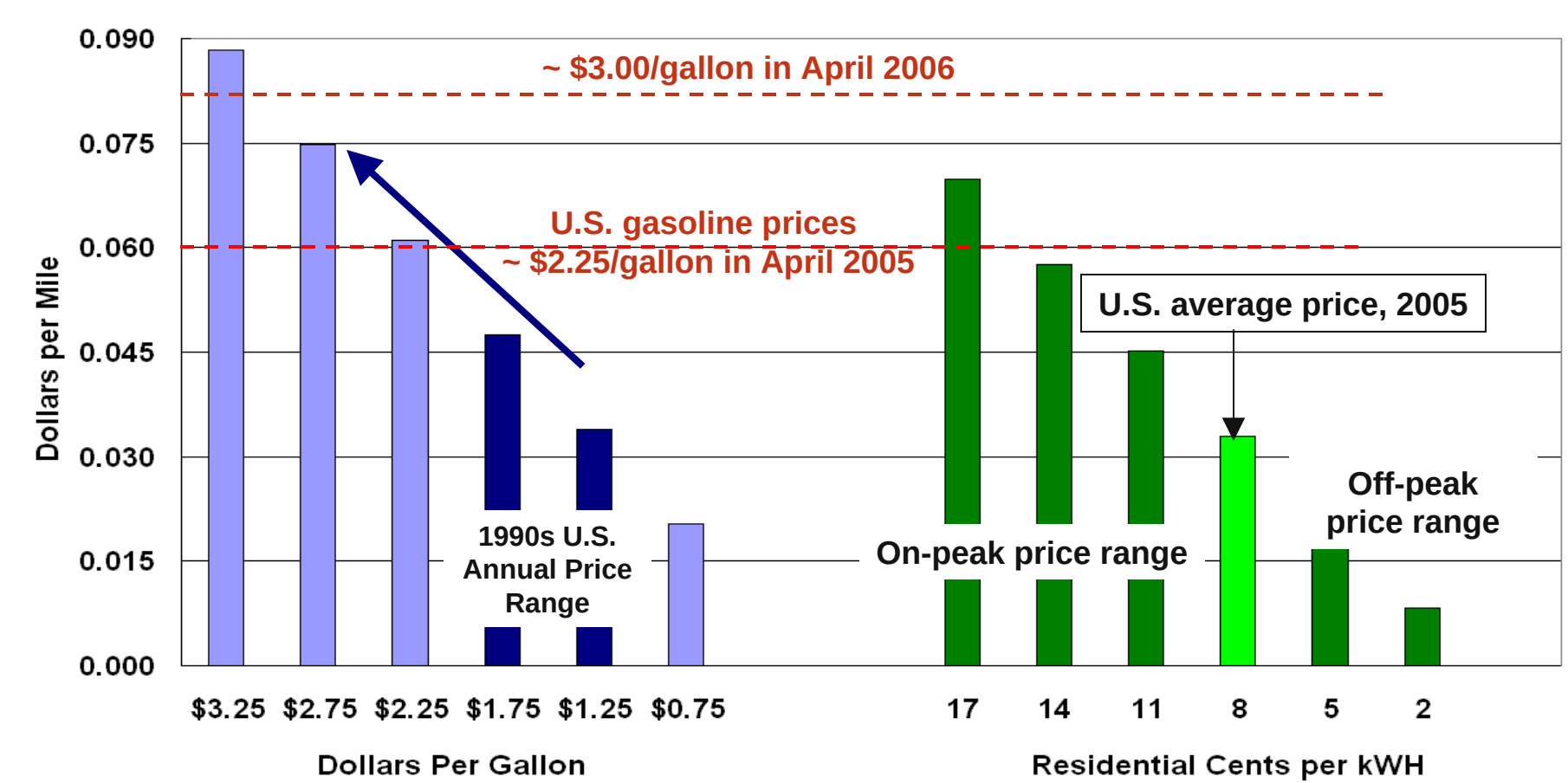
Note: Observation from U.S. NPTS and International studies: Hours per day are relatively constant across drivers in the U.S. and on average across nations



Predicted Hourly Fuel Savings by Switching from a Conventional Vehicle to Hybrid, by Driving Cycle

From Argonne Hybrid Electric Vehicle Technology Assessment, 2001

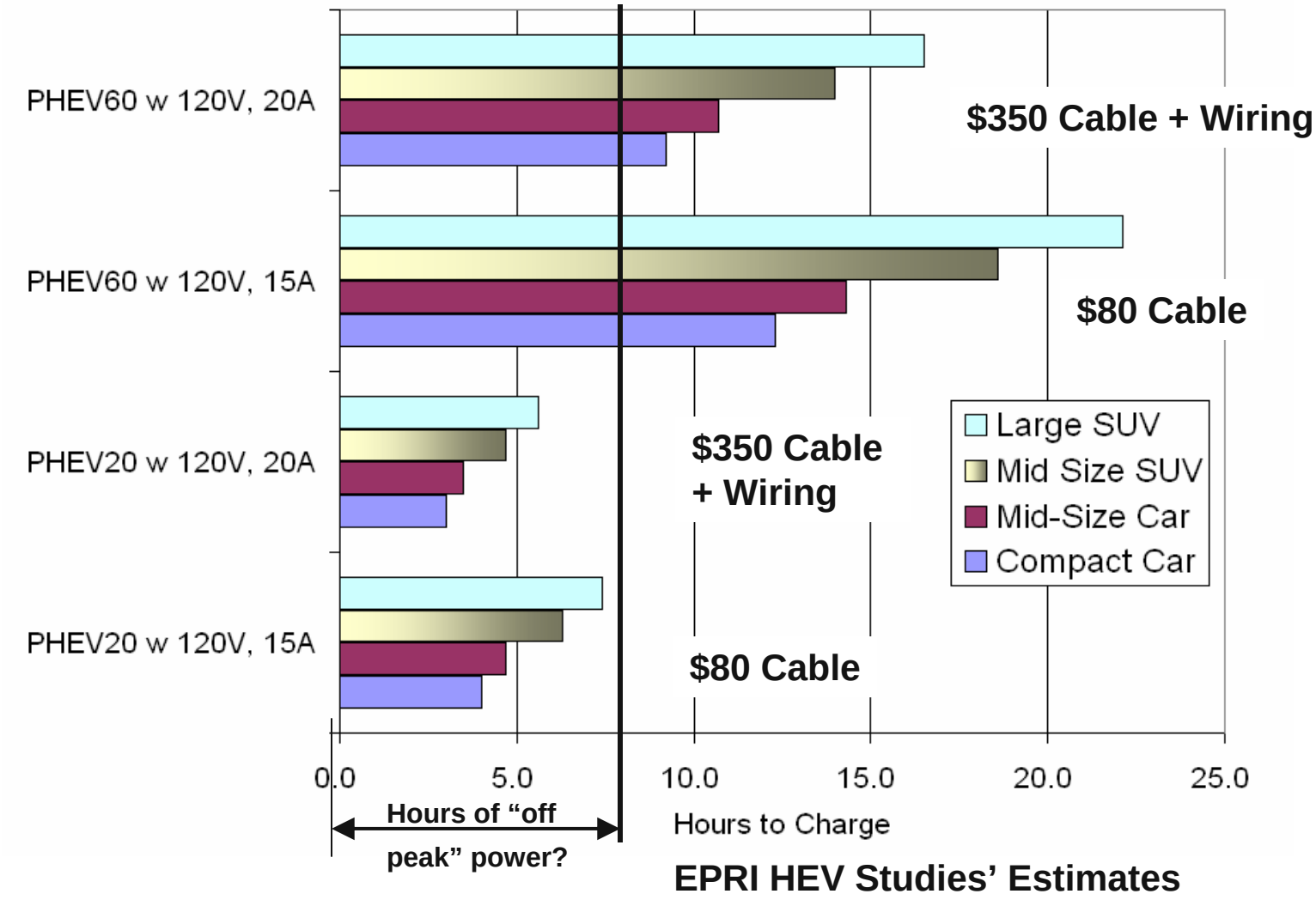
U.S. Average Electric Rates Imply Considerable Per Mile Savings for PHEV20 Electricity Use at Present Gasoline Prices



