Battery Requirements and Cost-Benefit Analysis for Plug-In Hybrid Vehicles

Ahmad Pesaran
Tony Markel

National Renewable Energy Laboratory
Golden, CO, USA
ahmad_pesaran@nrel.gov, Tel: 303 275-4441

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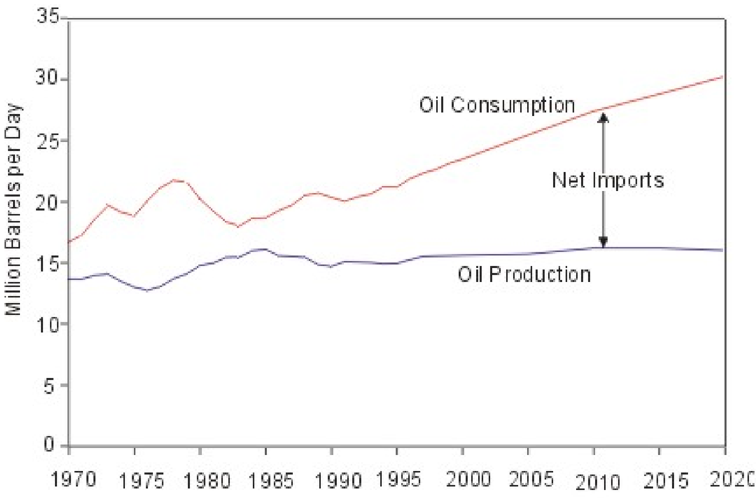
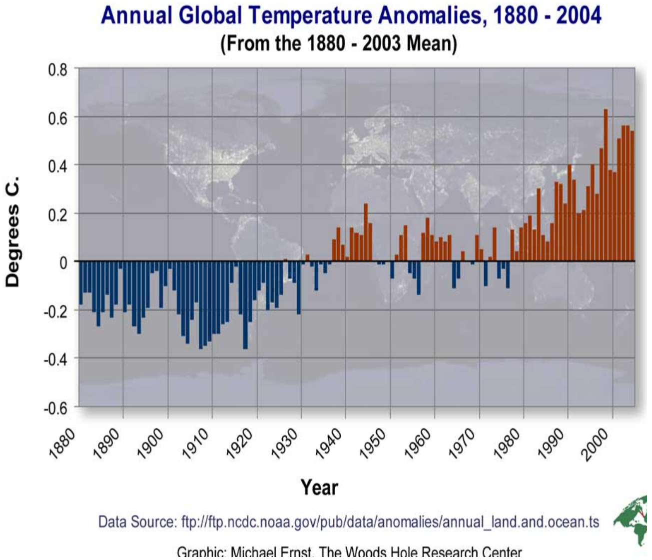
Outline

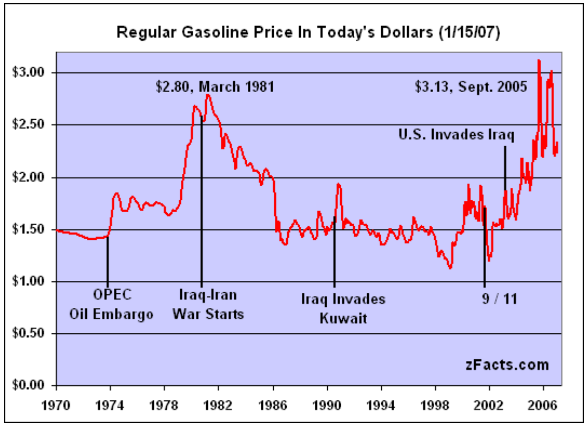
- Why Plug-In Hybrids?
- What is a Plug-In Hybrid?
- Definitions and Terminologies
- Current Plug-in Hybrid Conversions
- Battery Requirements
- Analysis – Benefits and Costs
- Summary

