A national laboratory of the U.S. Depart[ment of] Energy
Office of Energy Efficiency & Re[newable] Energy

NREL National Renewable Energy Laboratory

Innovation for Our Energy Future

Plug-in HEVs: A Near-Term Option to Reduce Petroleum Consumption

from FY05 Milestone Report

Tony Markel, Michael O'Keefe, Andrew Simpson, Jeff Gonder, Aaron Brooker

National Renewable Energy Laboratory

Golden, Colorado

January 19, 2006

NREL/PR-540-39415

Presented to DOE management staff on September 14, 2005 at the DOE headquarters in Washington DC.

Content updated January 19, 2006 for final publication.

NREL is operated by Midwest Research Institute . Battelle

Disclaimer and Government License

Project Objective

- *Assess the opportunity for a future research program that will address plug-in hybrid electric vehicle (PHEV) market & technology issues.*

- Approach
  - Collect and assemble information and analysis to enhance our understanding of the benefits and barriers of plug-in hybrid technology

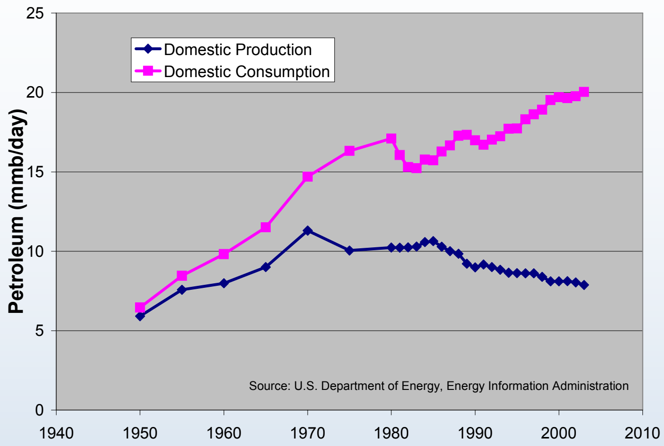
Messages

- Plug-in HEVs have the best near-term potential to reduce petroleum consumption by shifting demand to a variety of domestic sources including renewables

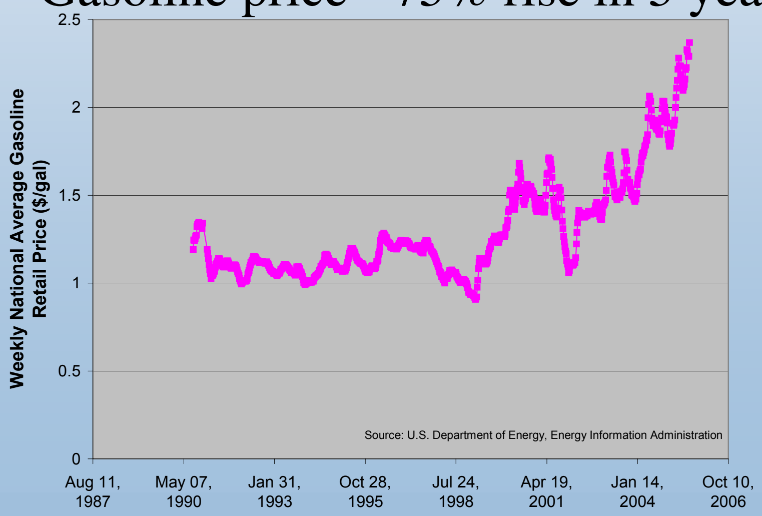
- Systems integration/optimization are essential to provide commercially viable options
  - Battery technology development critical but research pathway depends on application, vehicle configuration, and utility integration approach

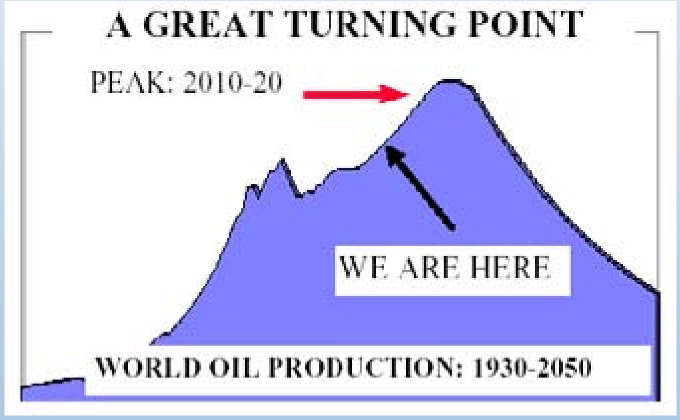
The Perfect Storm

- Petroleum consumption has steadily increased while domestic production has continued to decline
- World oil production will likely peak within the next 5-15 years
- Recent increase in gasoline price is indicator of growing tension between supply and demand



Gasoline price - 75% rise in 5 years!





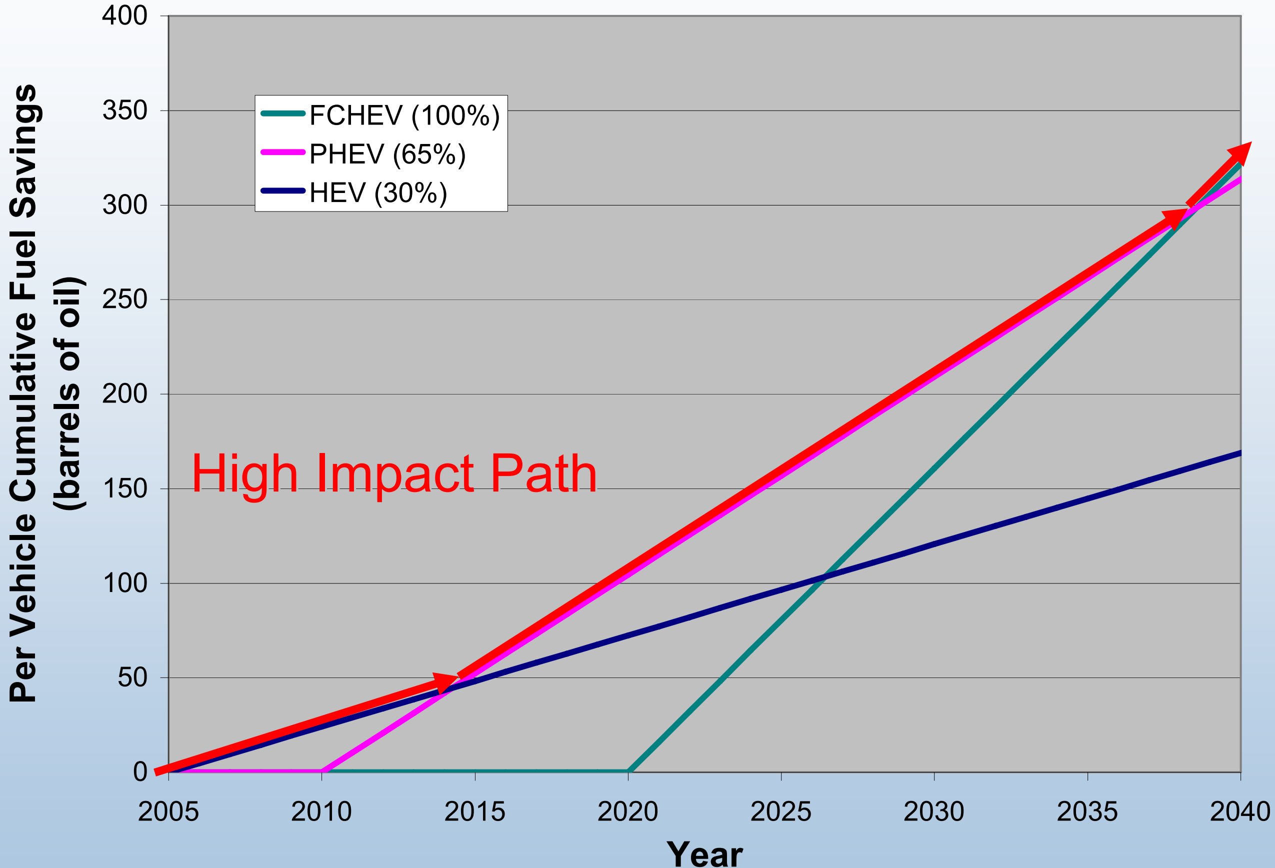
Source: Hubbert Center Newsletter #99/1 R. Udall and S. Andrews

What's our plan?