On-Road Fuel Costs Per Mile - EPRI Mid-Size HEV20 on Gasoline or Electricity, City Cycle (UDDS)

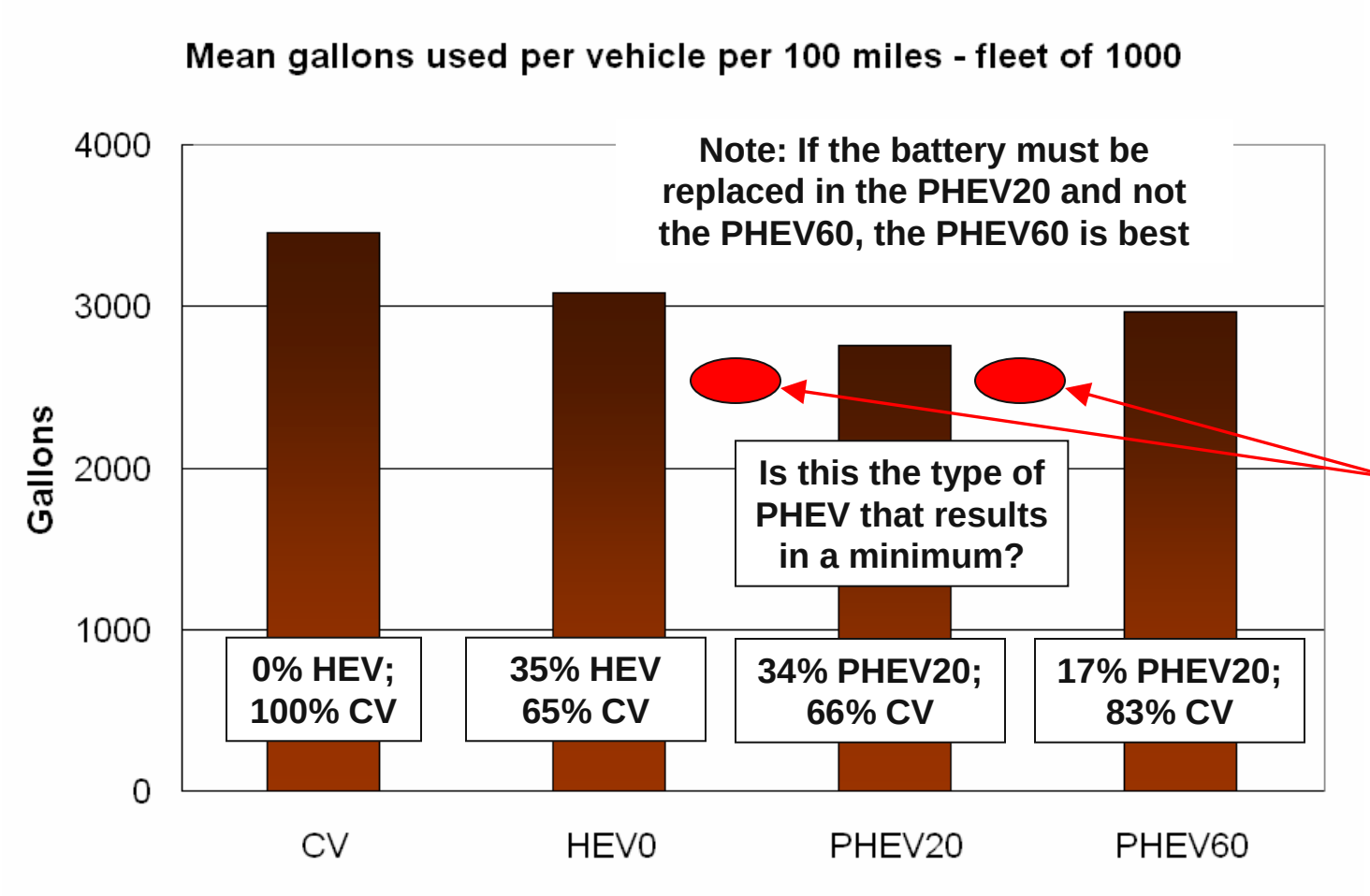
(HEV20 is a plug-in hybrid with 20 miles of AE range, 0.4 kWh/mi assumed [higher than EPRI study])

Charging PHEV60s Would Push Non-Vehicle Customer Costs Up Considerably, Due to Needed Rewiring to Allow Faster Charging to Stay in an Off-Peak Time Window



Source: EPRI 1006892, 2002 and 1000349, 2001

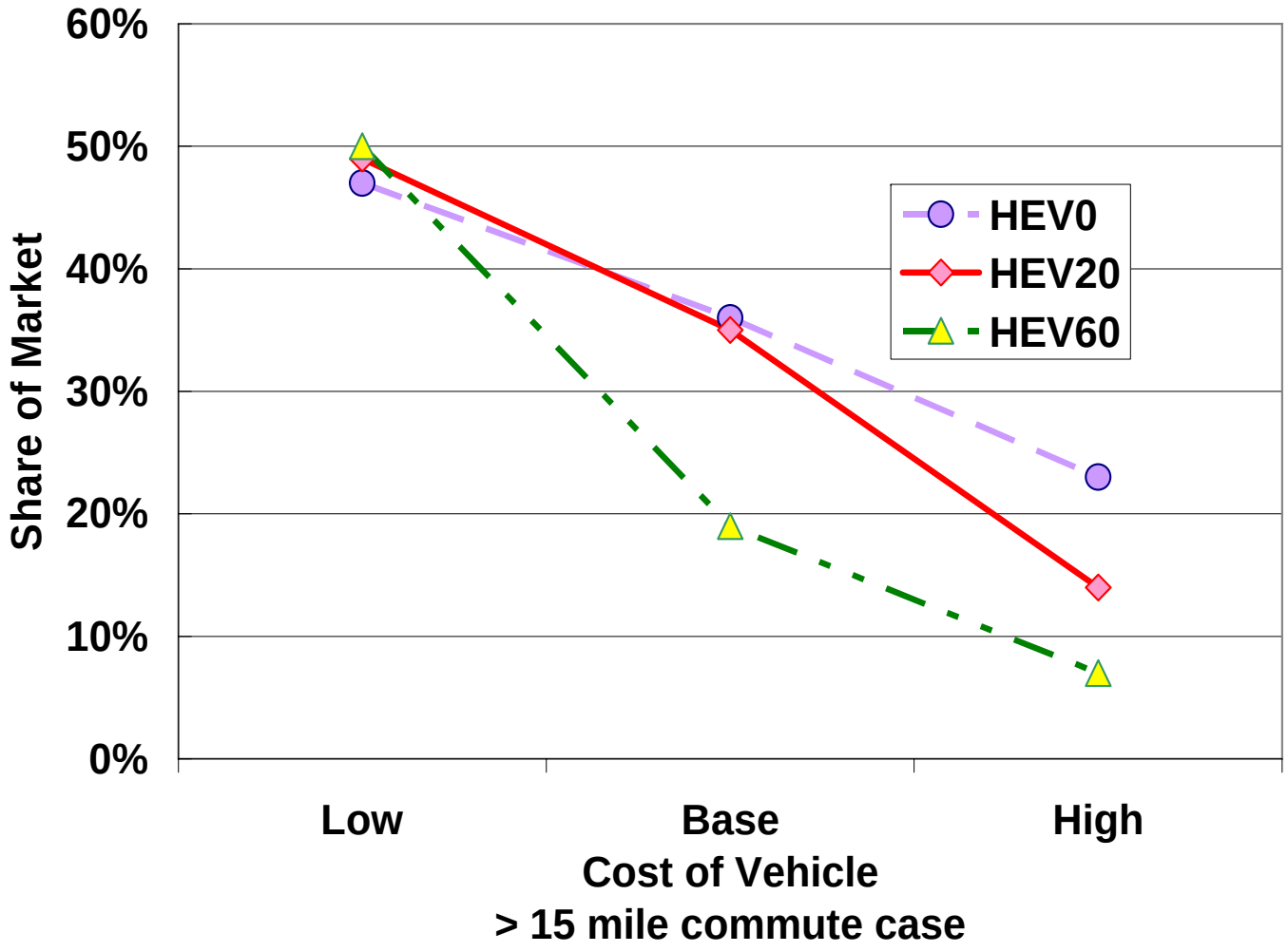
Considering EPRI HEV Type Market Share Estimates, Which PHEV Would Save Most Oil?



