Plug-In Hybrid Modeling and Application: Cost / Benefit Analysis

Presented at the 3rd AVL Summer Conference on Automotive Simulation Technology: Modeling of Advanced Powertrain Systems

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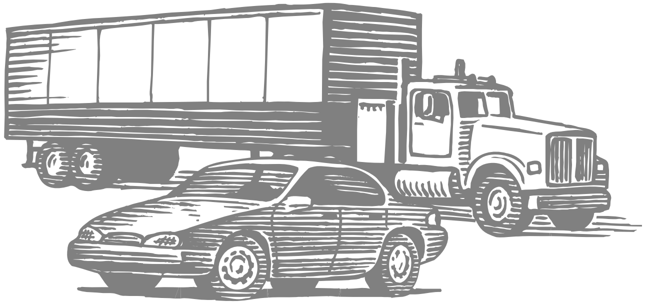

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Presentation Outline

- What is a plug-in hybrid-electric vehicle (PHEV)?
- Potential petroleum reduction from PHEVs
- Simulation of PHEV efficiency and cost
    - Baseline vehicle assumptions
    - Powertrain technology scenarios
    - Components models (cost, mass, efficiency)
- Results
    - Component sizing
    - Fuel Economy
    - Incremental cost
    - Payback scenarios
- Conclusions & Next Steps

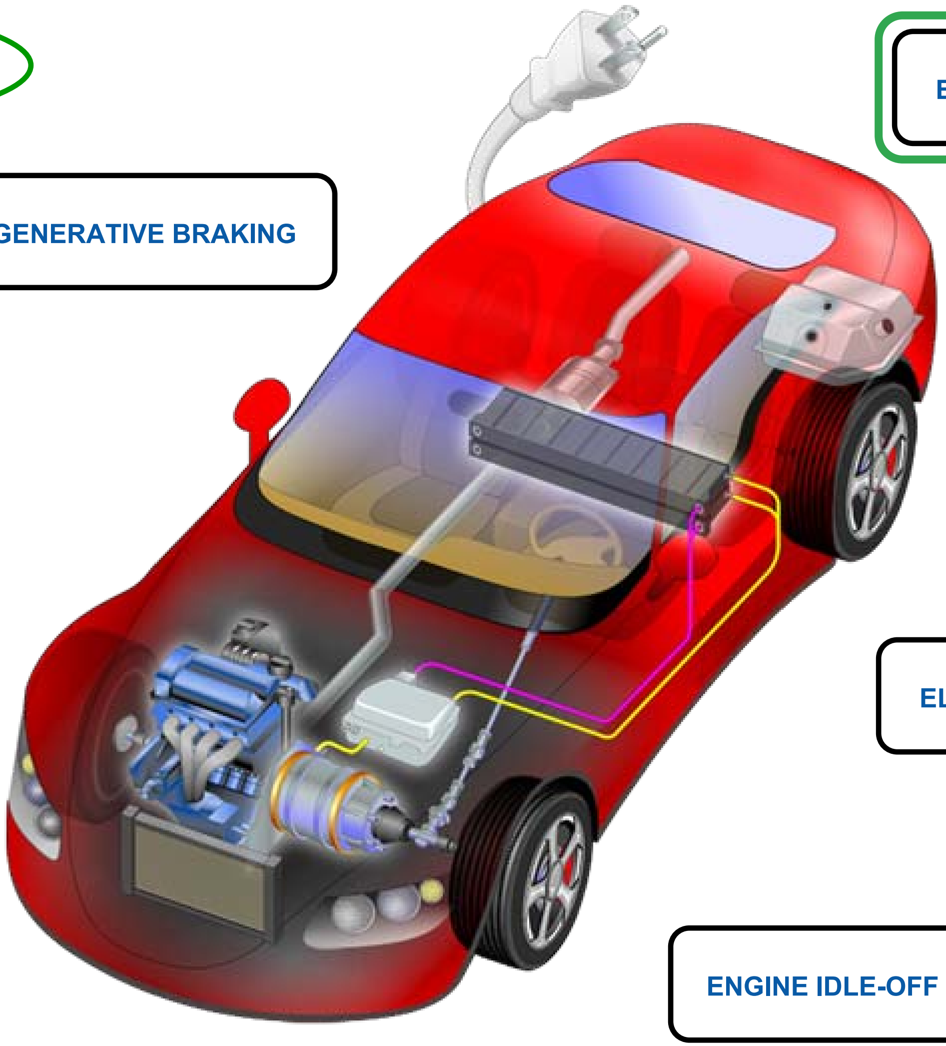
A Plug-In Hybrid-Electric Vehicle (PHEV)

Fuel Flexibility

PETROLEUM

AND/OR

ELECTRICITY



BATTERY RECHARGE

REGENERATIVE BRAKING

ELECTRIC ACCESSORIES

ADVANCED ENGINE

ENGINE IDLE-OFF

ENGINE DOWNSIZING

Some PHEV Definitions

All-Electric Range (AER): After a full recharge, the total miles driven electrically (engine-off) before the engine turns on for the first time.

Blended Mode: A *charge-depleting* operating mode in which the engine is used to supplement battery/motor power.

PHEV20: A PHEV with useable energy storage equivalent to 20 miles of driving energy on a reference driving cycle.

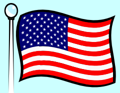
NOTE: PHEV20 does not imply that the vehicle will achieve 20 miles of AER on the reference cycle nor any other driving cycle. Operating characteristics depend on the power ratings of components, the powertrain control strategy and the nature of the driving cycle

PHEV Key Benefits and Challenges

KEY BENEFITS

Consumer:

- Lower "fuel" costs
- Fewer fill-ups
- Home recharging convenience
- Fuel flexibility



Nation:

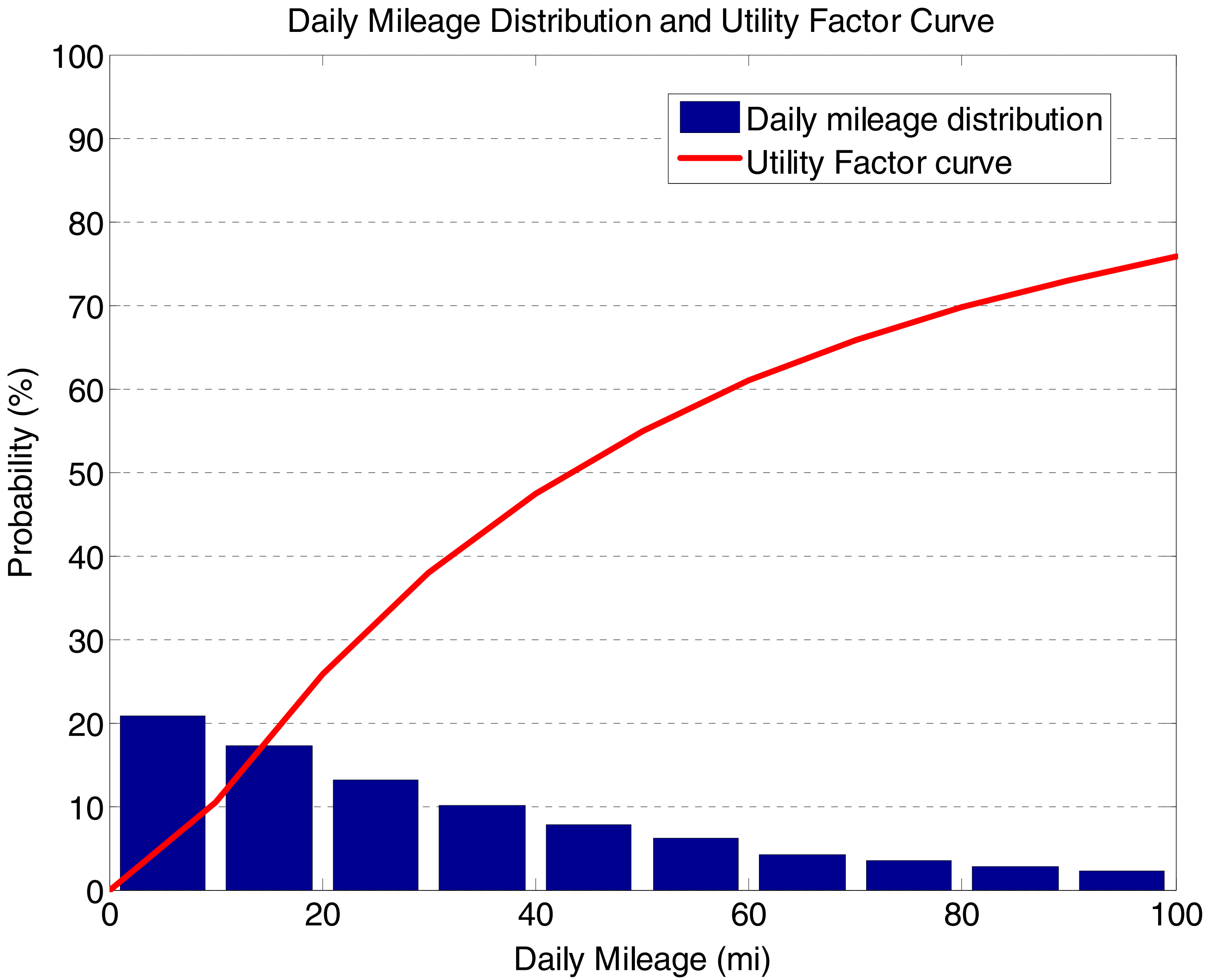
- Less petroleum use
- Less greenhouse and regulated emissions
- Energy diversity/security