Vehicle Technology Options to Reduce Petroleum Consumption

- Hybrid electric vehicles (charge-sustaining)
  - Combines petroleum engine with a small energy storage device used over narrow window of operation
- Plug-in HEVs (charge-depleting)
  - Use larger energy storage device with the ability to recharge from both on-board and off-board sources with a petroleum engine providing continuous fast refuel operation
- Fuel cell hybrid vehicles
  - Replaces the petroleum engine with highly efficient fuel cell consuming hydrogen from non-petroleum sources – could be charge-sustaining or charge-depleting
- Electric vehicles
  - Large energy storage is the only source of propulsion energy

Cumulative Petroleum Savings Potential of Technology Options

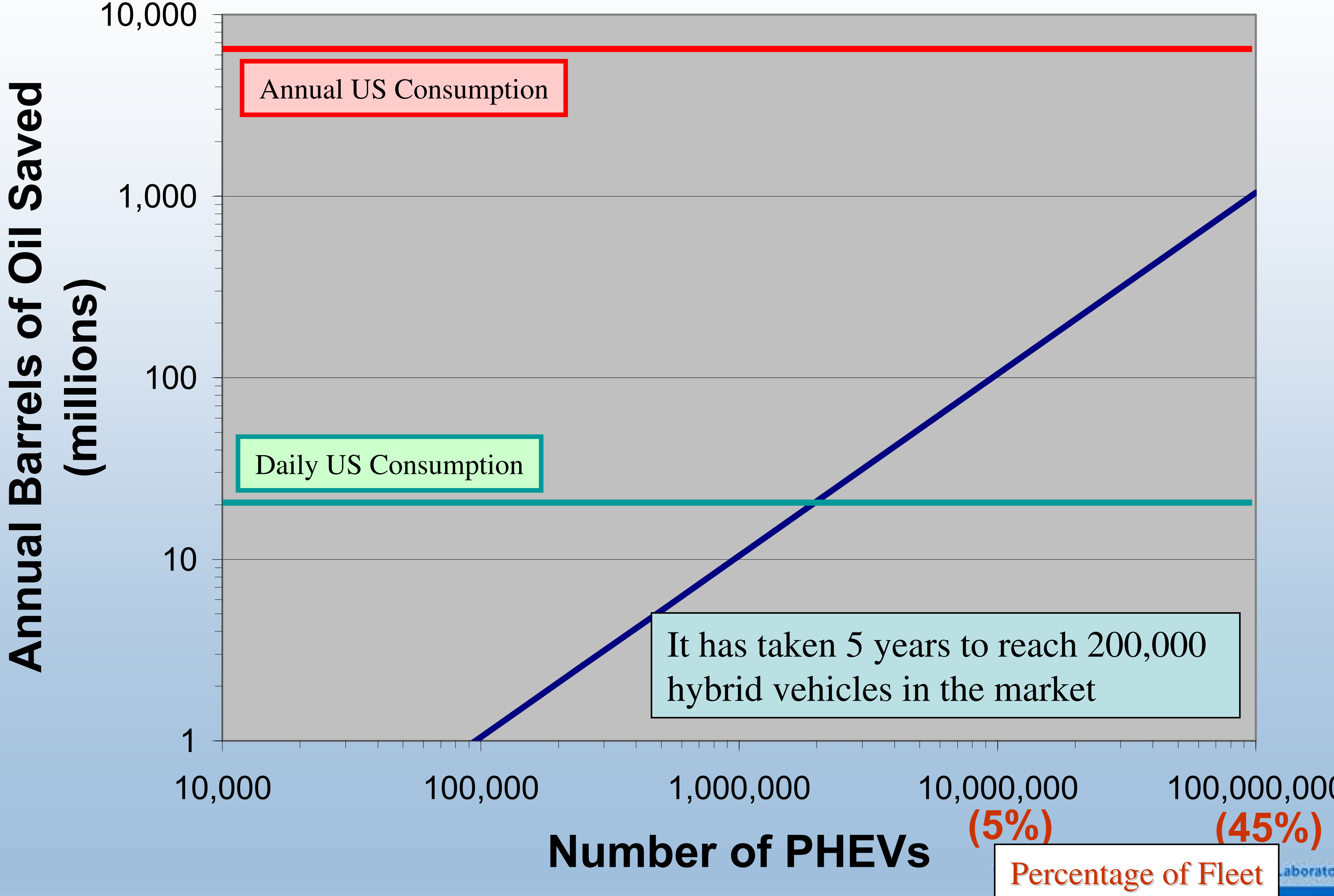


- Benefits from HEVs and PHEVs vary depending on application and design
- FCHEV assumes hydrogen fuel; and gains maximum benefit rate

Market penetration model not included - vehicle to vehicle comparison

❖ PHEVs provide the best combination of rate and timing to provide significant fuel consumption reduction benefits while hydrogen fuel cell technology is being developed

1,000,000 PHEVs Could Save ~10 Million Barrels of Oil Annually



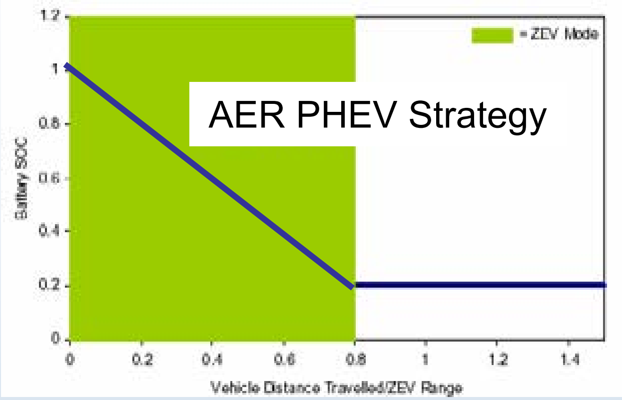
Messages

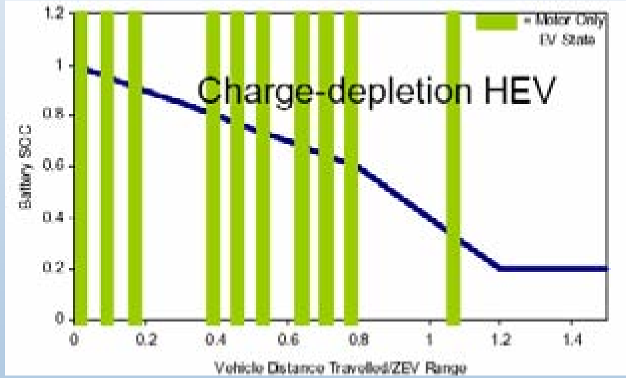
- Plug-in HEVs have the best near-term potential to reduce petroleum consumption by shifting demand to a variety of domestic sources including renewables

- Systems integration/optimization are essential to provide commercially viable options
  - Battery technology development critical but research pathway depends on application, vehicle configuration, and utility integration approach

Plug-In HEV Design Options

- Typical Plug-in HEV characterized by All Electric Range (AER)
  - AER - miles driven after a full recharge until the gasoline engine first starts to assist
- Alternatively, Plug-in HEV design may focus on maximizing the electric-only miles dispersed throughout a driving pattern
  - maximizes the effective and efficient use of grid-electricity
- Combination of these two scenarios likely to provide optimal reduction in petroleum consumption
  - Use grid-electricity to off-set use of gasoline improve cycle average efficiency of the engine