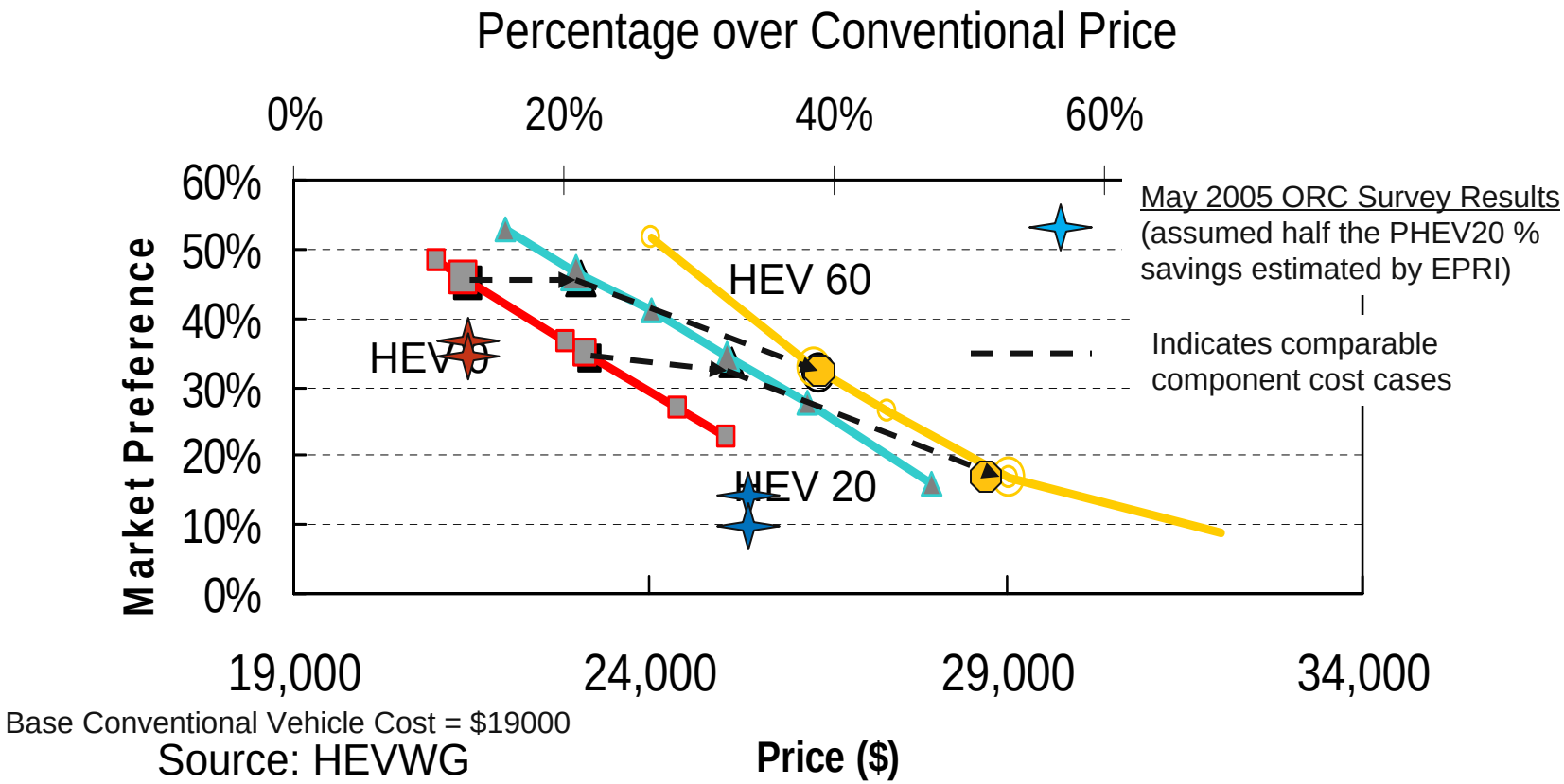
Mid-size car – HEV powertrain paired against the conventional (no other HEV competitor)

Source: EPRI 1000349, 2001

As Powertrain (Battery!) Costs Drop, Share of All HEVs Rises. For Long Commutes, Low Costs, PHEV60s Close the Gap & Compete



EPRI Survey Results Imply Significant Increase in Share if Research Leads to Declining PHEV Incremental Costs. Markets Exist Even at High Costs



Base Conventional Vehicle Cost = $19000

Source: HEVWG

Each line represents market potential versus price for a simple market in 2010 where HEV 0 and conventional models are available in each mid-size model, or HEV 20 and conventional models compete. The six points on each line are calculated with a common methodology. The two enlarged points on each line show the base case range (before government or automaker incentives). The base case range assumes costs using 100,000 HEVs per year and also reflect different methods of estimating the retail price estimate.

Summary on PHEV Range and Market Opportunities

- Half of U.S. households have daily mileage under 30 mi.
- For these customers, at costs used, NREL cost effectiveness analysis implies PHEV40s and PHEV60s would have a net cost, while PHEV10s and PHEV20s have net benefits.
- EPRI consumer preferences analysis indicated a subset of urban drivers with short commutes, with total driving averaging ~ 20 mi/day, have greatest interest in PHEV20s over HEVs, and consistently prefer PHEV20s over PHEV60s, regardless of price.
- The EPRI survey also indicates that if less expensive batteries and PHEV powertrains emerge from R&D, a significant expansion of the market for longer range PHEVs could be realized among long range commuters.
- For long range commuters, in the EPRI low powertrain cost case, PHEV60s were as likely to be chosen as PHEV20s.