KEY CHALLENGES

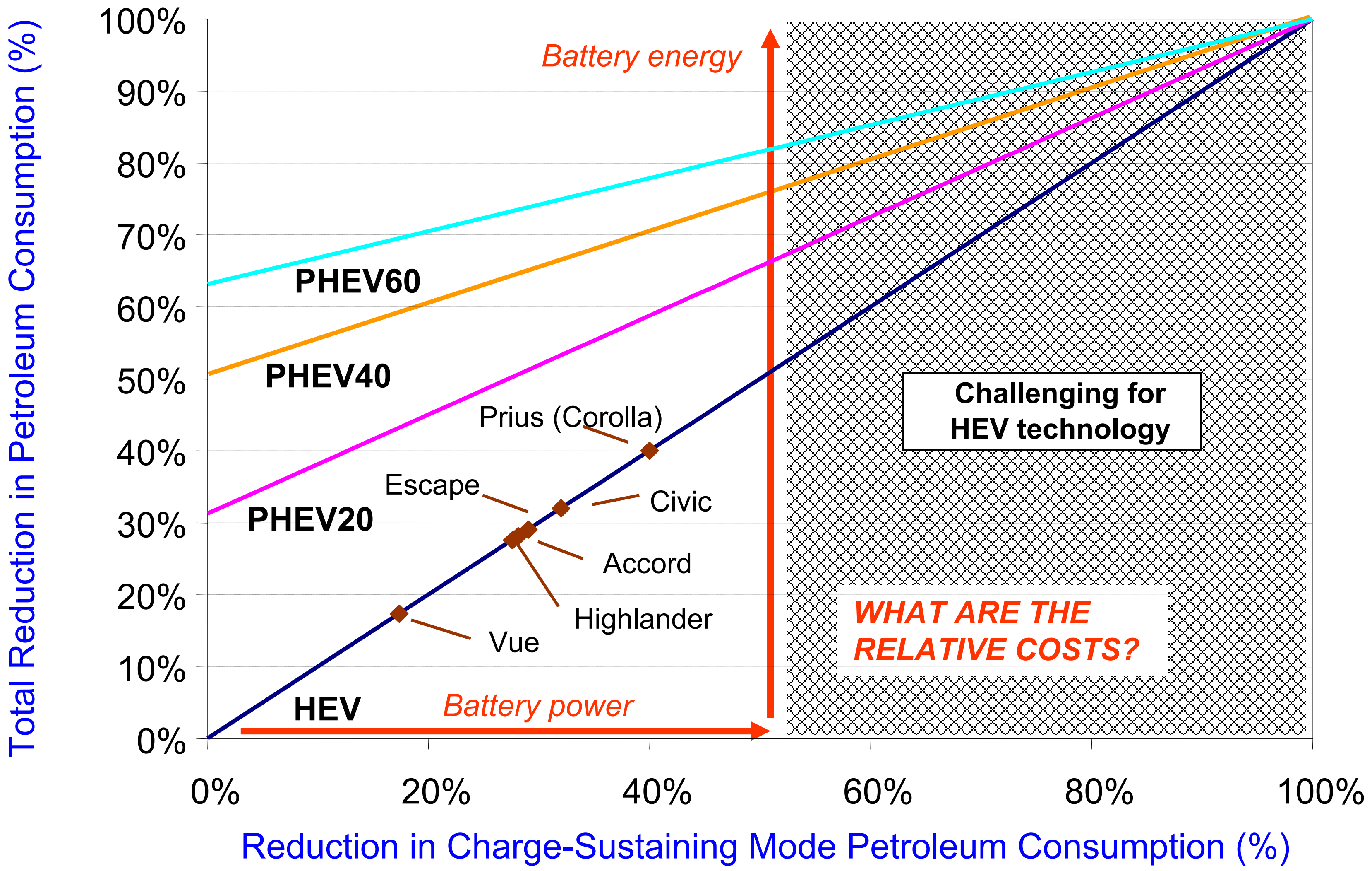
- Recharging locations
- Battery life ?
- Component packaging
- Vehicle cost

Cost-Benefit Analysis

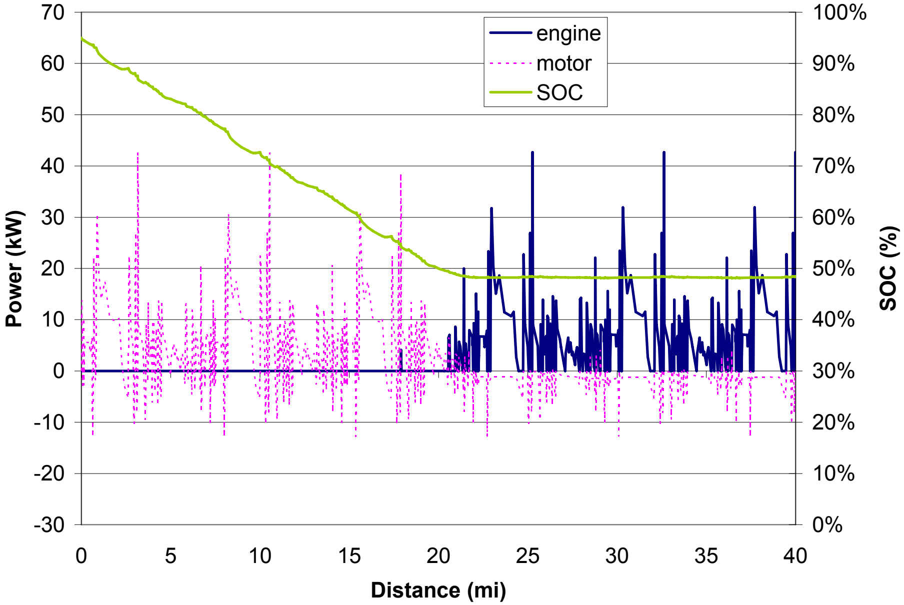
National Driving Statistics:
1995 National Personal Transportation Survey



Potential Petroleum Reduction from PHEVs



PHEV Efficiency and Cost Model



Vehicle Configurations

- conventional automatic
- pre-transmission parallel hybrid: HEV or PHEV
- 2 technology scenarios
  – near term and long term

Approach

- Dynamic, power-flow simulation
- Calculates component sizes and costs
- Iterative mass-compounding
- Measures fuel/electricity consumption using NREL-proposed revisions to SAE J1711
- *Battery definition is key input to the simulation*