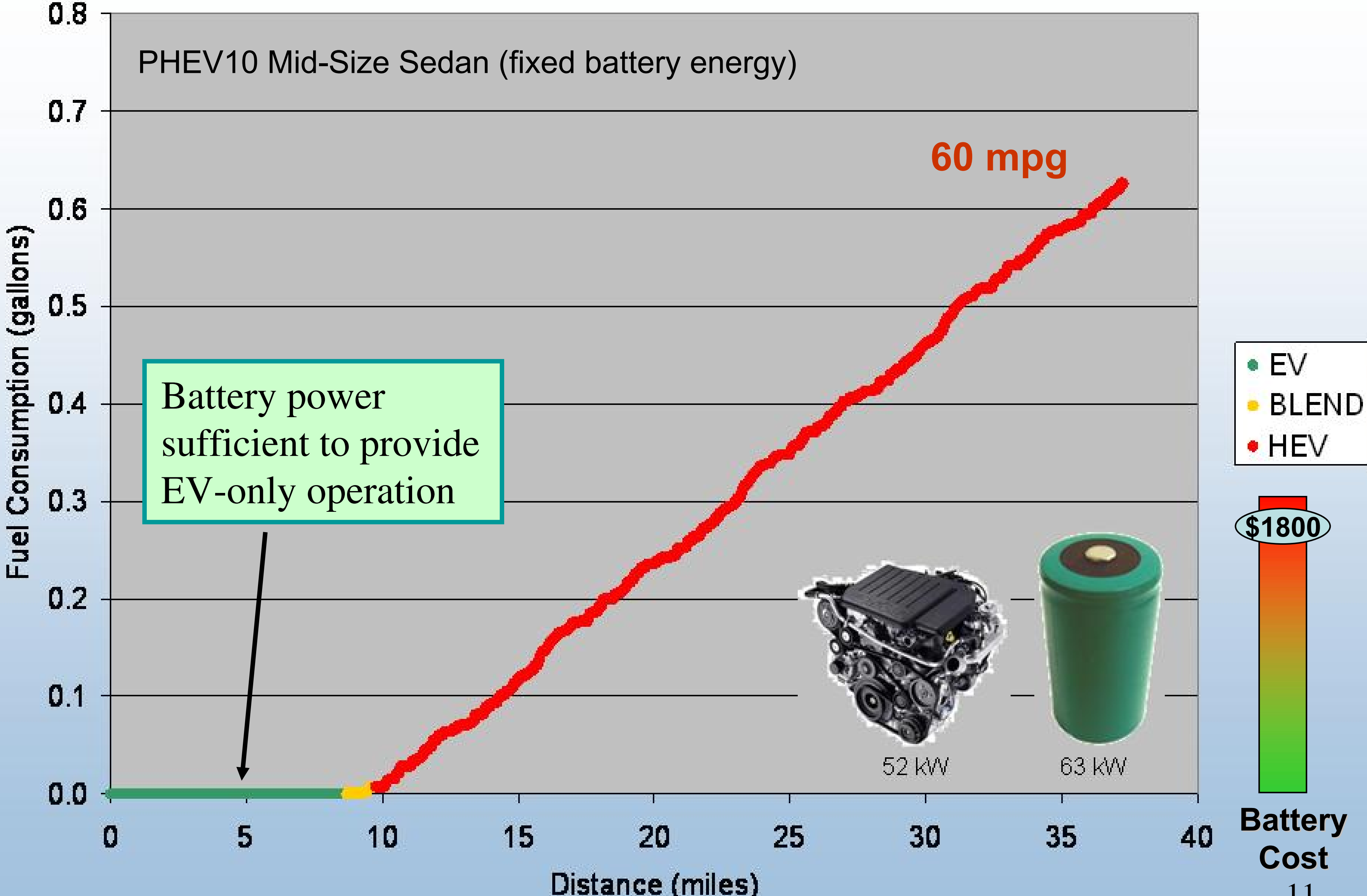




Source: Duval, M. "Plug-in HEV Workshop" EVS20

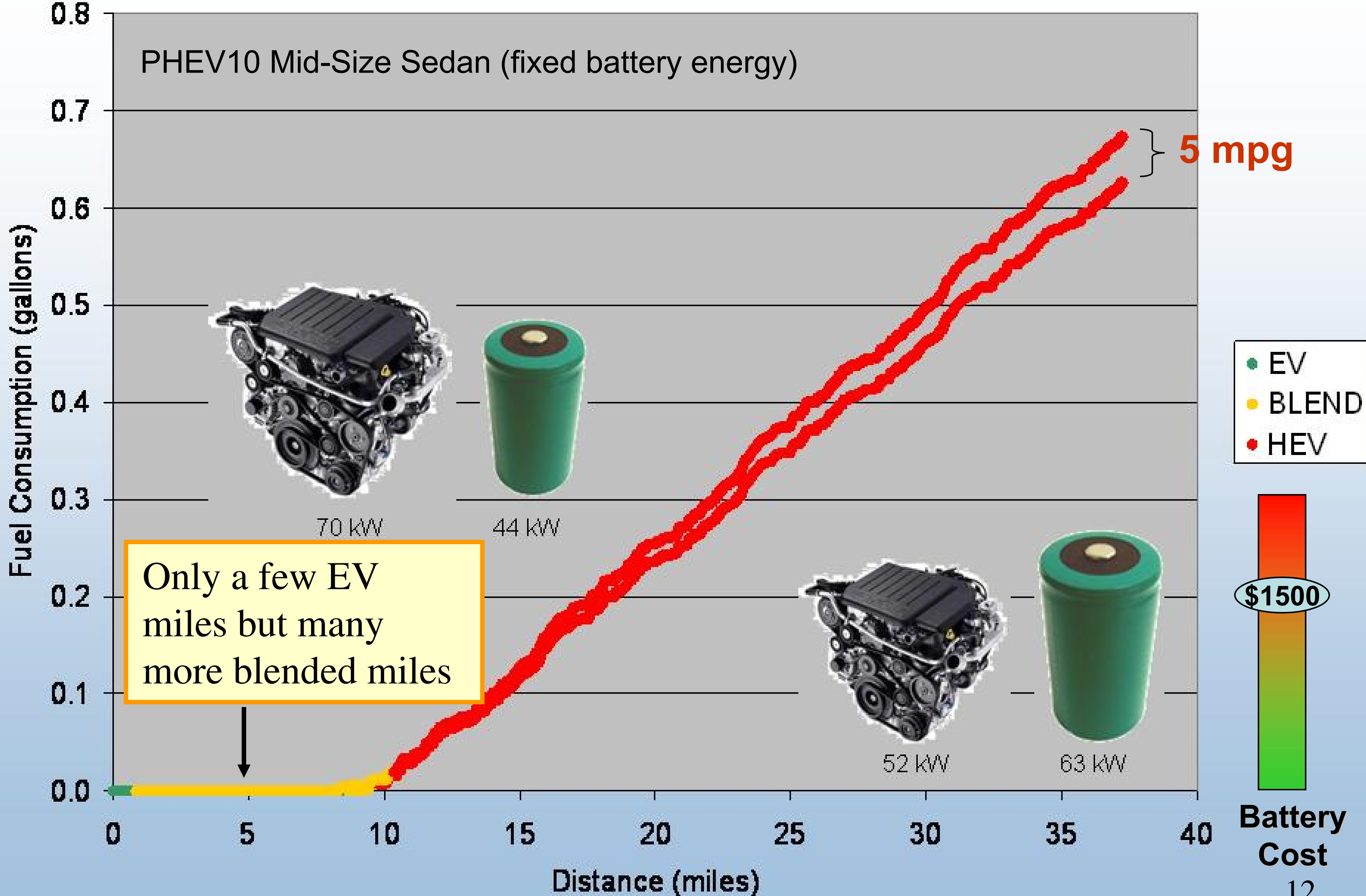
Component Sizing and Control Options

P/E = 20



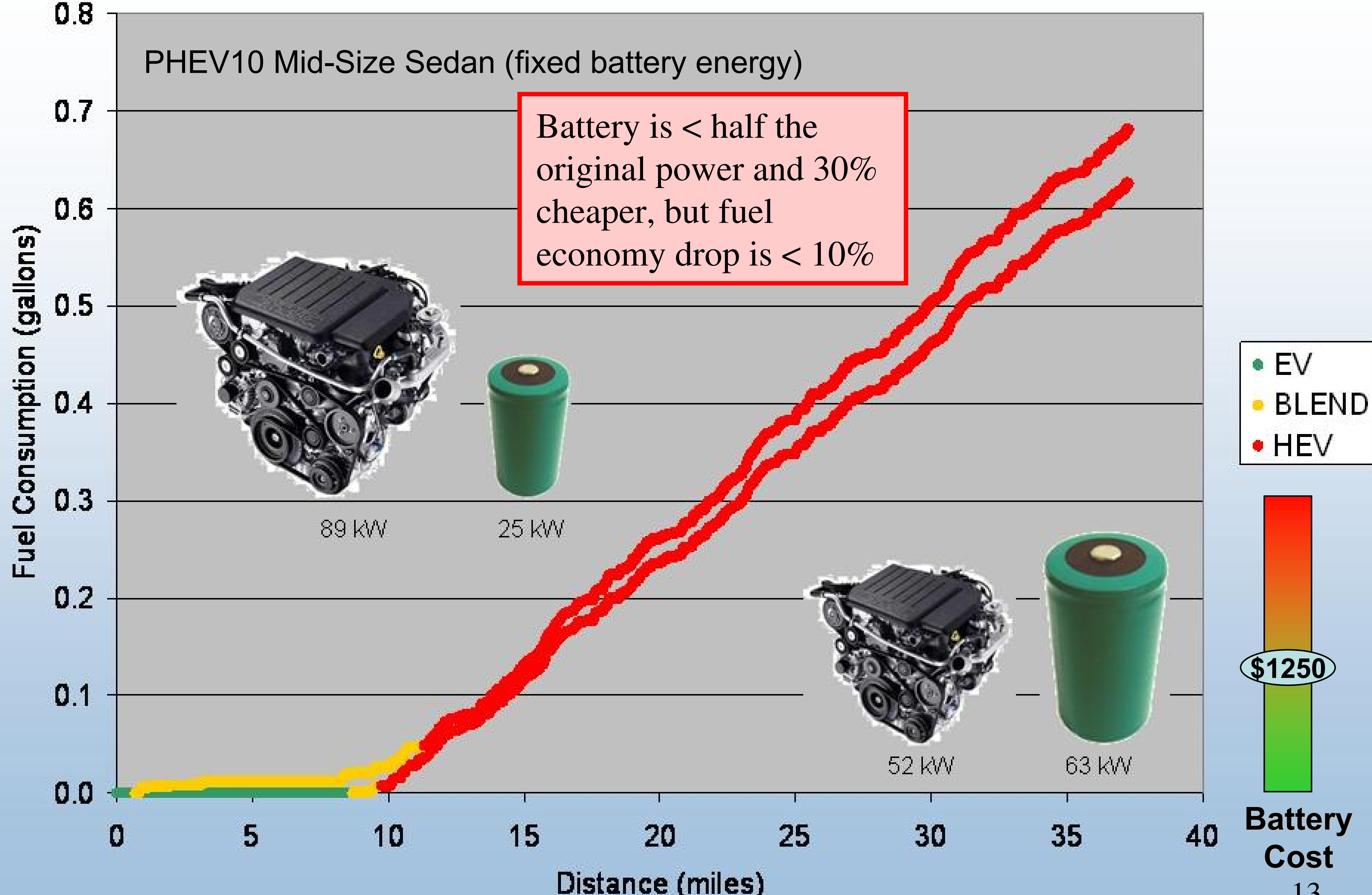
Component Sizing and Control Options

P/E = 14



Component Sizing and Control Options

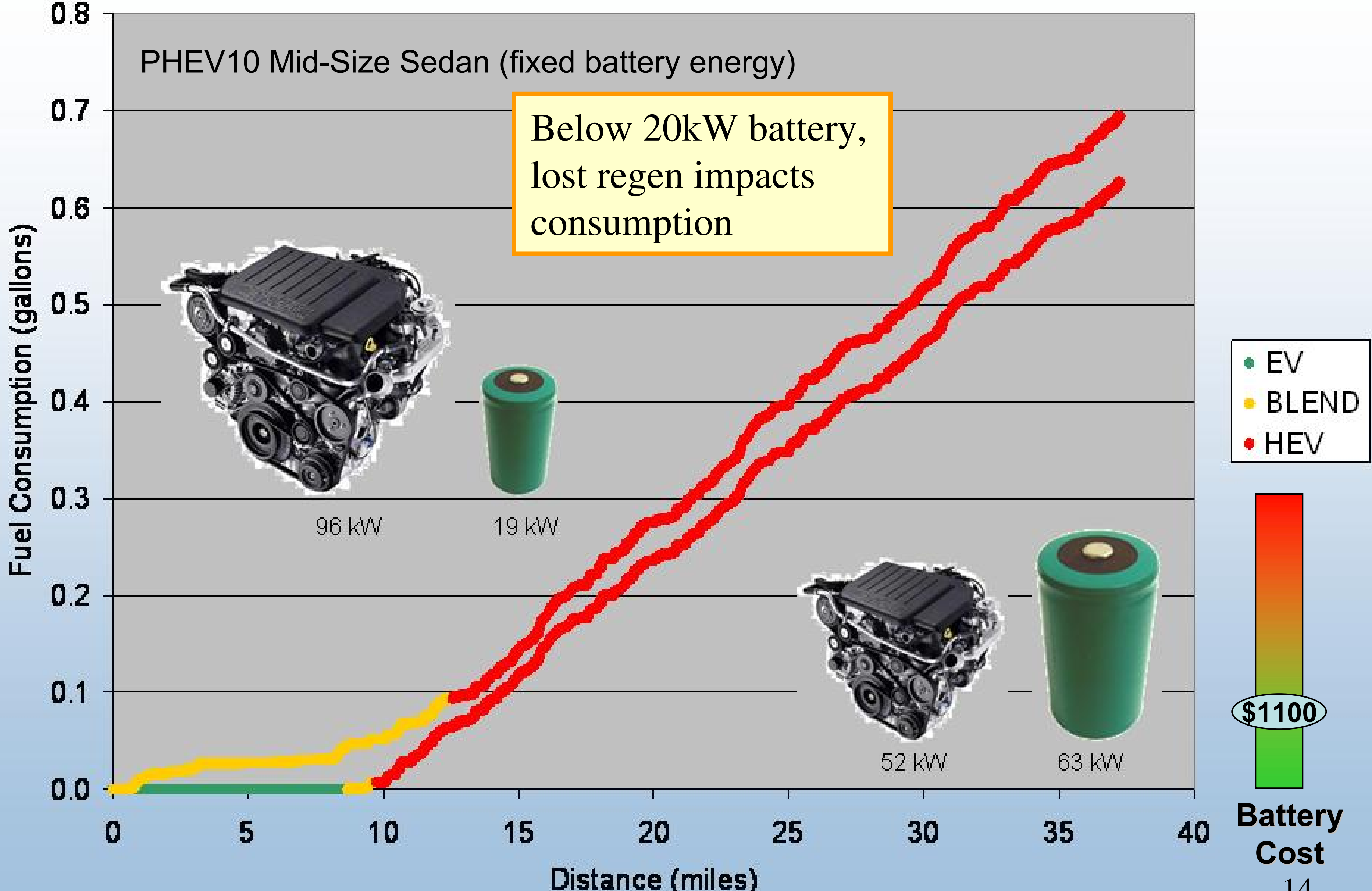
P/E = 8



NREL National Renewable Energy Laboratory

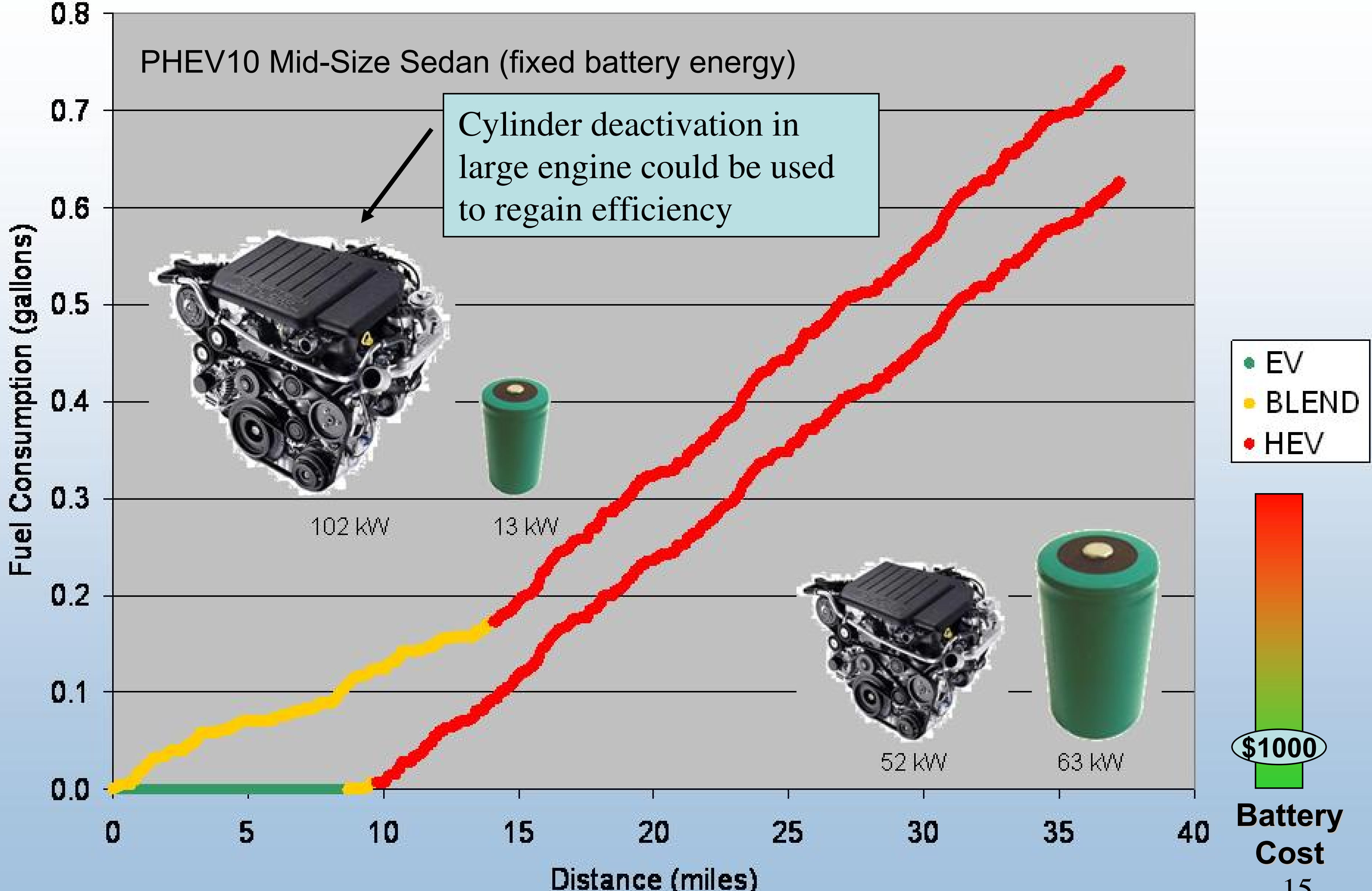
Component Sizing and Control Options

P/E = 6



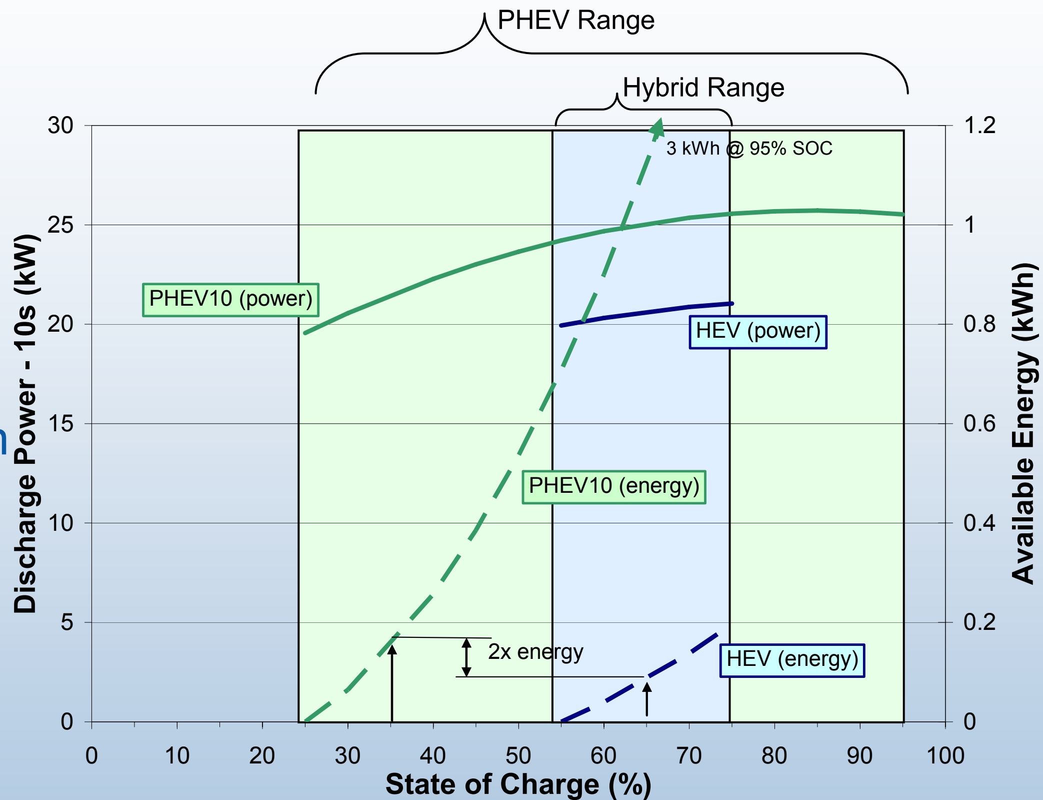
Component Sizing and Control Options

P/E = 4



Performance Variability Challenge

- Larger engine provides better continuous performance
  - Charge-sustaining fuel economy improvement potential directly related to engine downsizing
  - Peak power capability is a function of battery/motor power
- Battery power capability varies with state of charge
  - In charge-sustaining mode, battery/motor must be sized to maintain performance
- If vehicle performs best when fully charged, it is an incentive for the consumer to recharge often