A Sequence of Announcements: Interest in a Plug-in Feature for Hybrids is Emerging Jointly with the Lithium Ion Battery in HEVs

- 2000 DOE Shifts Battery R&D to Li-ion for Advanced Hybrids and Hybrid FCVs
- 2001 EPRI and Argonne Publish PHEV Analyses Based on NiMH
- DaimlerChrysler Diesel PHEV Sprinter Vans (9/04) (initial plans for NiMH, Li-ion now preferred)
- Turning the Prius into a Plug-in Hybrid (12/04) (initial experiments with PbA)
- Commercial Retrofit for Plug-in Prius by E-Drive Using Li-ion Pack (5/05)
- Hymotion Unveils Plug-in Hybrid Kits for Toyota and Ford Hybrids, Both Using Li-ion Packs (2/06)
- SAAB Unveils E100 Hybrid (show car with 6-12 mi. electric range if < 31 mph and if li-ion battery pack is used) 3/06
- Mitsubishi Fuso Shows Medium Duty Hybrid Cabover Work Truck in U.S. 4/06
  - (not a plug-in, but with li-ion battery pack)

Fundamental Question:

What is the hybrid battery chemistry of the future?

Nickel metal hydride

Lithium ion

Is that also the plug-in hybrid battery chemistry of the future?

Many Questions and Technology Options Were Not Previously Examined

- **Items not addressed in the 2001 studies**
  - **Li-ion batteries**
  - **Desirability of a wide spectrum of electric ranges**
  - **Varying electric operations capabilities – top speed, acceleration rate**
  - **Effects of highly variable, often wide SOC swings on battery power/life**
  - **Multiple HEV powertrain configurations**
  - **In-use vs. certification cycle fuel economy**
  - Incremental cost/benefit evaluations
  - Charge depletion w/o EV only operation
  - Towing requirement effects
  - Isolation of HEV vs. PHEV incremental benefit/cost
  - Urban vs. non-urban & morning vs. other emissions
  - New studies indicate U.S. trips are shorter than assumed

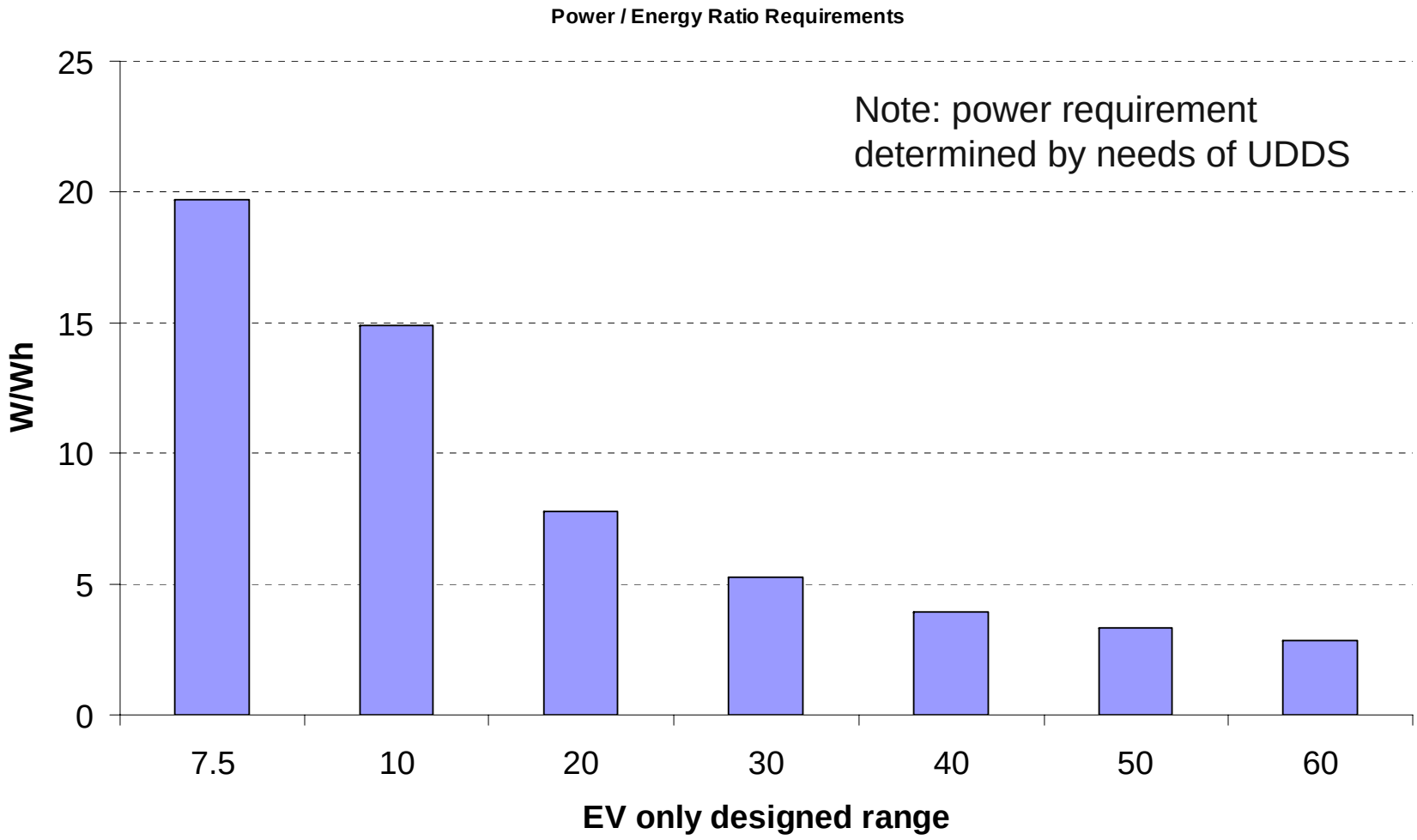
The Balance of Engine and Battery (or Motor) Power for PHEVs Could Vary Significantly, Depending on Performance Specifications, Design Strategy, Customer Needs

Selected statistics from some PHEV simulations – 2000-2006

Parameter	Camry	EPRI	Argonne	Argonne	EPRI	Argonne	NREL	Argonne	EPRI
Electric range (mi.)	0	0	7.5	10	20	30	40	50	60
Date prepared	2006	2000	2006	2006	2000	2006	2006	2006	2000
Engine Power (kW)	110	67	75	75	61	76	82	83	38
Motor Power (kW)	105	44	40	40	51	41	48	45	75
Battery Power (kW)	30	49	50	60	54	50	52	100	99
Battery (kWh)	1.8	2.9	2.5	3.5	5.9	9.5	18.5	16	17.9
Vehicle Mass (kg)	1669	1603	1609	1610	1651	1665	1703	1843	1767
Peak EV mph	30s	>80	>55	>55	>80	>55	>80	>55	>80