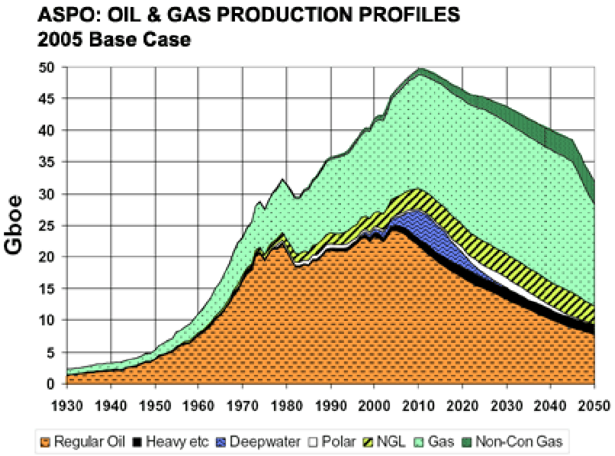
Why are Alternative Fuel and Efficient Vehicles Needed?

- Petroleum consumption has steadily increased while domestic production has continued to decline
- Energy security and oil independence are major concerns in US
- World oil production will likely peak within the next 5-15 years
- Recent increase in gasoline price is an indicator of growing tension between supply and demand
- Greenhouse gas emission and global warming concerns





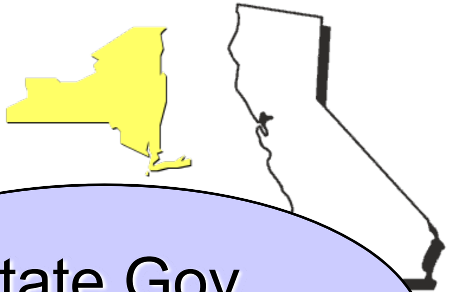




Why are Plug-In Hybrids Getting a lot of Attention?

- Most hybrid vehicles still consume petroleum.
- Alternative fuel vehicles such as E85 are available, but fuel and required infrastructure are not ready.
- Mass production of hydrogen fuel cell vehicles is not likely in the next 15 years.
- Electric vehicles are not likely to be mass produced in the next 20 years due to battery cost, charging time and fast charging infrastructure requirements.
- Plug in hybrids offer potential for both energy efficiency and use of domestic energy (electricity) without paradigm shift in a new fueling infrastructure.
- A majority of US drivers travel fewer than 40 miles a day, so a vehicle with short EV range and long petroleum range is very attractive.
- The President's State of Union Address in 2006 & 2007