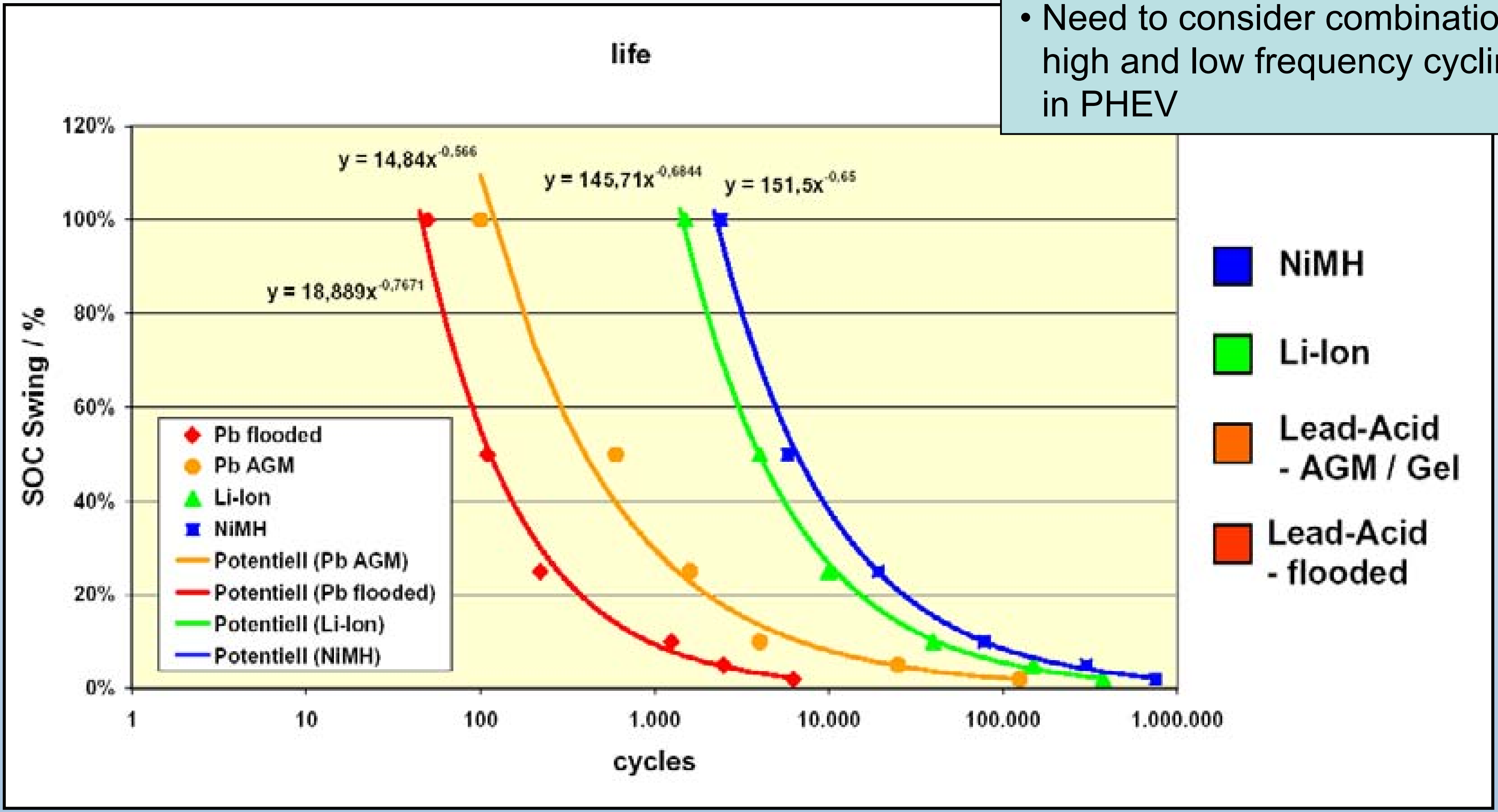
Plug-in HEV10 battery even at low SOC level has equivalent power and twice the available energy of typical hybrid battery

Cost and Life Challenge

- Deep cycling of batteries tends to shorten the number of cycles before end of life
  - Characterization of real-world cycling important
- Cost of advanced batteries high under today's low volume production situation
  - Selection of battery characteristics and system management provides solutions

Existing data sets provide limited view of future potential
Need more data to support conclusions

Battery Cycle Life Data



- Existing data is limited
- Need to consider combination of high and low frequency cycling as in PHEV

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

Battery Cost Model: Specific Cost vs. P/E Ratio

- Slope and magnitude of relationship are long-term and debatable

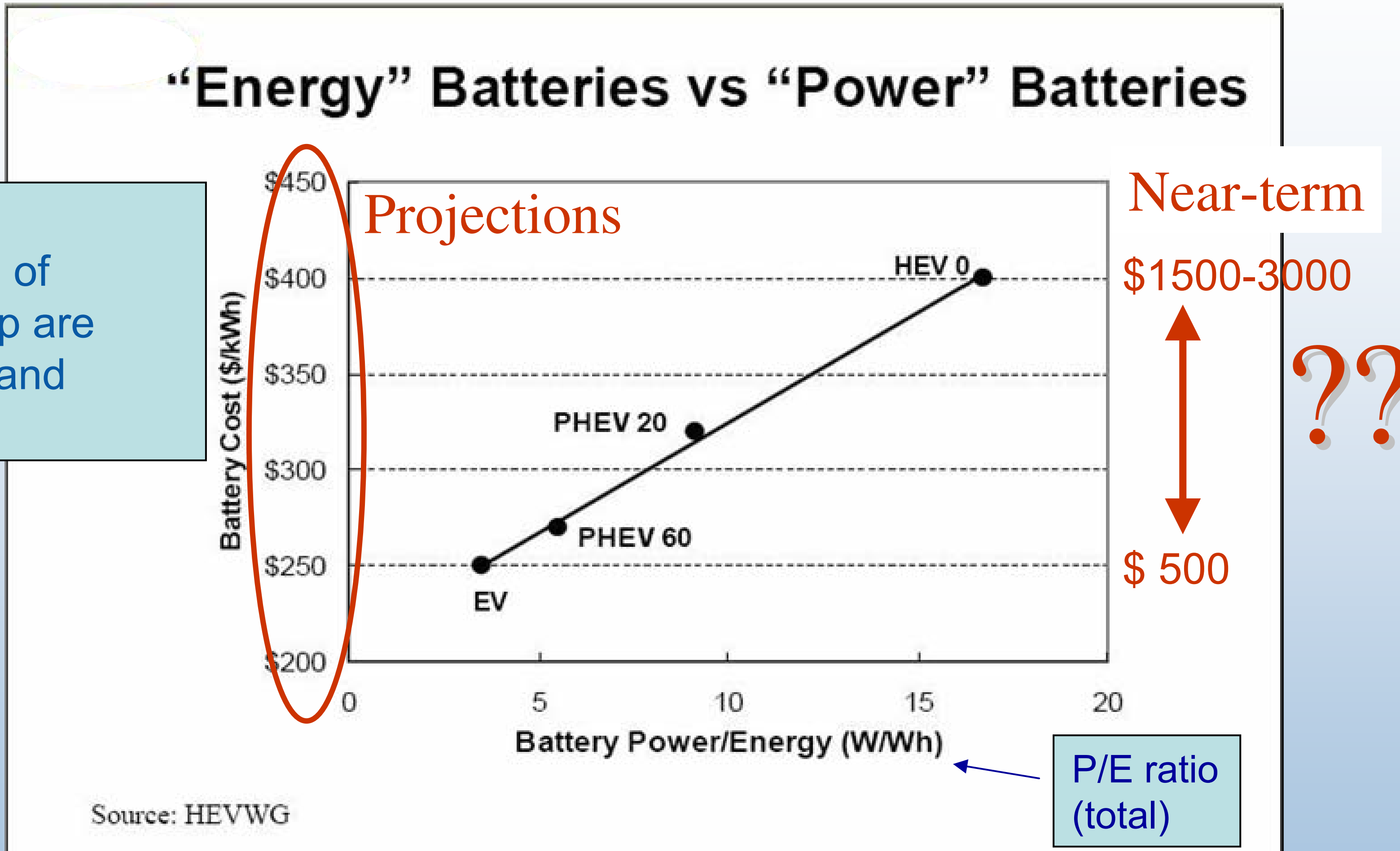
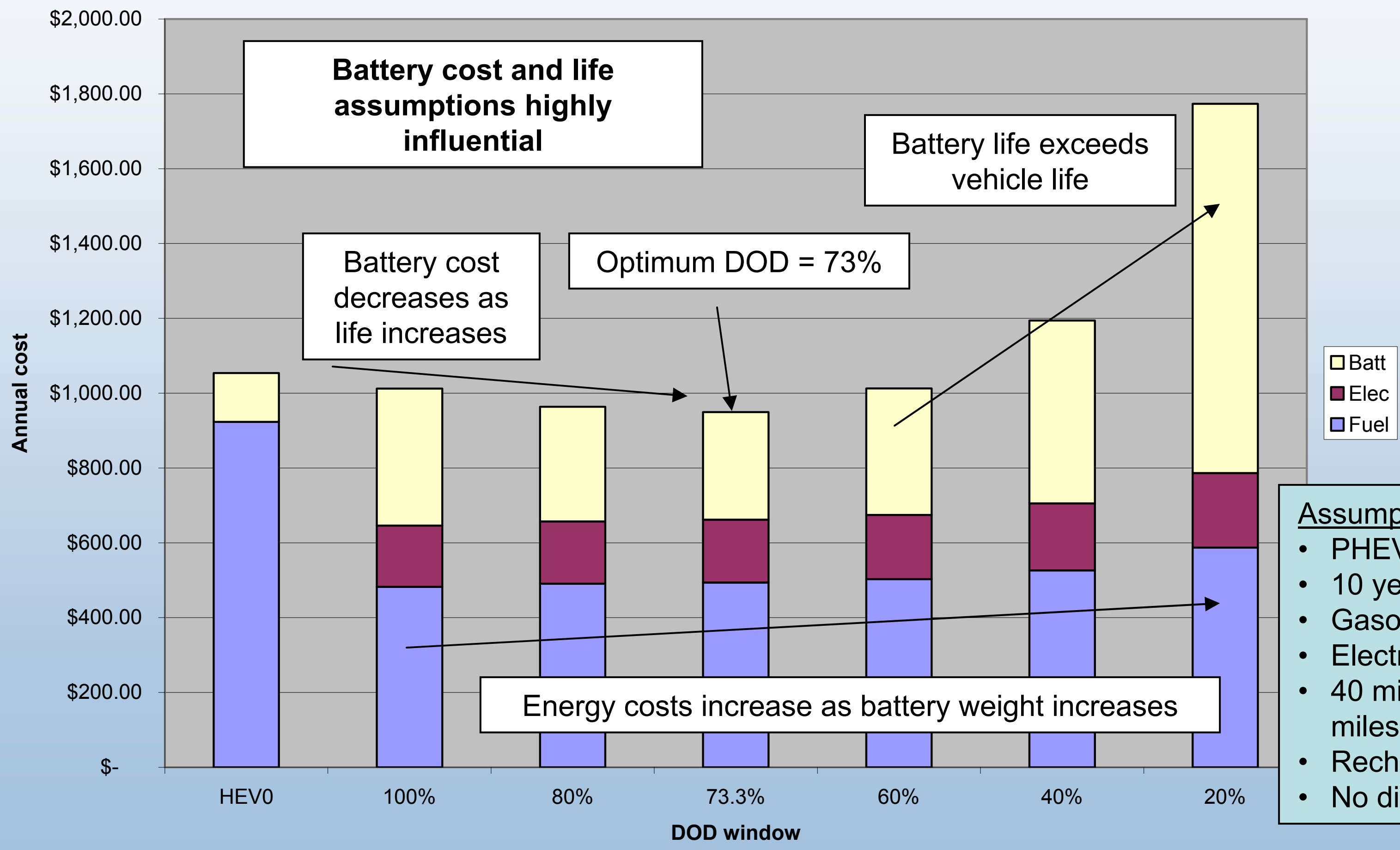