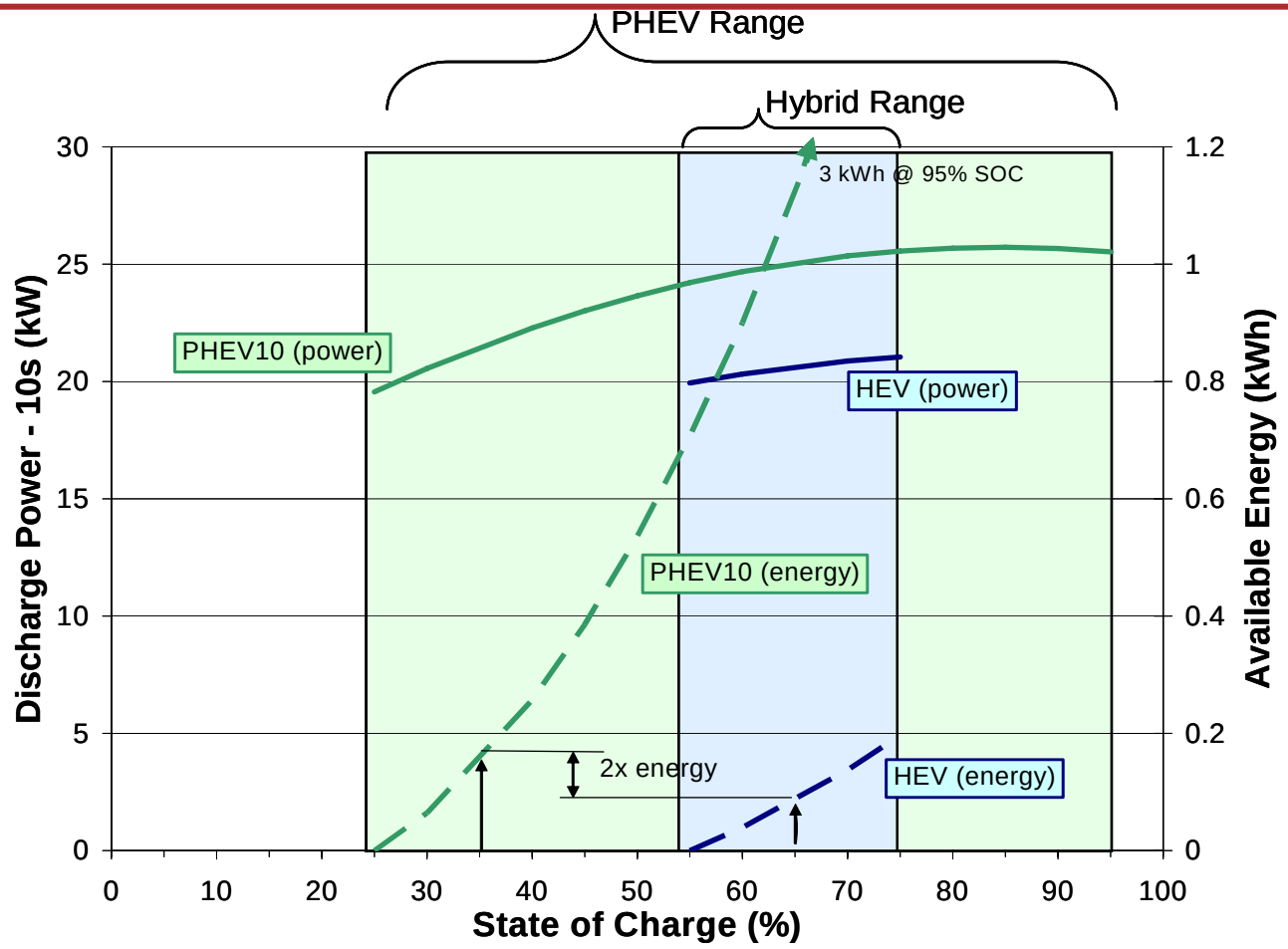
Note: Recently prepared Argonne examples are selected from the “low tech” cases
EPRI cases are from the conventional mid-size glider case, not the low load vehicle
All cases are for a mid-size passenger car

As the Range of PHEVs Rises, the Needed Battery Power to Energy Ratio Declines.
(This reduces $/kWh costs [not shown])



Source: PSAT simulations courtesy of A. Rousseau, Argonne

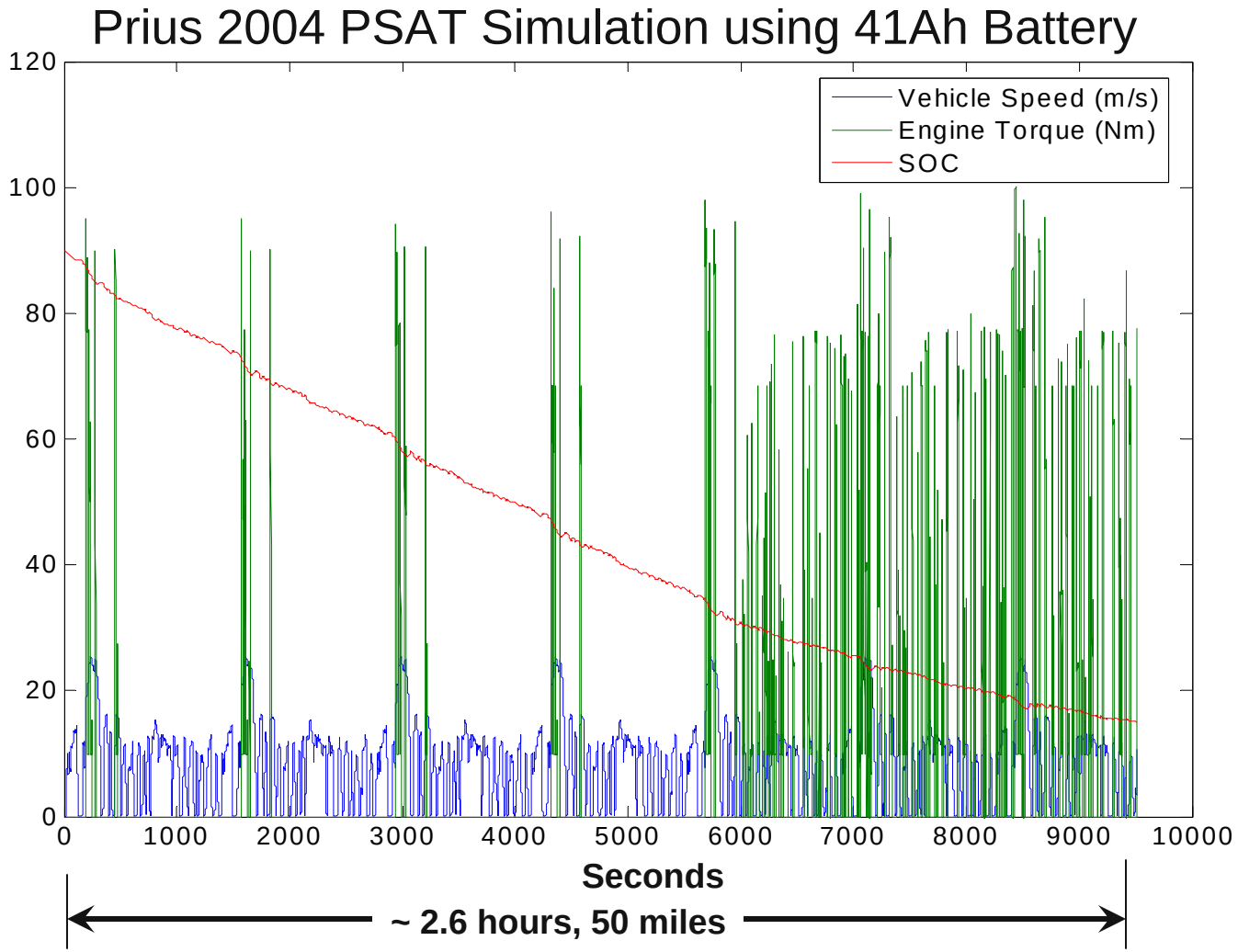
The Ability to Pull Electricity From a Battery to Move a Vehicle is Related to Power. Below Demanded Power, Less Power = More Time to Use a kWh. Battery Power Drops with DOD