Plug-in Hybrid Stakeholder Objectives



US Gov./DOE
Reduced petroleum use;
Use alternative energy

Consumers
Drive affordable functional, fun, and feel good cars

State Gov.
Reduced air pollution;
Use renewable energy

Auto Manufacturers
Sell cars

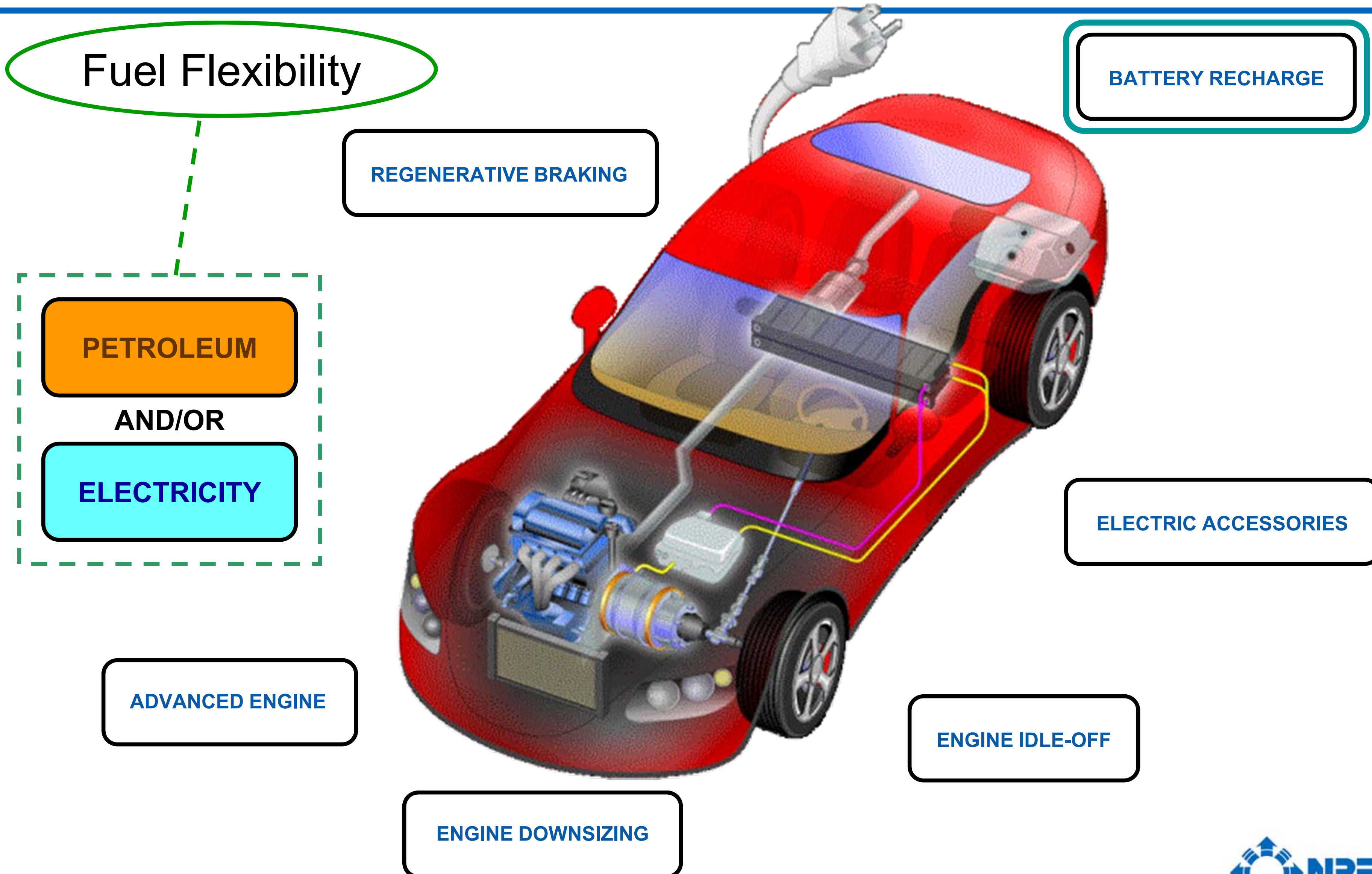
Electric Utilities
Sell electricity

Battery Manufacturers
Sell batteries

Security advocates, Environmentalists, Consortiums
Conversion companies, Component suppliers

What is a Plug-In Hybrid Electric Vehicle

An HEV with an energy storage system that could be charged with off-board electricity



Some PHEV Definitions

Charge-Depleting (CD) HEV Mode: Vehicle operation on the electric drive, engine subsystem or both with a net decrease in battery state-of-charge.

Charge-Sustaining (CS) HEV Mode: Vehicle operation on the electric drive, engine subsystem or both at 'relatively constant' battery state-of-charge (i.e. within a narrow range).

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

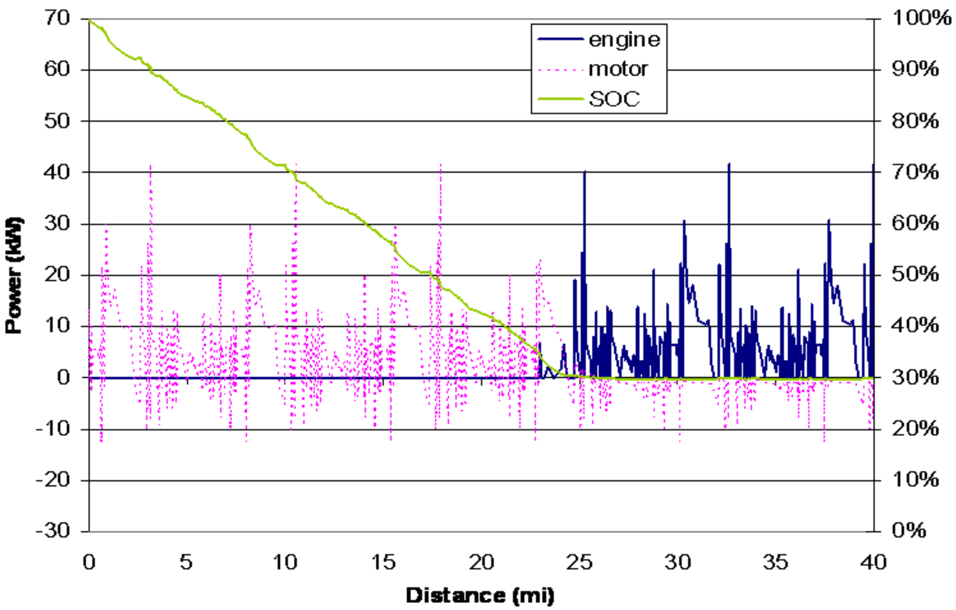
Charge-Depleting Range (CDR): After a full recharge, the total miles driven before the vehicle reaches charge-sustaining mode.