Baseline Vehicle Characteristics – Midsize Sedan

MIDSIZE SEDAN (AUTOMATIC)	
Platform Parameters	
Glider Mass	905 kg
Curb Mass	1429 kg
Test Mass	1565 kg (136 kg load)
Gross Vehicle Mass (GVM)	1899 (470 kg load)
Drag coefficient	0.30
Frontal area	$2.27m^2$
Rolling resistance coefficient	0.009
Baseline accessory load	800 W elec. + 2900 W A/C
Performance Parameters	
Standing acceleration	0-60 mph in 8.0 s
Passing acceleration	40-60 mph in 5.3 s
Top speed	110 mph
Gradeability	6.5% at 55 mph at GVM with 2/3 fuel converter power
Vehicle attributes	
Engine power	121 kW
Fuel economy	**22.2 / 35.2 / 26.6 mpg** (urban / highway / composite, unadjusted)

Powertrain Technology Scenarios

Battery	**Near-Term Scenario**	**Long-Term Scenario**
Chemistry	NiMH	Li-Ion
Module cost	Double EPRI projections, see slide 12	EPRI projections, see slide 12
Packaging cost	EPRI	Same
Module mass	NiMH battery design function (Delucchi), see slide 12	Li-Ion battery design function (Delucchi), see slide 12
Packaging mass	Delucchi	Same
Efficiency	Scaleable model based on P/E ratio	Same
SOC window	SOC design curve based on JCI data for NiMH cycle-life, see slide 11	Same (assumes Li-Ion achieves same cycle life as NiMH)

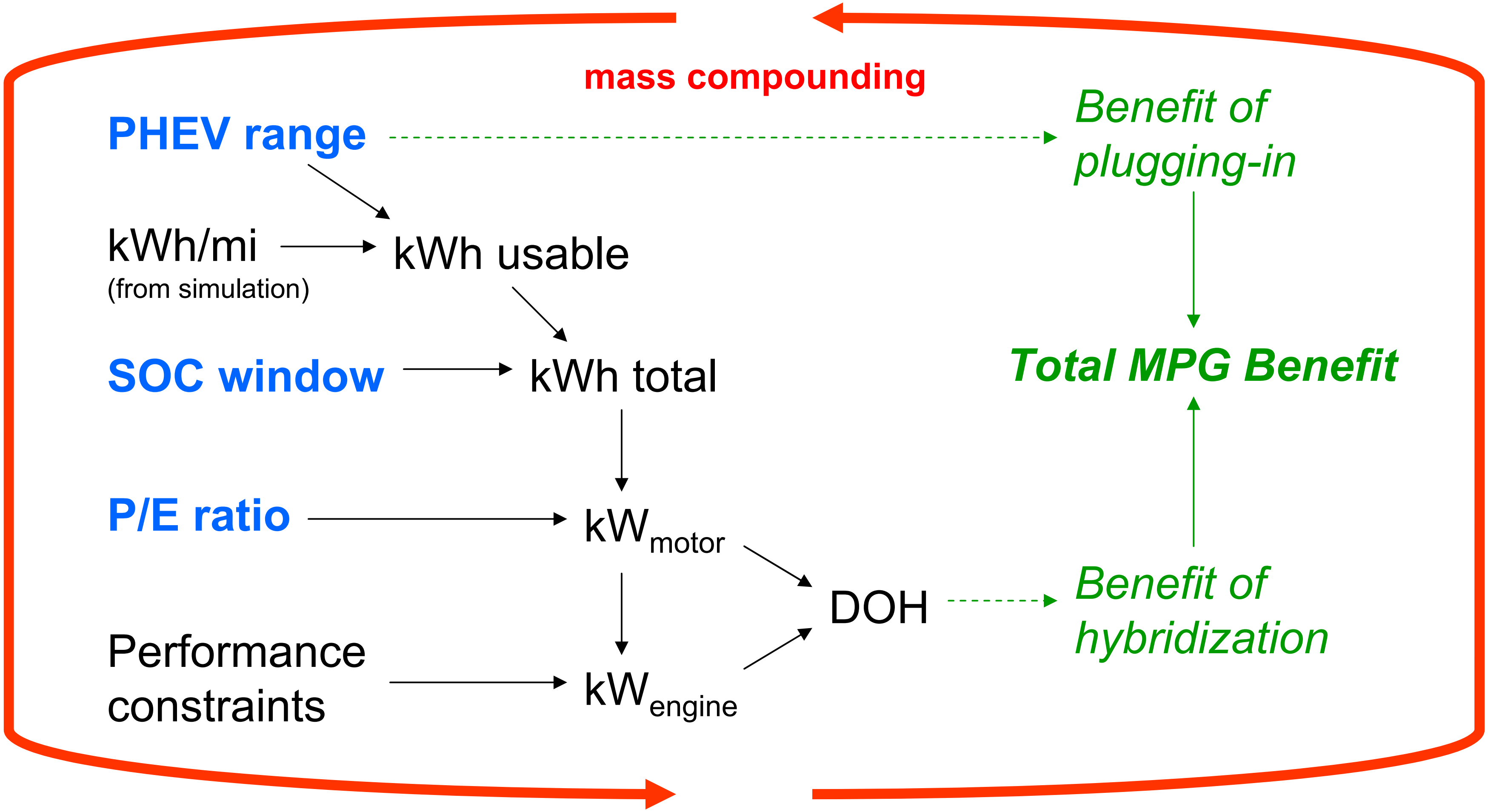
Motor	**Near-Term Scenario**	**Long-Term Scenario**
Mass	DOE 2006 current status	Based on GM Precept motor drive
Efficiency	95% peak efficiency curve	Same
Cost	EPRI (near term)	EPRI (long term)

Engine	**Near-Term Scenario**	**Long-Term Scenario**
Mass	Based on MY2003 production engines	Same*
Efficiency	35% peak efficiency curve	Same*
Cost	EPRI	Same*

* Engine technologies were not improved so as to isolate the benefits of improved plug-in hybrid technology