Example: PHEV10 vs. HEV0, Li-ion pack simulation

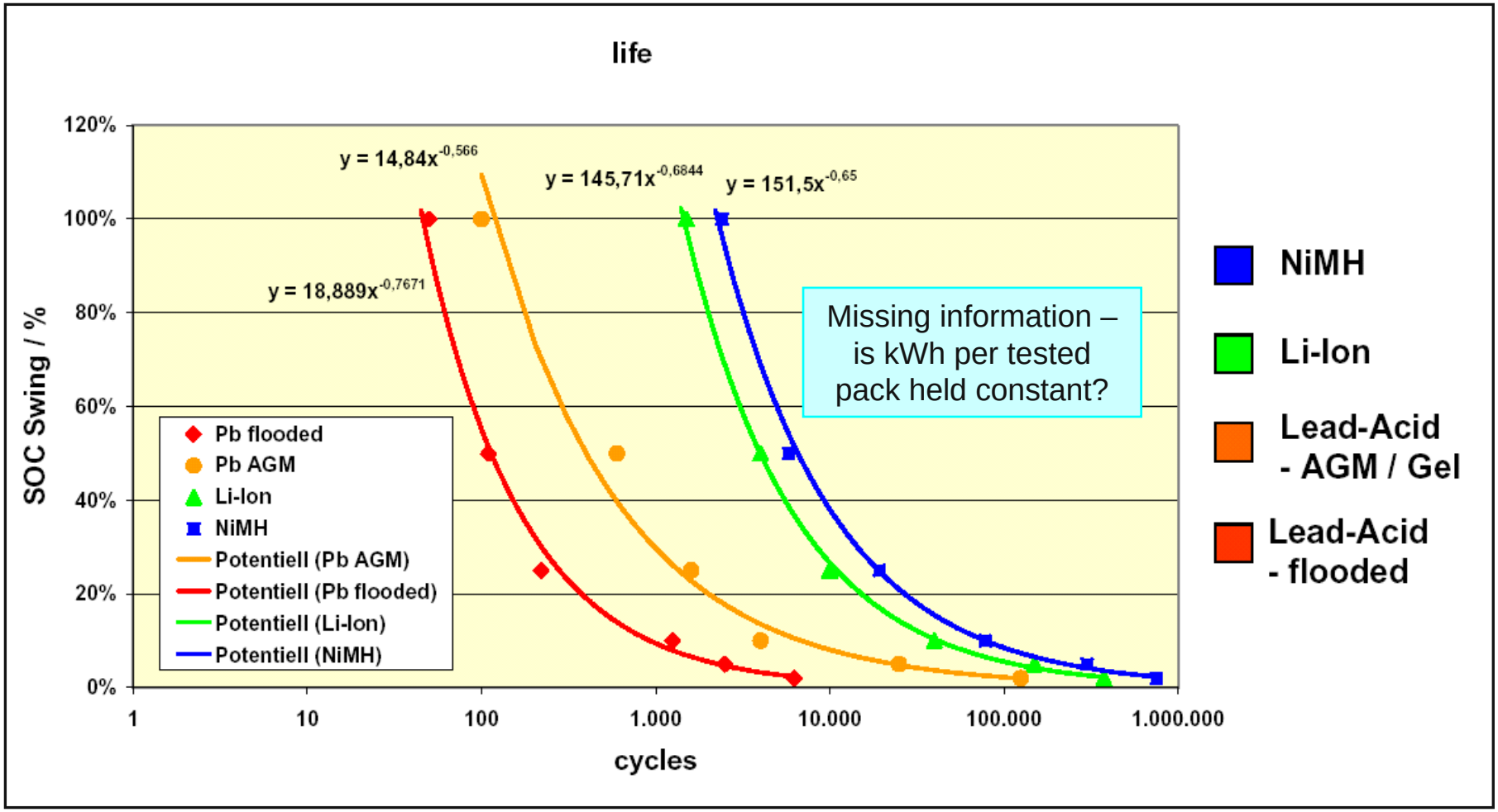
Source: Plug-in HEVs: A Near-Term Option to Reduce Petroleum Consumption. T. Markel et al. NREL 05 Milestone Report, Jan., 19, 2006

Simulation of a Hypothetical Prius PHEV Conversion Implies Intermittent Engine Starts and Relatively Slow Battery Depletion on UDDS



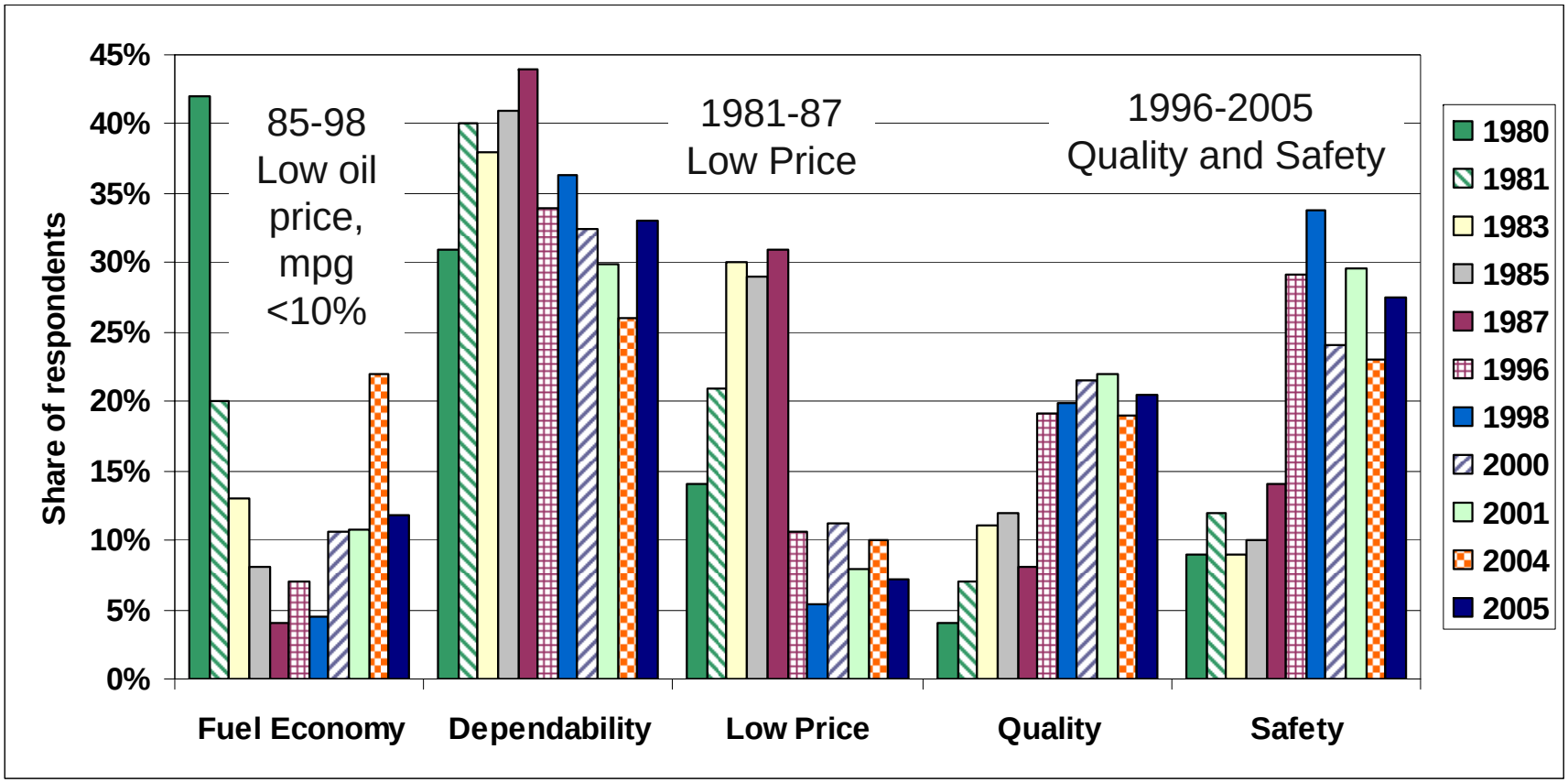
Source: PSAT simulations courtesy of A. Rousseau, Argonne