PHEV20: A PHEV with useable energy storage equivalent to 20 miles of driving energy on a reference driving cycle. A PHEV20 can displace petroleum energy equivalent to 20 miles of driving on the reference cycle with off-board electricity.

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

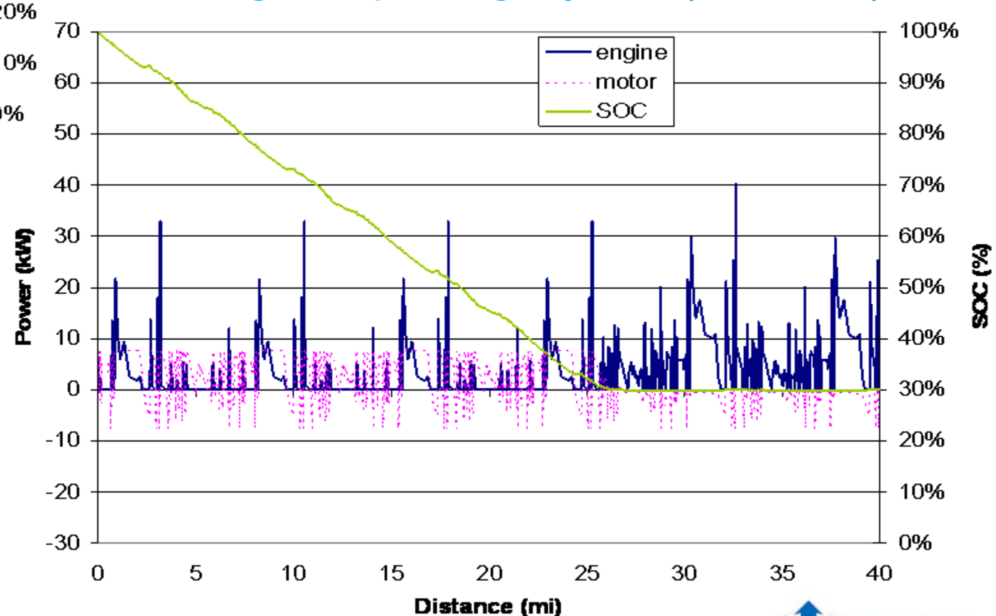
Operating Strategy Options
All-Electric or Blended/Hybrid

Charge Depleting Electric



- Engine is off during the electric range
- Engine turns on when battery reaches low state of charge
- Requires high power battery and motor

Charge Depleting Hybrid (Blended)