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

$\text{kW}_{\text{engine}}$

DOH

Benefit of plugging-in

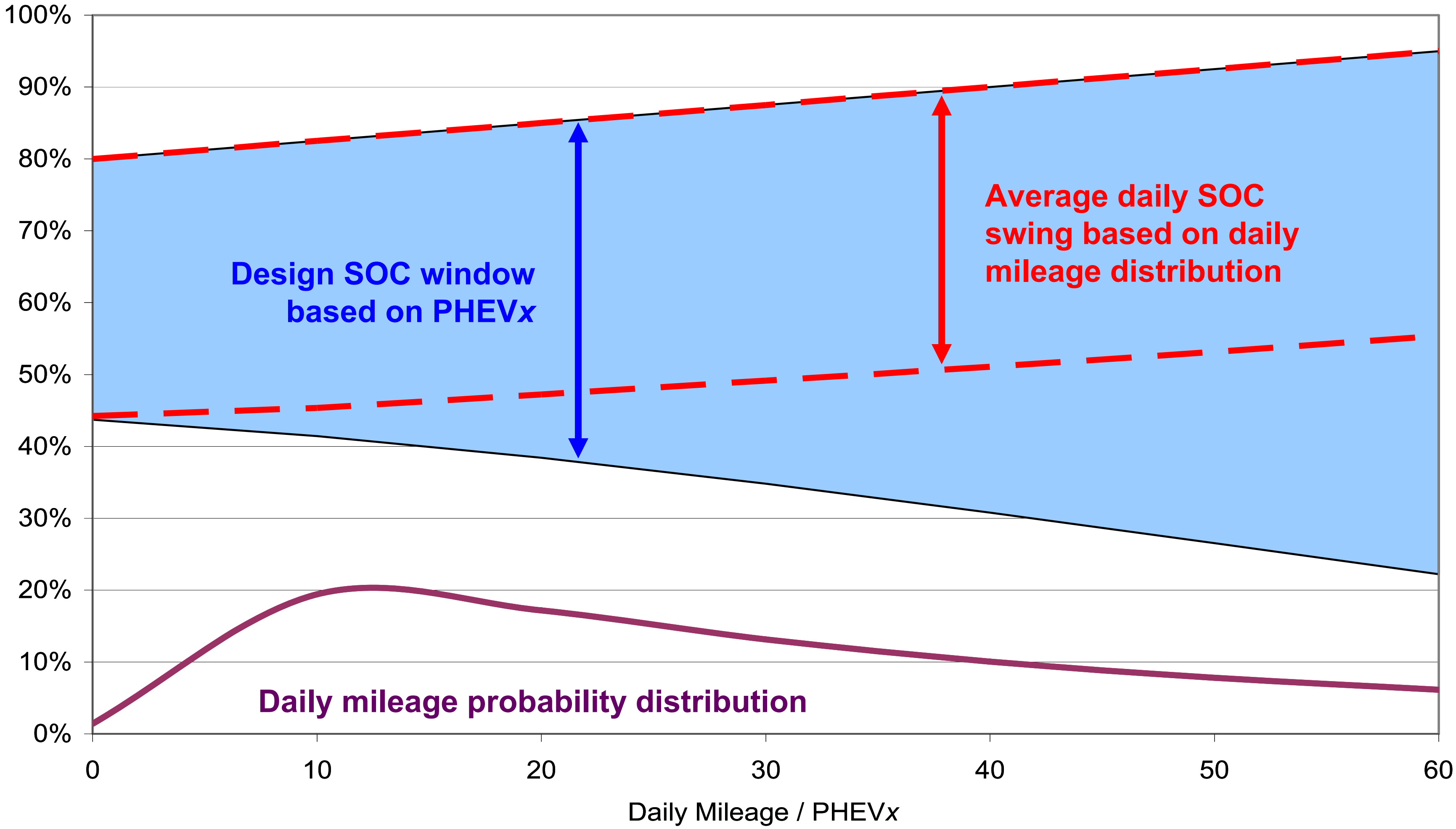
Total MPG Benefit

Benefit of hybridization

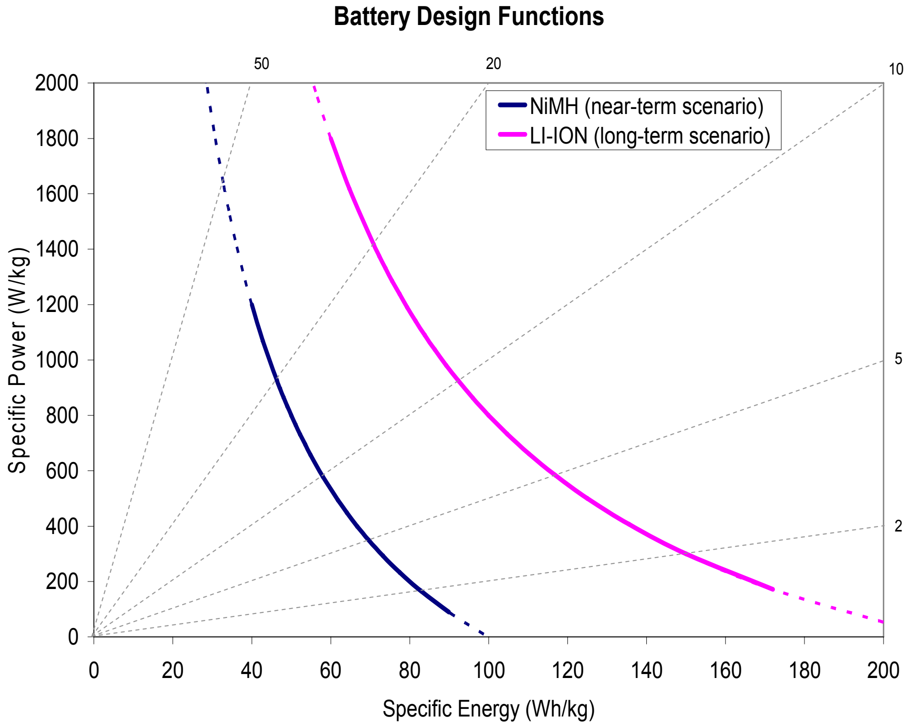