Figure 2: NiMH Battery Module Cost vs. Power/Energy Ratio

Taylor D. & Browning L. (2003) "Simplified Life Cycle Cost Analysis of Plug-in HEVs, Engine Dominant HEVs & Conventional Vehicles in 2012", EVS20 Plug-In HEV Workshop, Long Beach, CA.

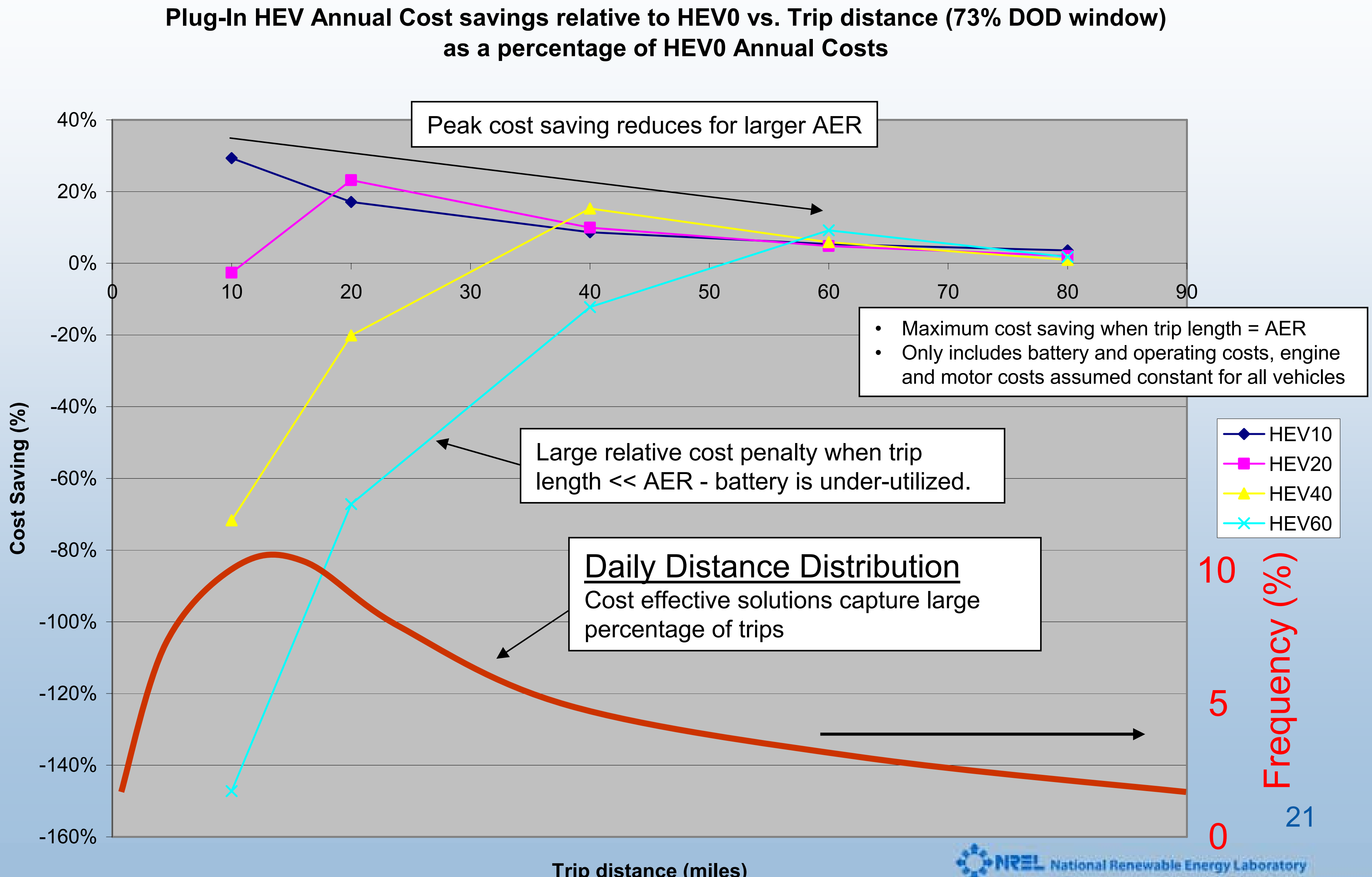
Optimal Depth of Discharge (DOD) is Dependent on Battery Life and Cost, Vehicle Life, Duty Cycle, …

Requires systems approach!



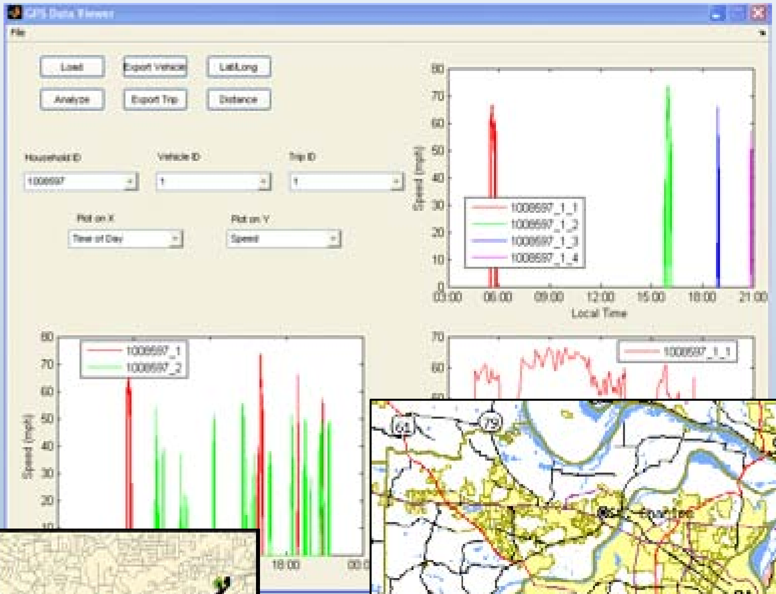
Assumptions:
- PHEV20 (~6 kWh usable)
- 10 year vehicle life
- Gasoline @ $2.50/gal
- Electricity @ $0.06/kWh
- 40 mile daily trip (~15,000 miles annually)
- Recharge daily
- No discount rate

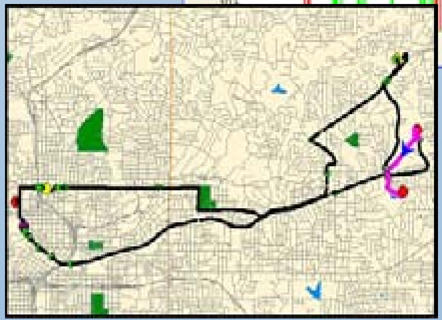
Designing for Requirements Provides Cost Effective PHEV Solution