Limited *Tests to Date Indicate Two Major Battery Problems: (1) Deep Discharges Needed for PHEVs Reduce Battery Life (2) Li-ion Packs Don't Have the Cycle Life of NiMH Packs*



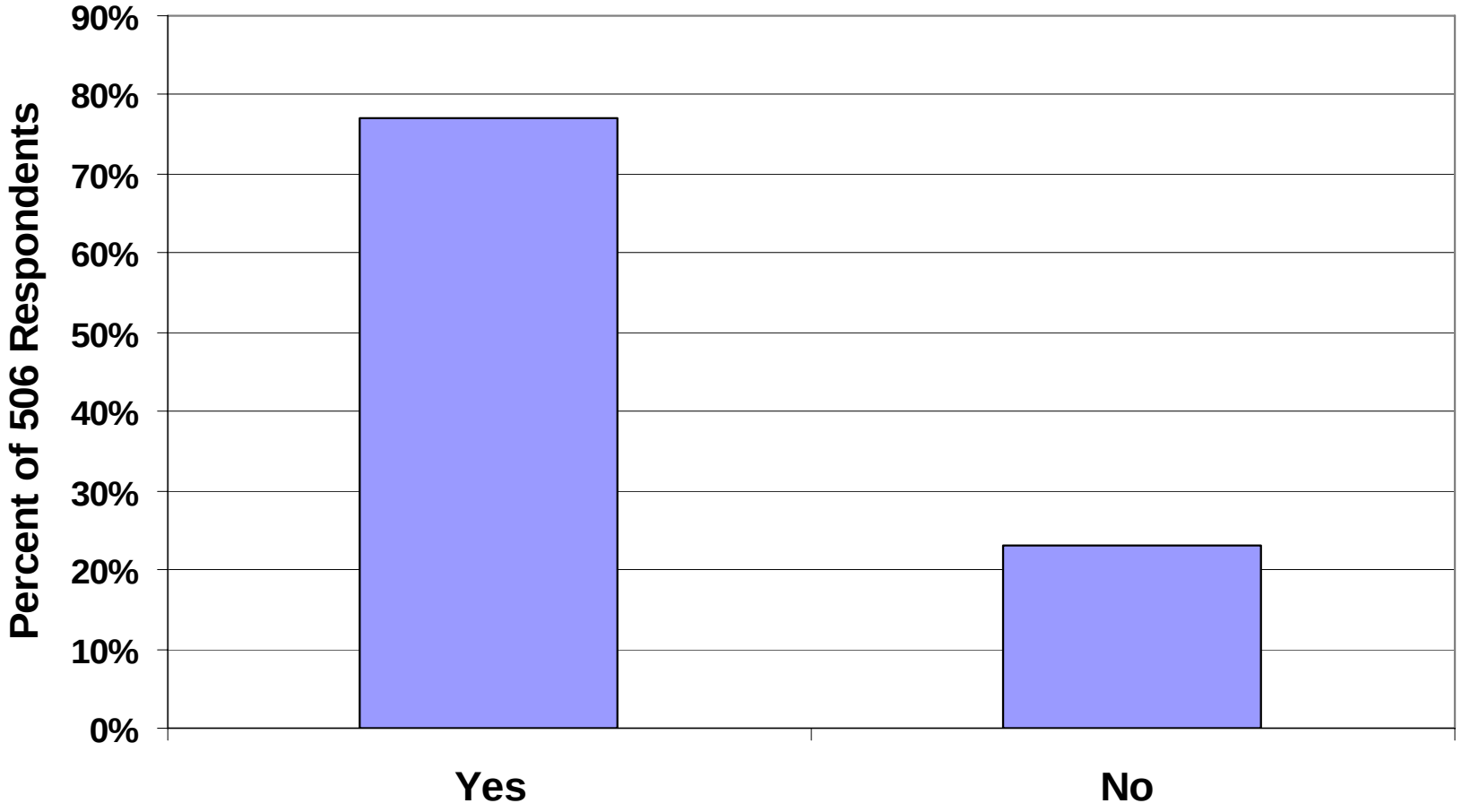
Source: Presented by Christian Rosenkranz (JCI) at EVS 20

If Vehicle Quality is High, Today's Customers Are Less Concerned With Price Than After 1970s Oil Shocks. Interest in Fuel Economy is Up Again



Which of These Five Vehicle Attributes Is Most Important?