DOH = degree of hybridization

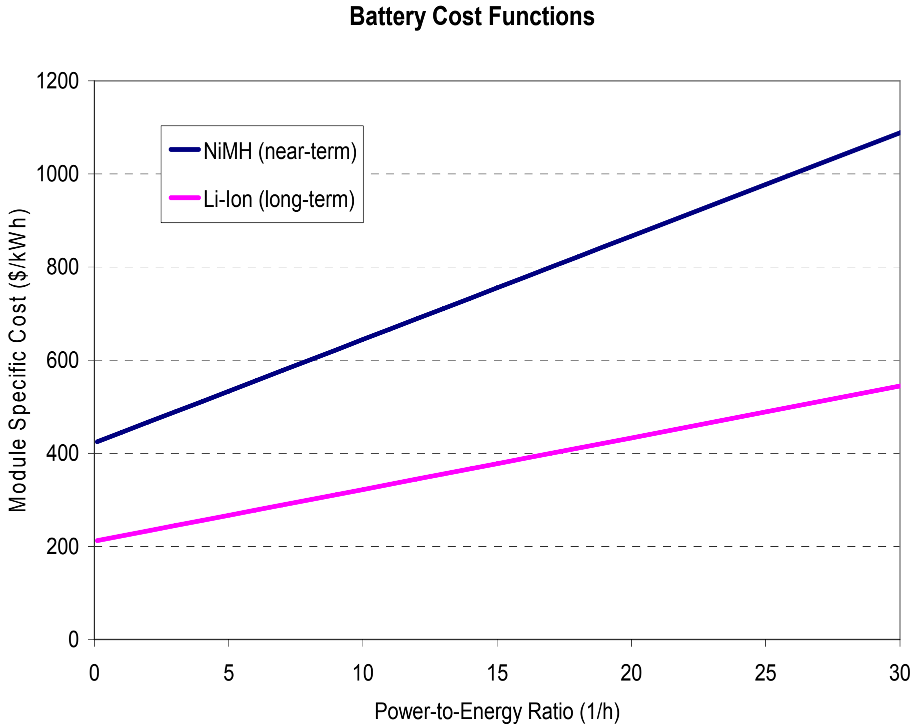
Battery SOC Design Window

Battery SOC design curve for 15 year cycle life



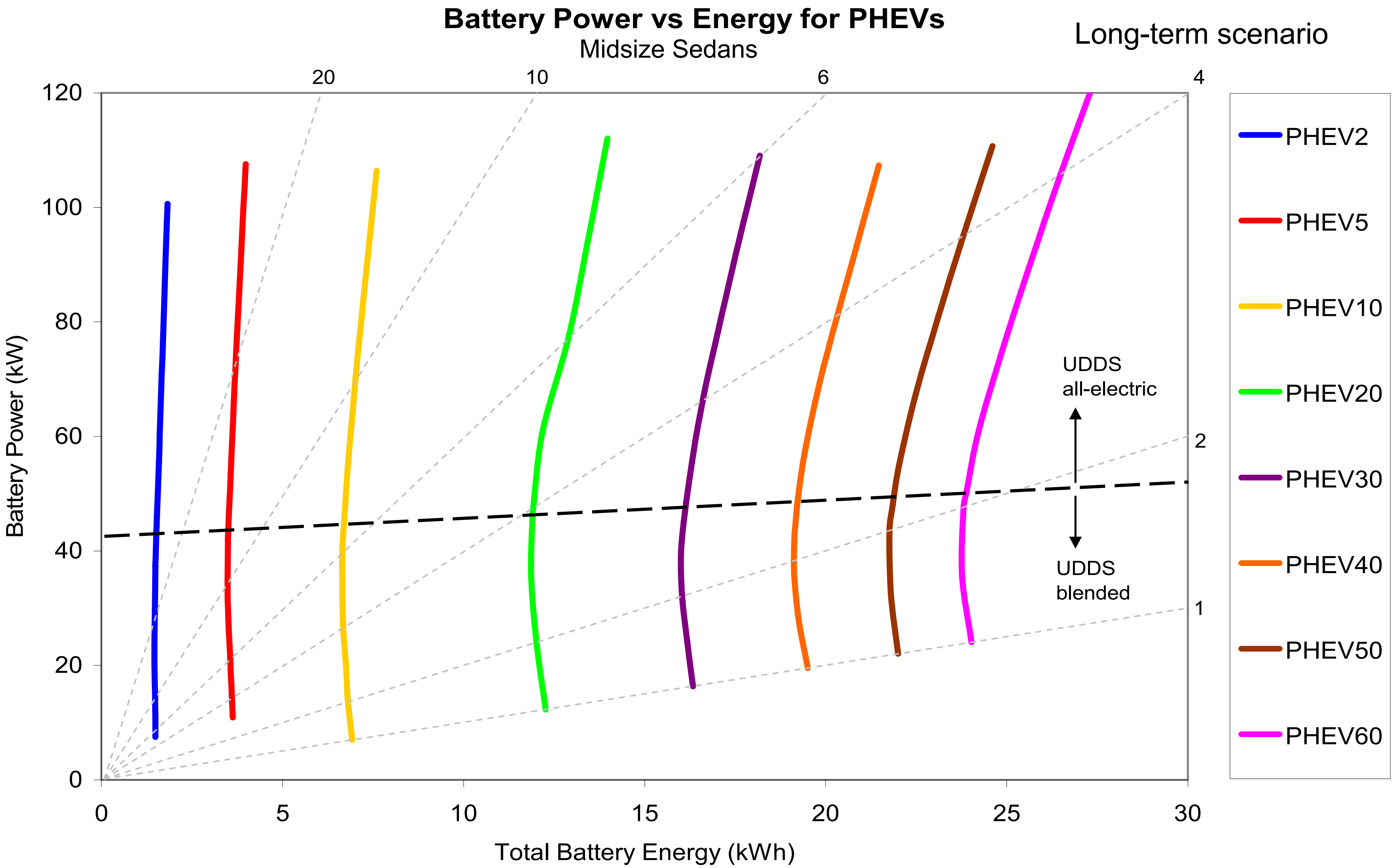
Battery Models (Scaleable)