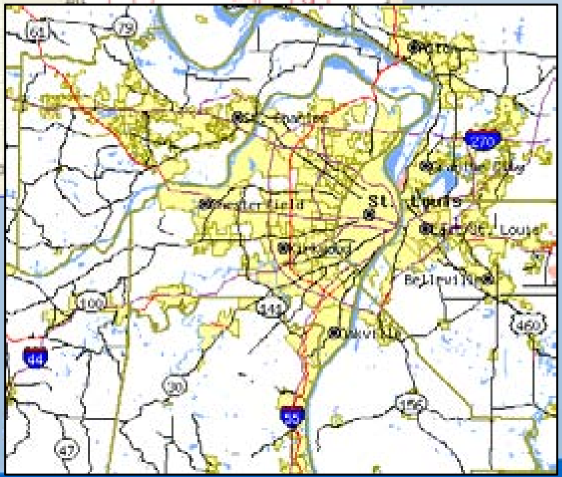


Development of Vehicle Requirements Based on Real-World Driving Data

- Optimal design for greatest cost/benefit is highly dependent on duty cycle
- National personal transportation surveys provide a potential data source
- St. Louis data used as an example data set
- Similar data sets for other areas required to fully characterize national behavior

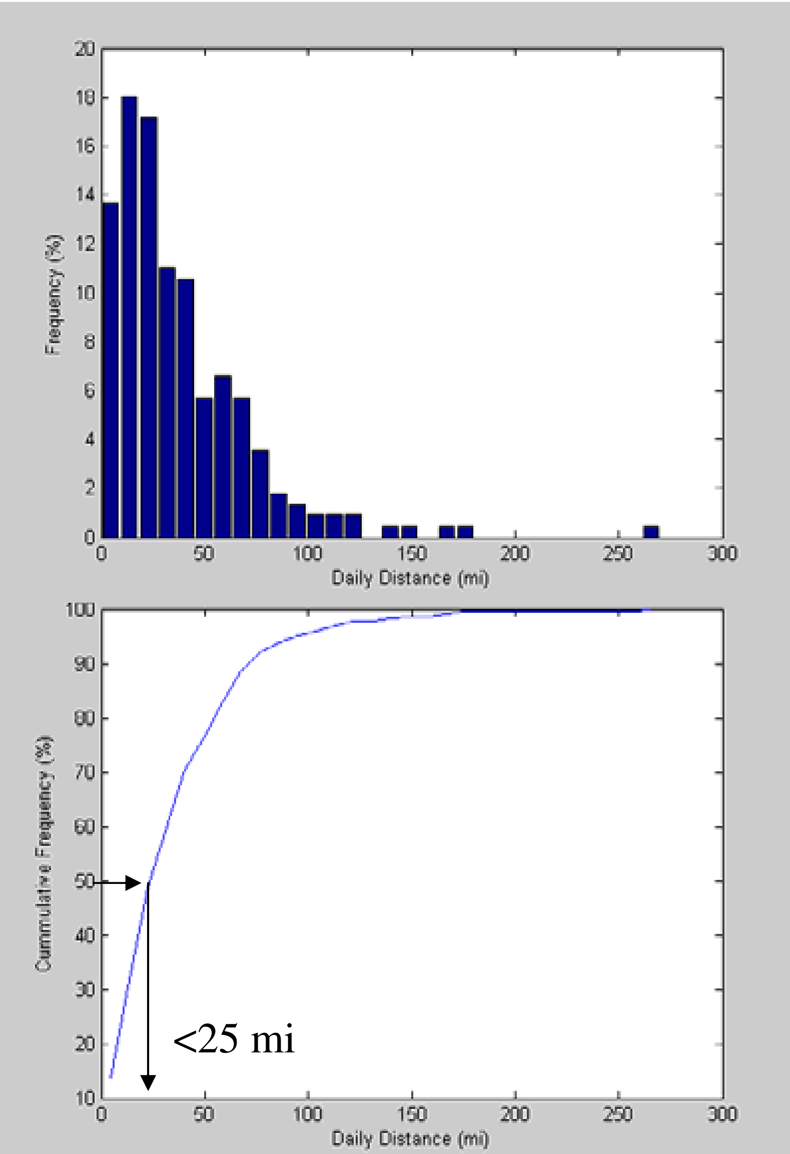


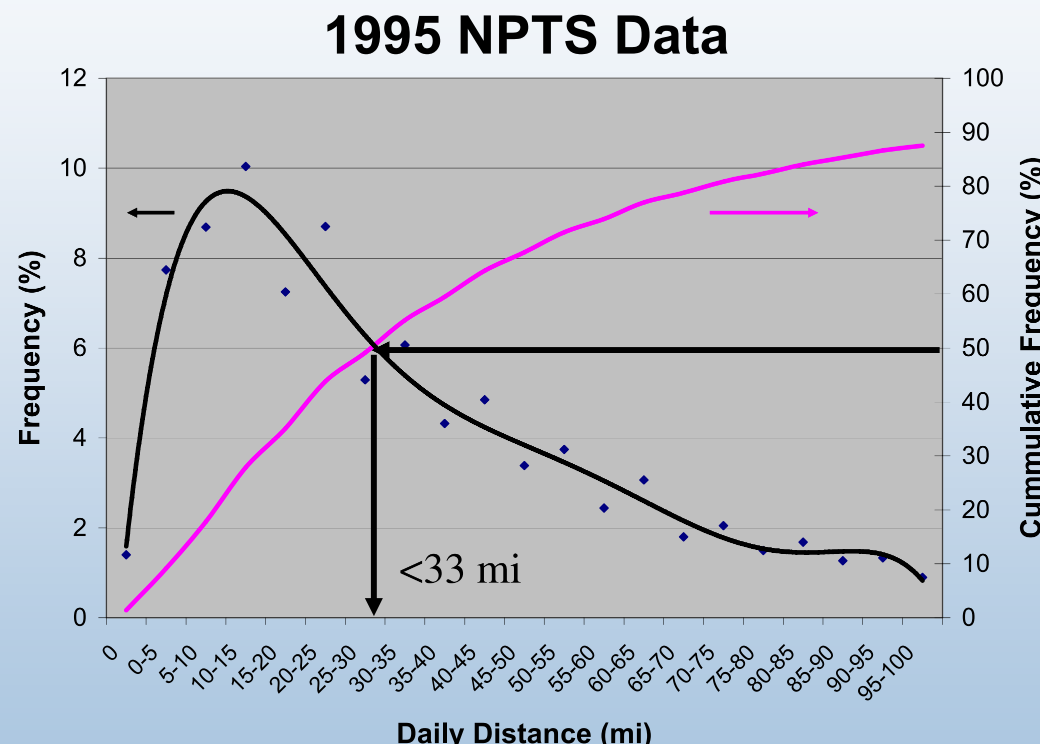




St. Louis Travel Data Analysis

Daily Driving Distance Slightly Shorter than 1995 NPTS Data

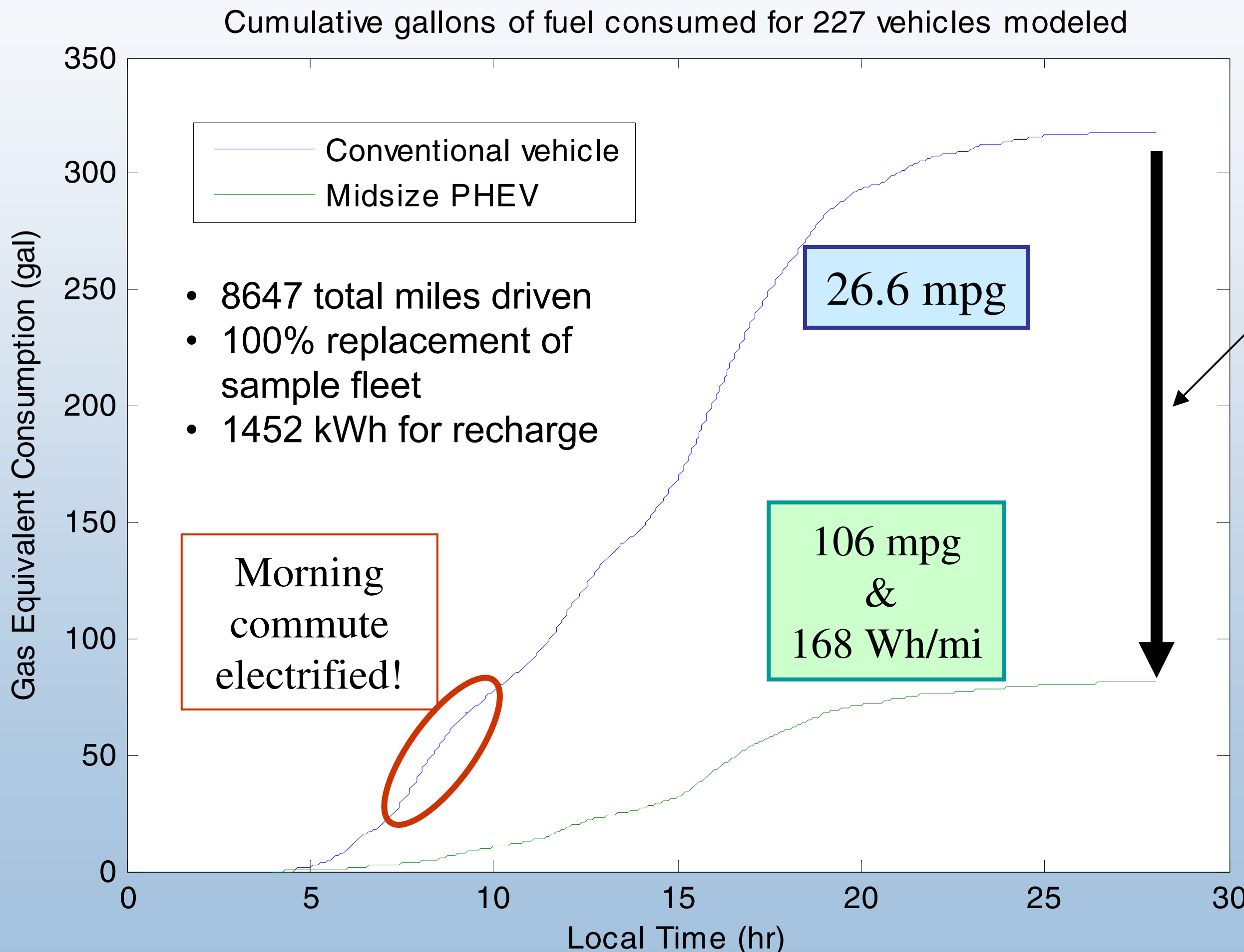




St. Louis is a fairly dense metro area

Preliminary PHEV In-Use Fuel Consumption

Each vehicle in St. Louis data set was modeled both as a conventional and PHEV



PHEV30 saves ~1 gal/day/vehicle

	Conv	PHEV
Gas	$3.50	$0.90
Elec	$0	$0.38
Total	$3.50	$1.28
¢/mile	9.2	3.4

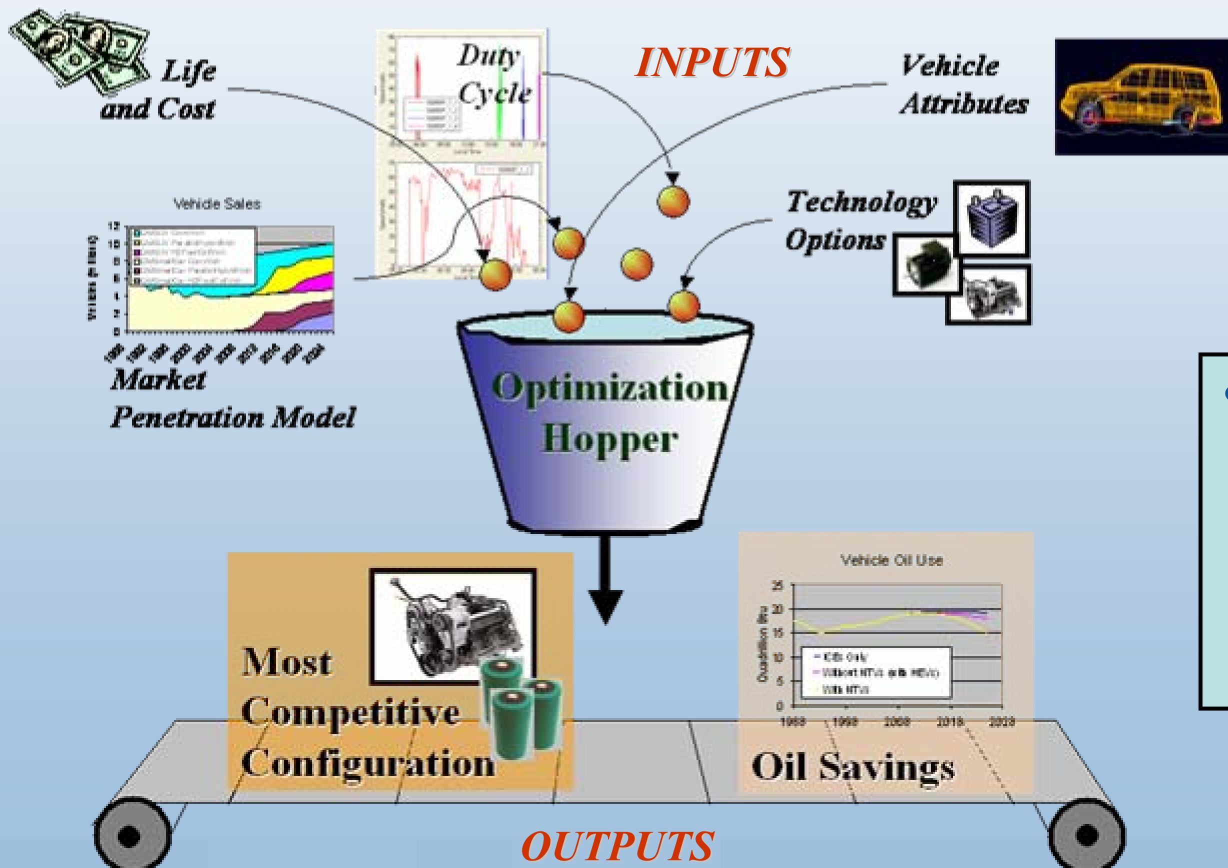
>50% reduction in operating costs

~$700 annual savings

Assumes $2.50/gal and 6¢/kWh

Optimal Configuration & Associated Oil Savings Based on Realistic Market Penetration

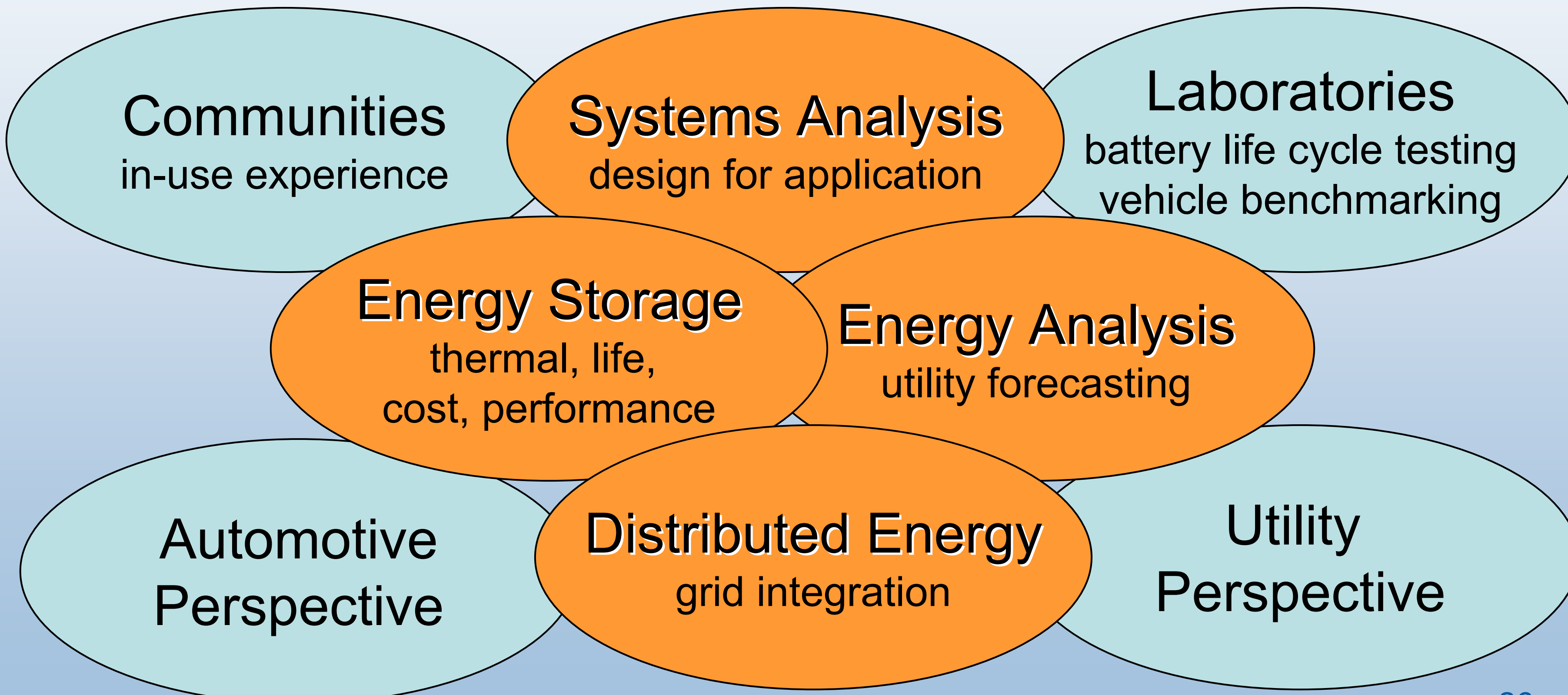
- Technical Target Tool (T3) competes PHEVs, HEVs, conventional, and FCHEVs
- Sales predictions based on vehicle attributes



- **Outputs:**
  - Most competitively configured PHEV
  - Associated oil savings

Opportunity for Collaboration

- Multidisciplinary challenges can be best solved with collaborative effort



Future Work

- Planned FY06 Activities
  - Explore design options to address challenges and define requirements
  - Develop realistic 24hr PHEV drive cycle including charging for life cycle testing
  - Demonstrate technology viability and functionality

Focus on:
- Battery Cost and Life
- Systems Integration
- Hybrid Evolution

- Additional Needs
  - Collaborative multidisciplinary modeling effort to model integration and implementation opportunities (WinDS, HOMER®,…)
  - Support the development of parametric battery cost and life models through data collection
  - Estimate market penetration potential and oil savings for Plug-in HEVs using analysis tools

Messages (Just a Reminder)

- Plug-in HEVs have the best near-term potential to reduce petroleum consumption by shifting demand to a variety of domestic sources including renewables

- Systems integration/optimization are essential to provide commercially viable options
  – Battery technology development critical but research pathway depends on application, vehicle configuration, and utility integration approach