Awareness of Plug-in Hybrids is Now Significant



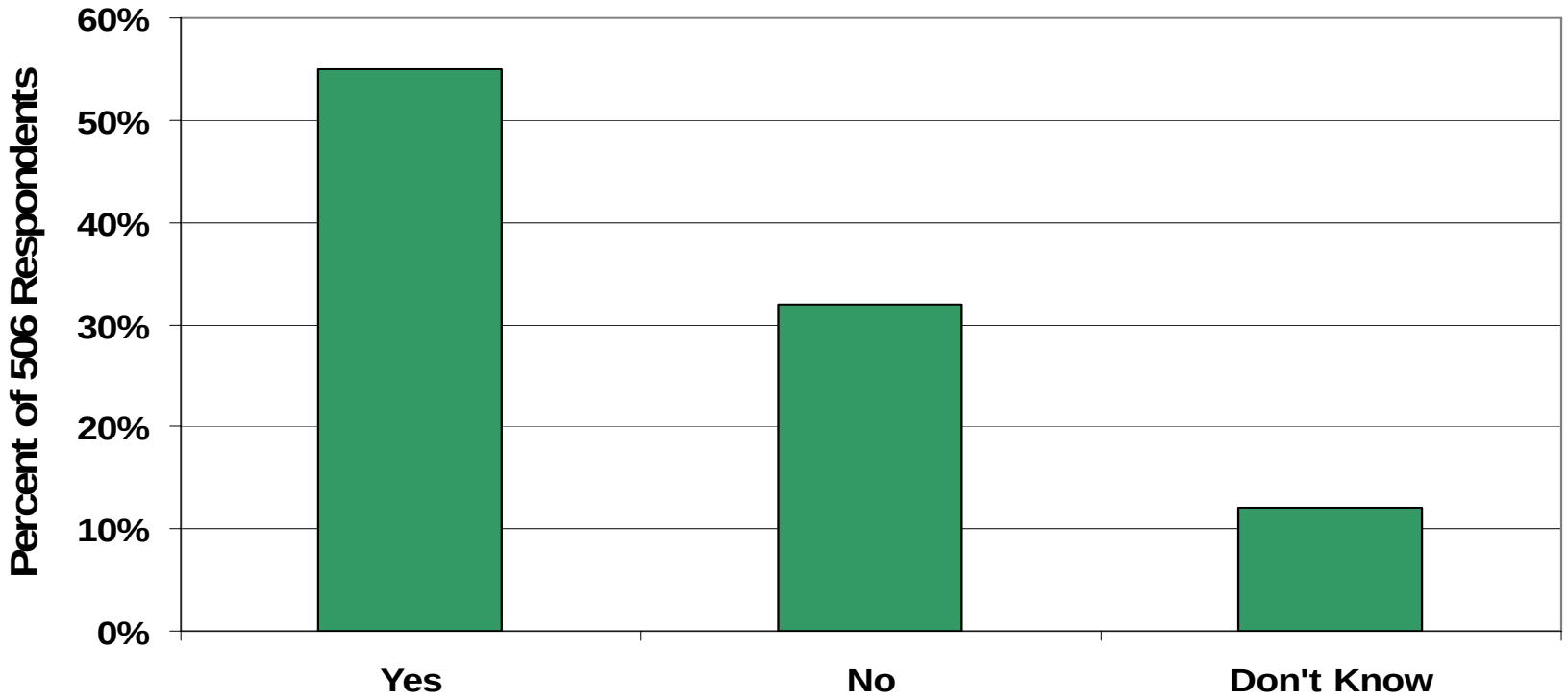
Have you heard about PHEVs?

Opinion Research Corporation survey conducted for P. Patterson, April 22, 2006

A Very Recent Opinion Research Corp. Survey Indicates a Great Deal of Interest in PHEVs

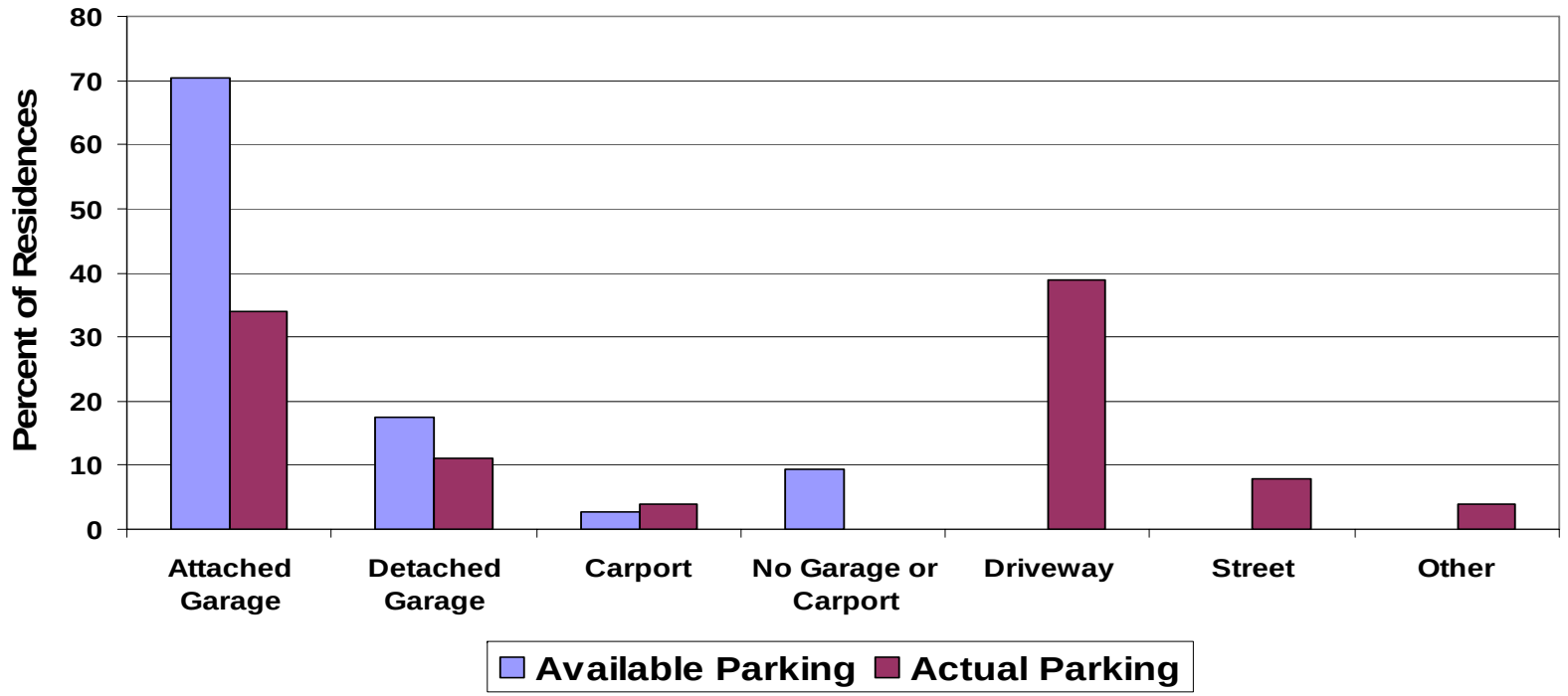
PHEV Would Be a Good Idea for Your Household

(ORC Survey April 22, 2006)



At Least 30% of Present Households Park the "Most Used" Vehicle in a Garage or Carport

Available Parking Facilities and Actual Parking
(of the most used vehicle)
for People in Detached Residences
(59% of all U.S. households live in detached residences)



Original Source: EIA Residential Energy Consumption Survey

Will Desire for Features Other Than Reduced Fuel Cost be Important?

How badly do customers want various attributes?

- Gasoline savings
- Reduced trips to gasoline stations
- Emissions reductions
- Power back-up
- Emergency transport capabilities
- All-electric operations capability

Can the Market Share Assumptions Made in the National Lab Scenarios be Achieved? Which Questions Below Are The Most Important to PHEV Market Success? Which Others?

- Will oil prices stay near current levels or above in coming decades?
- Will carbon taxes be imposed over the time horizon under consideration?
- Will fear of international turmoil create an incentive for electricity as a back-up?
- Will hybrid powertrains capture a large share of the market?
- Are PHEVs likely to capture a significant share of the hybrid market?
- How will market share differ as a function of electric range capability?
- Can li-ion batteries be made for as little $/kWh and $/kW as nickel metal hydride?
- Can safety concerns with li-ion be successfully addressed?
- Can variations in battery performance as a function of temperature be reduced?
- What is the long-run value of packaging benefits of li-ion packs vs. nickel metal hydride, relative to savings of vehicle glider cost?
- Will technological improvements in batteries push costs down more than demand for battery materials pushes battery cost up?
- Will complex battery SOC management strategies be needed and cause market share to be limited to a group of enthusiasts and/or highly educated users?
- Will batteries last the life of vehicles? Do they need to?
- Can secondary uses/recycling make battery value high at end of life in the PHEV?

Conclusions

None, it is too early to draw conclusions -

except - there is a lot to discuss in the breakout sessions