Results: Battery Specifications

Long-term scenario



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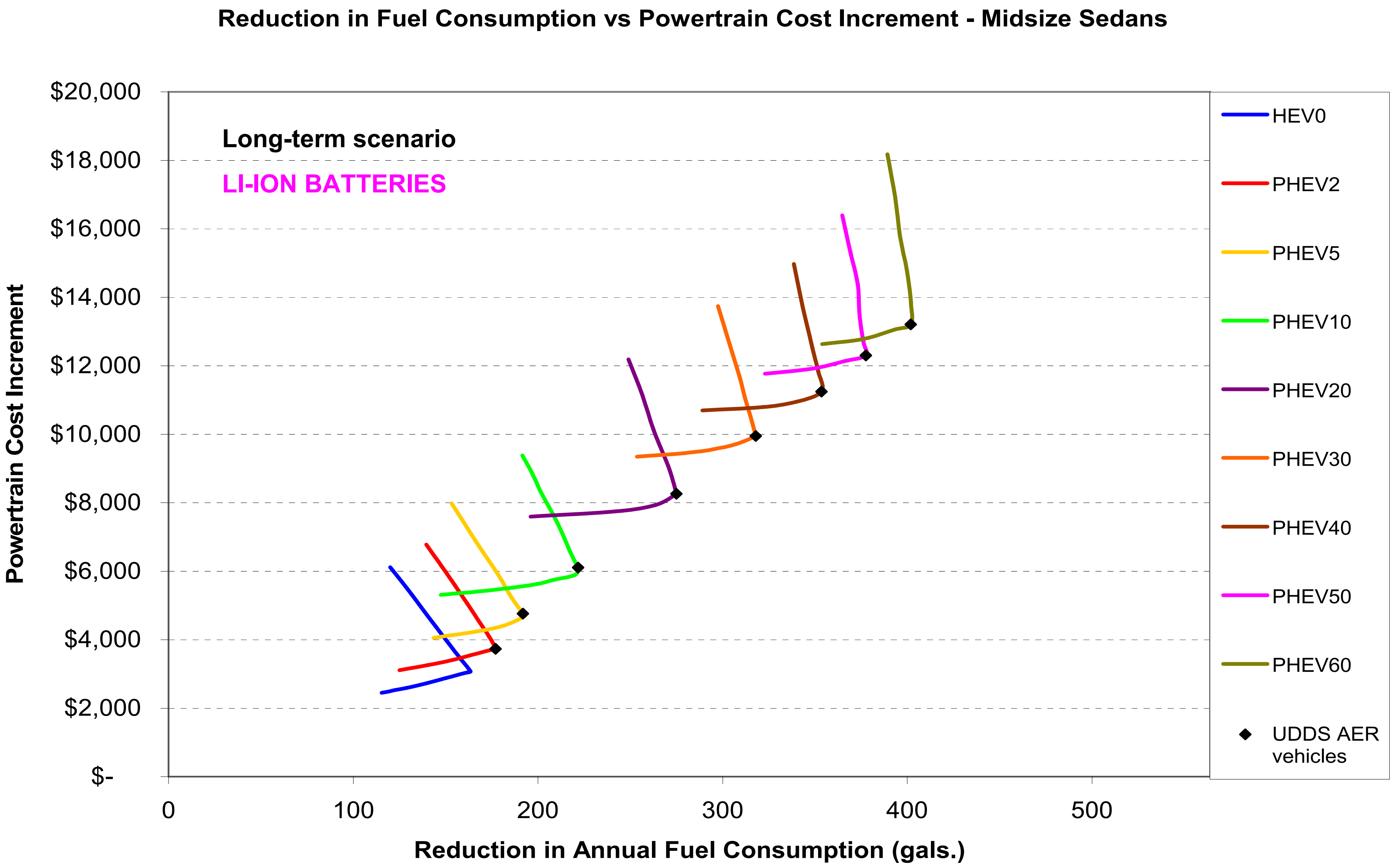
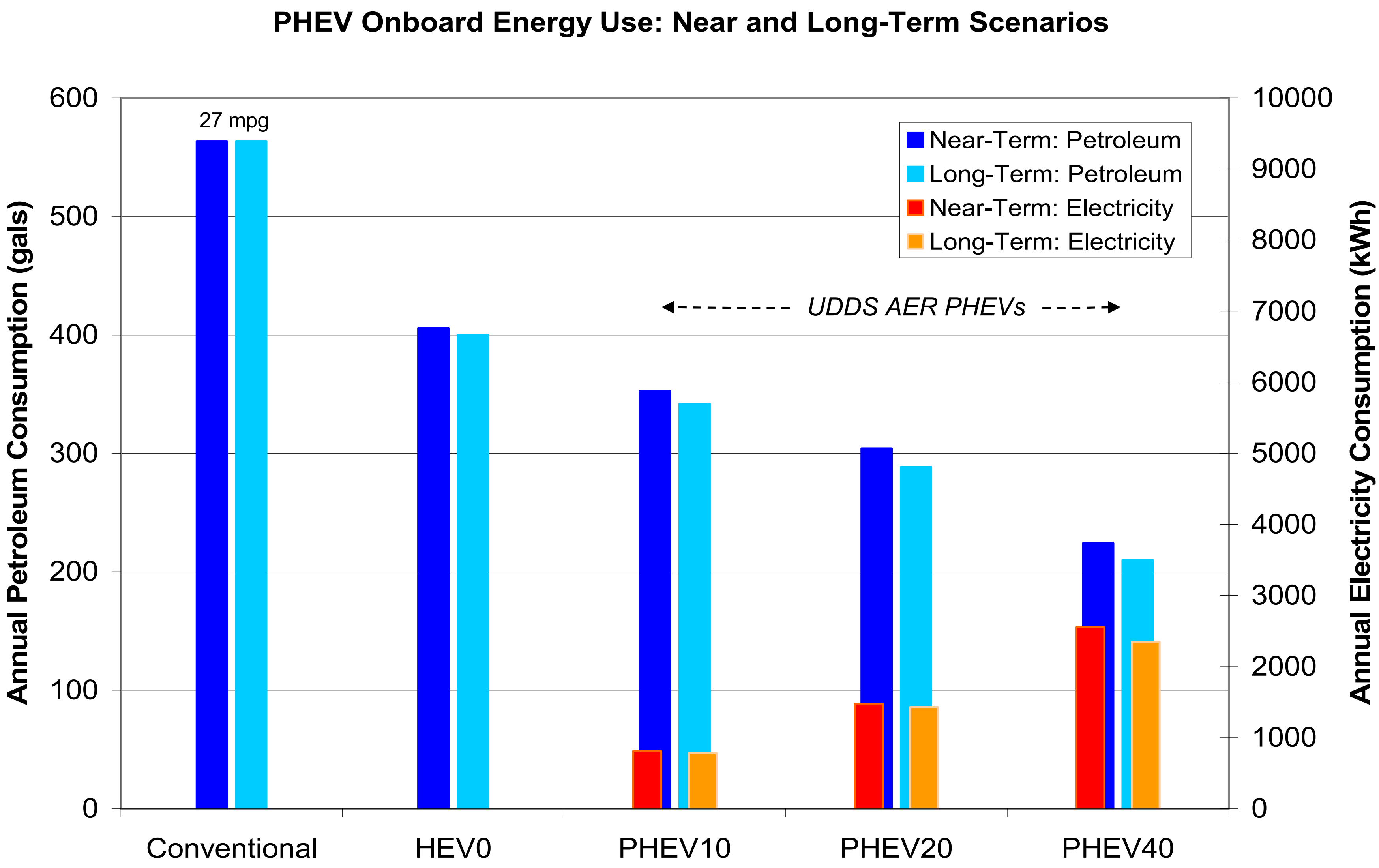
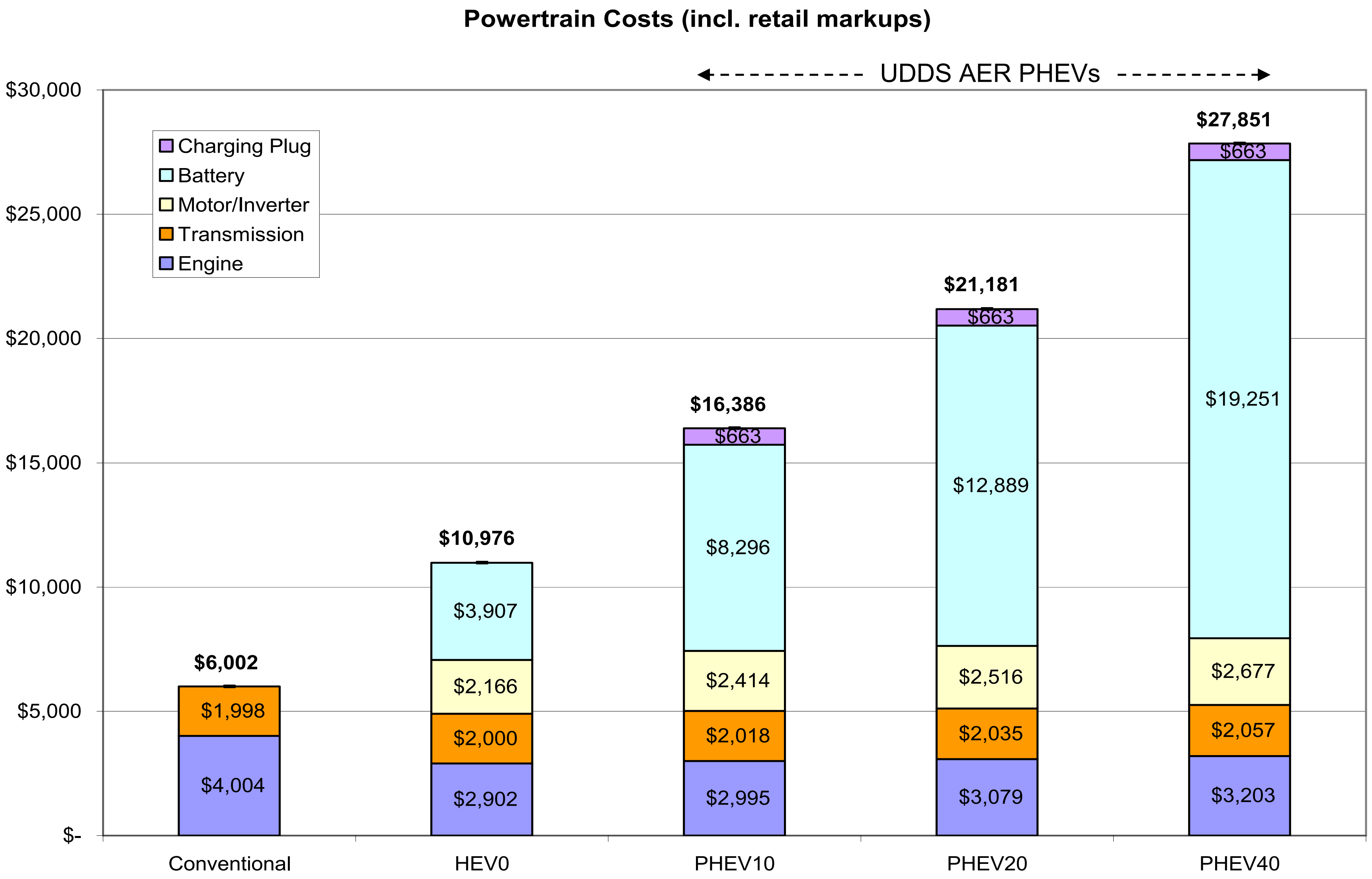


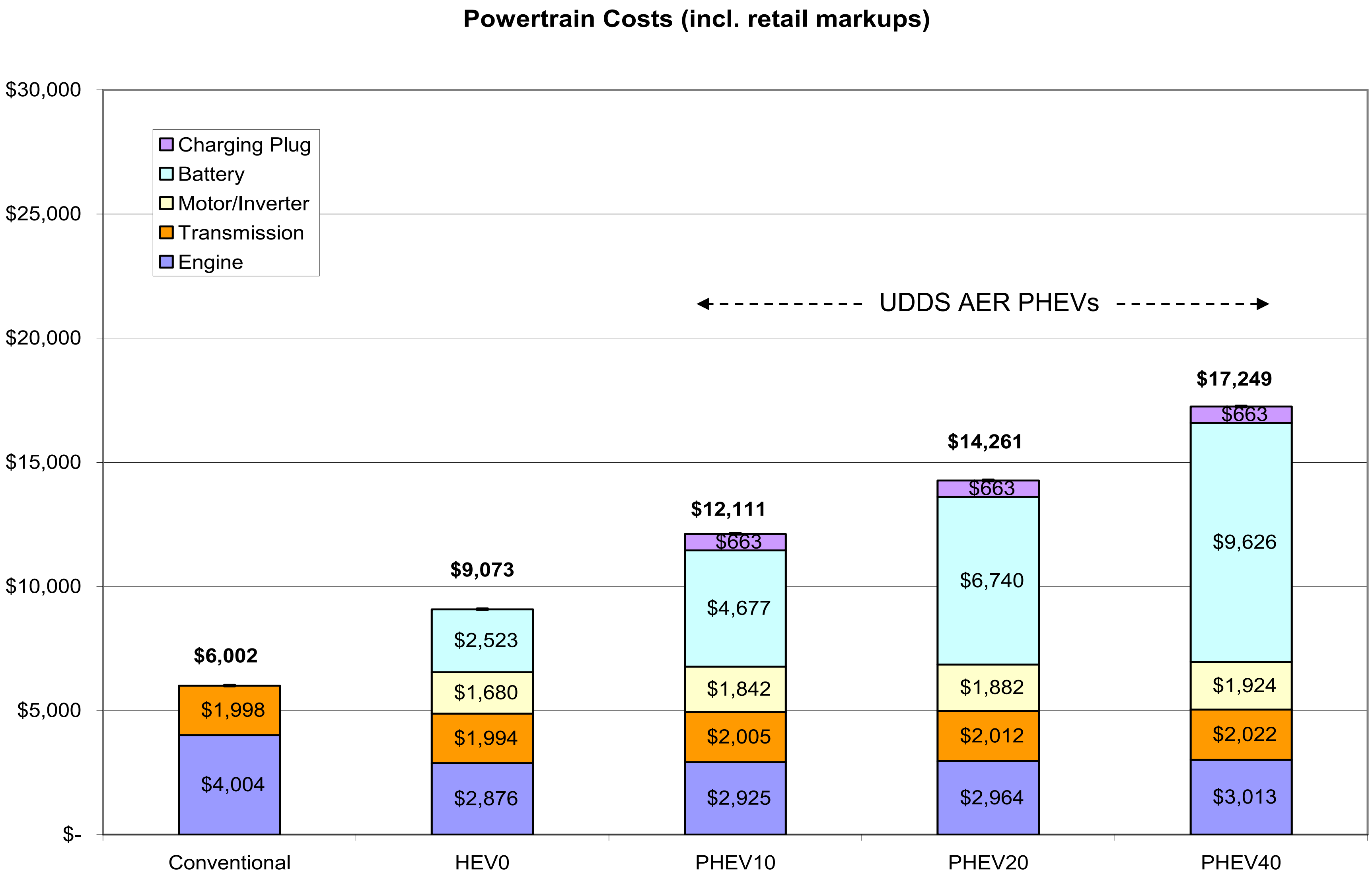
PHEV Energy Use



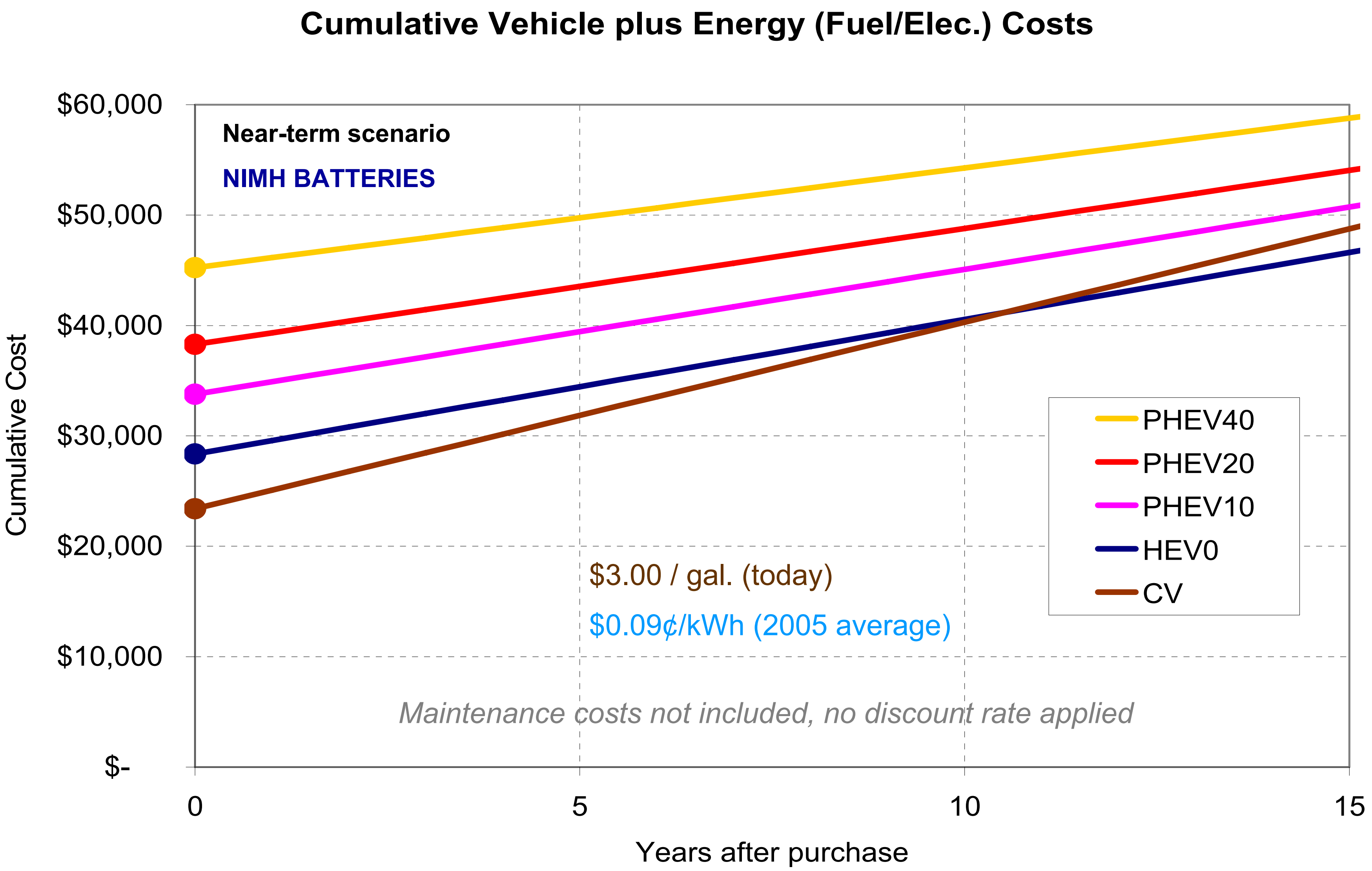
Powertrain Costs Comparison – Near Term



Powertrain Costs Comparison – Long Term



Overall Cost Comparison for HEVs and PHEVs



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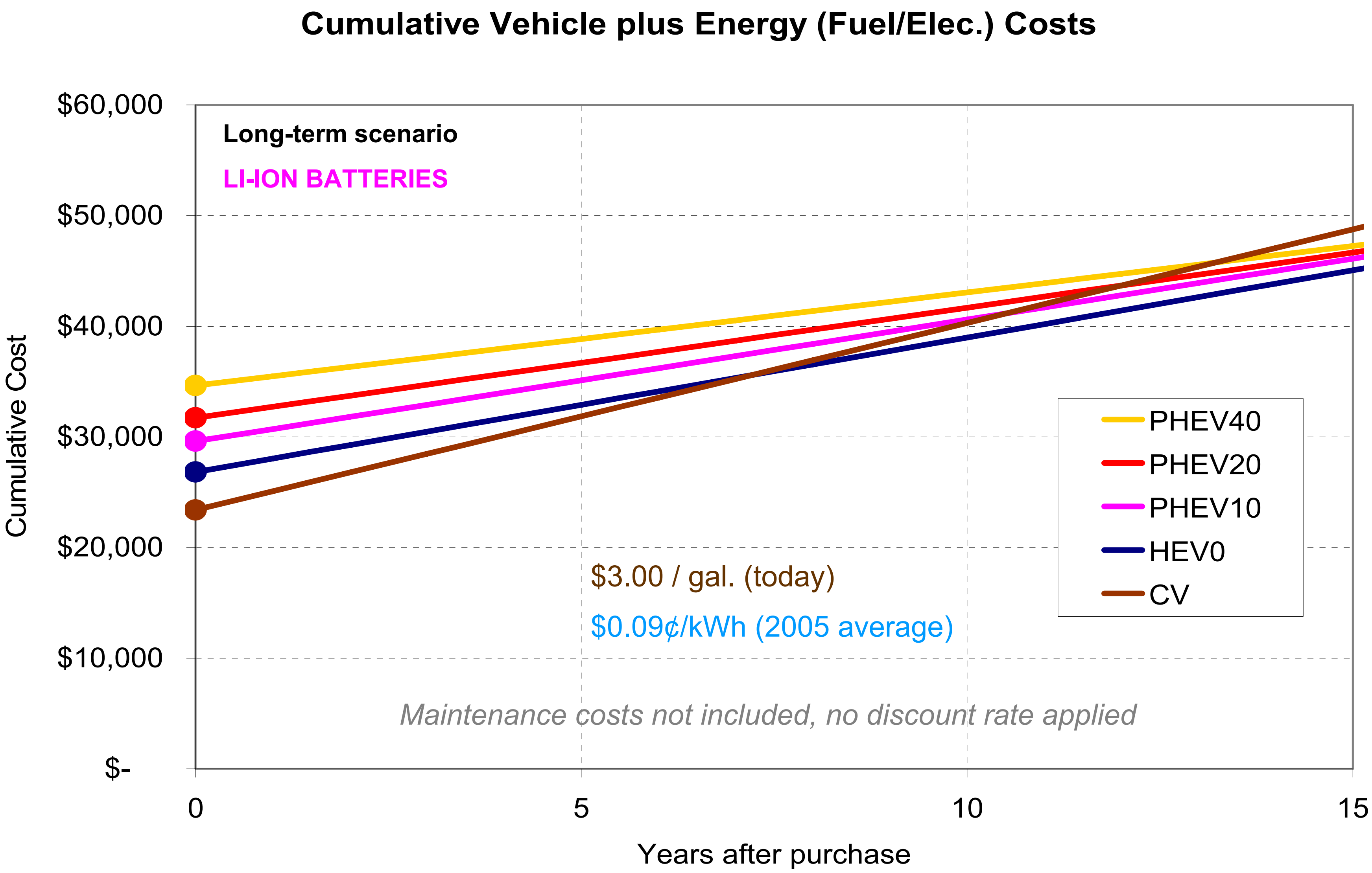

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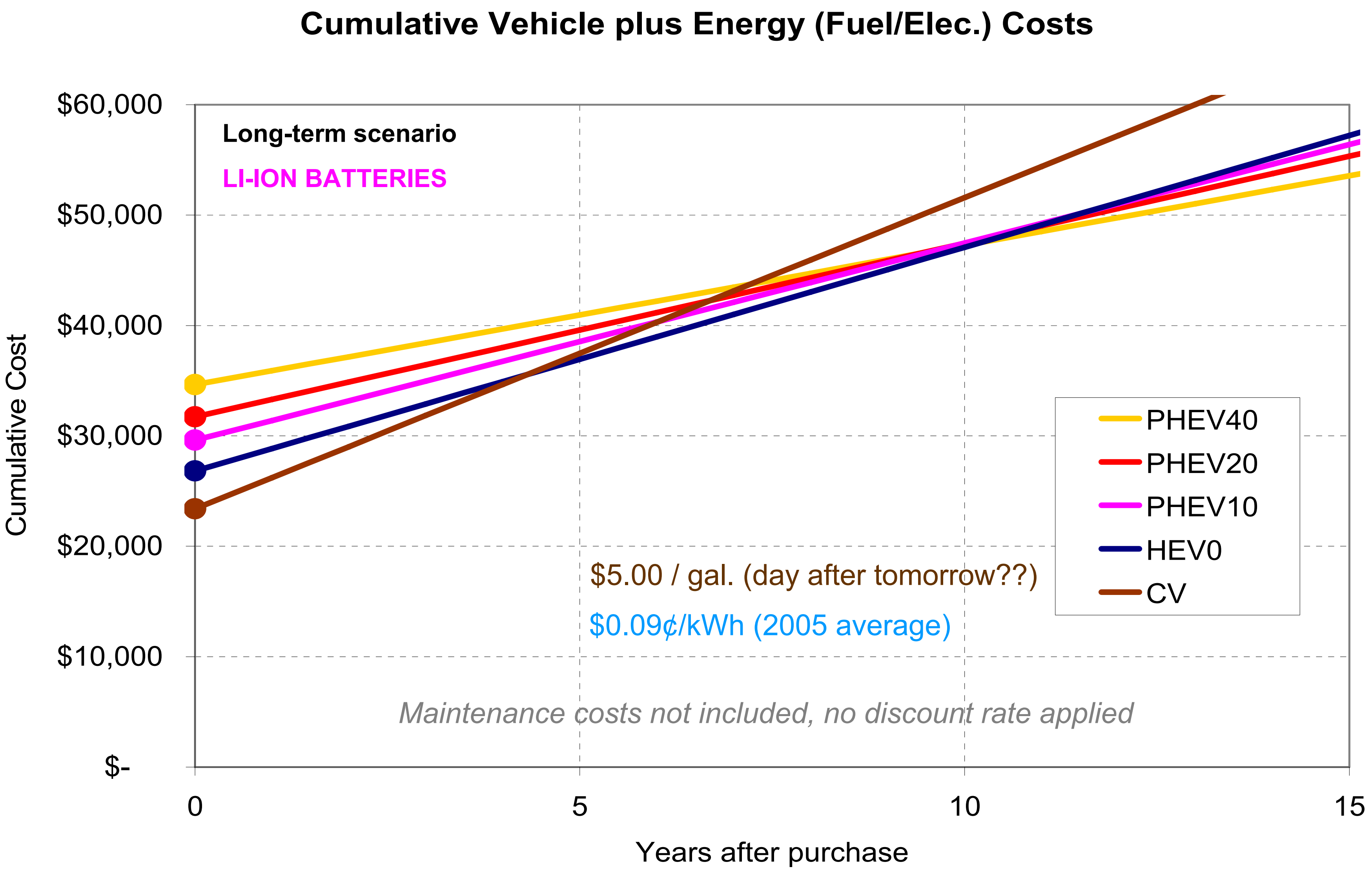

Vehicle Costs cont.

Why might PHEV buyers pay more?

1. Tax incentives
2. Reduced petroleum use, air pollution and CO_2
3. National energy security
4. Less maintenance
5. Reduced fill-ups
6. Convenience of home recharging (off-peak)
7. Improved acceleration (high torque of electric motors)
8. Green image, “feel-good factor”
9. Backup power
10. Vehicle-to-grid (V2G)

Conclusions

1. There is a very broad spectrum of HEV-PHEV designs.

2. Key factors in the HEV/PHEV cost-benefit equation include:
   - Battery costs
   - Fuel costs
   - Control strategy (particularly battery SOC window)
   - Driving habits (annual VMT and trip-length distribution)

3. Based on the assumptions of this study:
   - HEVs can reduce per-vehicle fuel use by approx. 30%.
   - PHEVs can reduce per-vehicle fuel use by up to 50% for PHEV20s and 65% for PHEV40s.
   - In the long term, powertrain cost increments are predicted to be $2-6k for HEVs, $7-11k for PHEV20s and $11-15k for PHEV40s assuming that projected component (battery) costs can be achieved.
   - Note this study did not consider benefits from platform engineering (i.e. mass/drag reduction).

Conclusions (cont.)

4. Based on overall costs (powertrain plus energy):
   - At today's fuel and powertrain component costs, conventional vehicles are the most cost-competitive.
   - HEVs become the most cost-competitive EITHER if fuel prices increase OR projected battery costs are achieved.
   - PHEVs become cost-competitive ONLY if projected battery costs are achieved AND fuel prices increase.
   - Tax incentives and/or alternative business models (e.g. battery lease) may be required for successful marketing of PHEVs

Next Steps

- Present this work at EVS22

- Expand the HEV-PHEV analysis space to include:
  - Platform engineering (mass/drag reduction)
  - Different performance constraints / component sizes

SAE 2007 paper

- Detailed simulation of promising PHEV designs:
  - Real world driving patterns (e.g. St Louis data)
  - Control strategy optimization

TRB 2007 paper

- Optimization of PHEV market competitiveness using Technical Targets Tool

Ongoing analysis