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

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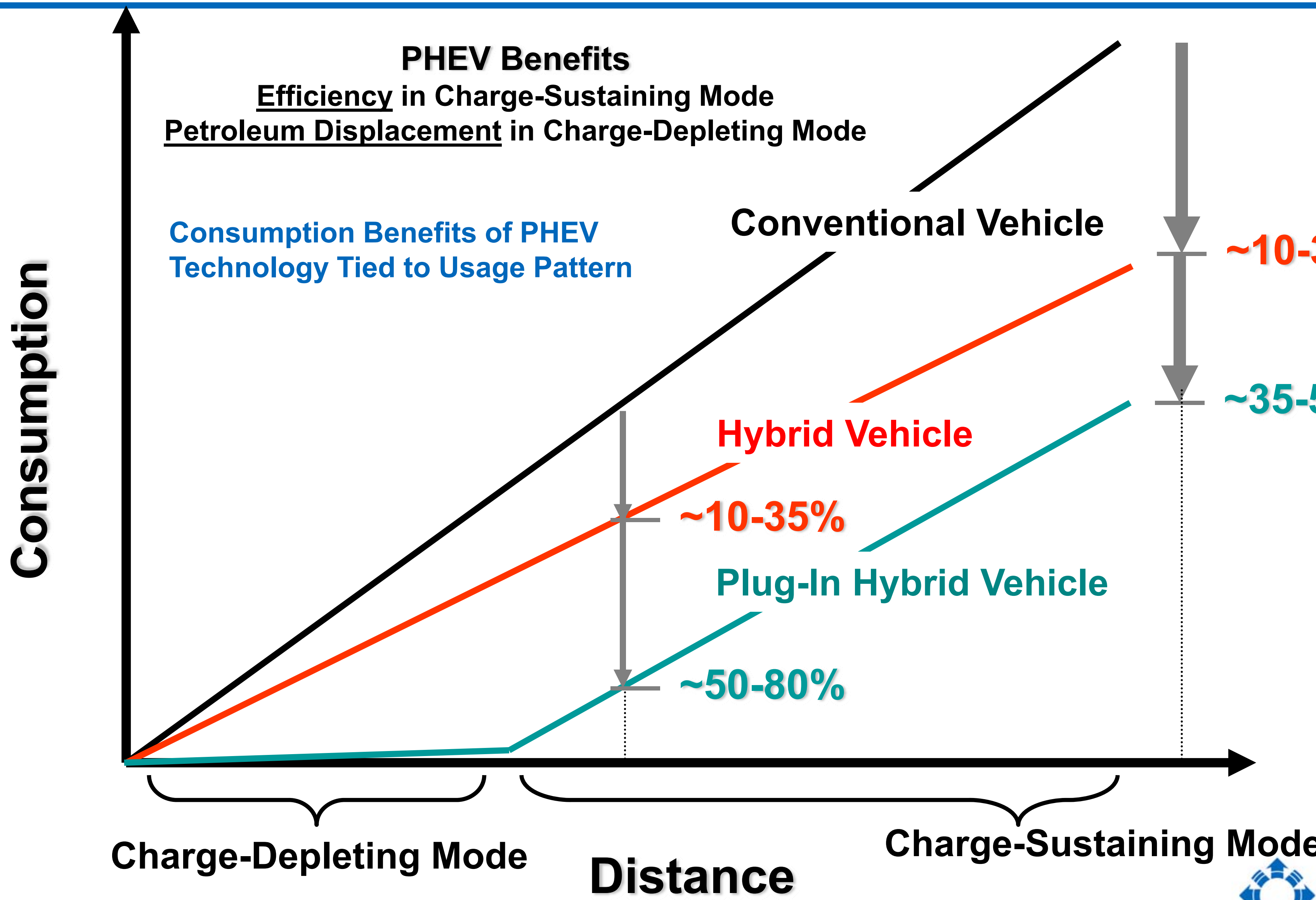
How Do PHEVs Reduce Petroleum Consumption?



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Some of PHEV Prototypes

EnergyCS Plug-In Prius

Hymotion Escape PHEV

AFS Trinity Extreme Hybrid™

DaimlerChrysler Sprinter Van PHEV

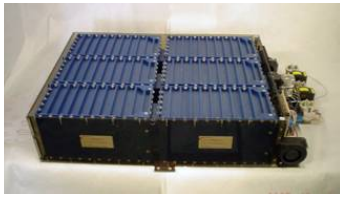
AC Propulsion Jetta PHEV

Renault Kangoo Elect'road

Batteries in Current PHEVs

Johnson Controls / Varta

NiMH



Electro Energy Inc.

Johnson Controls / SAFT

Co/Ni based Li-Ion

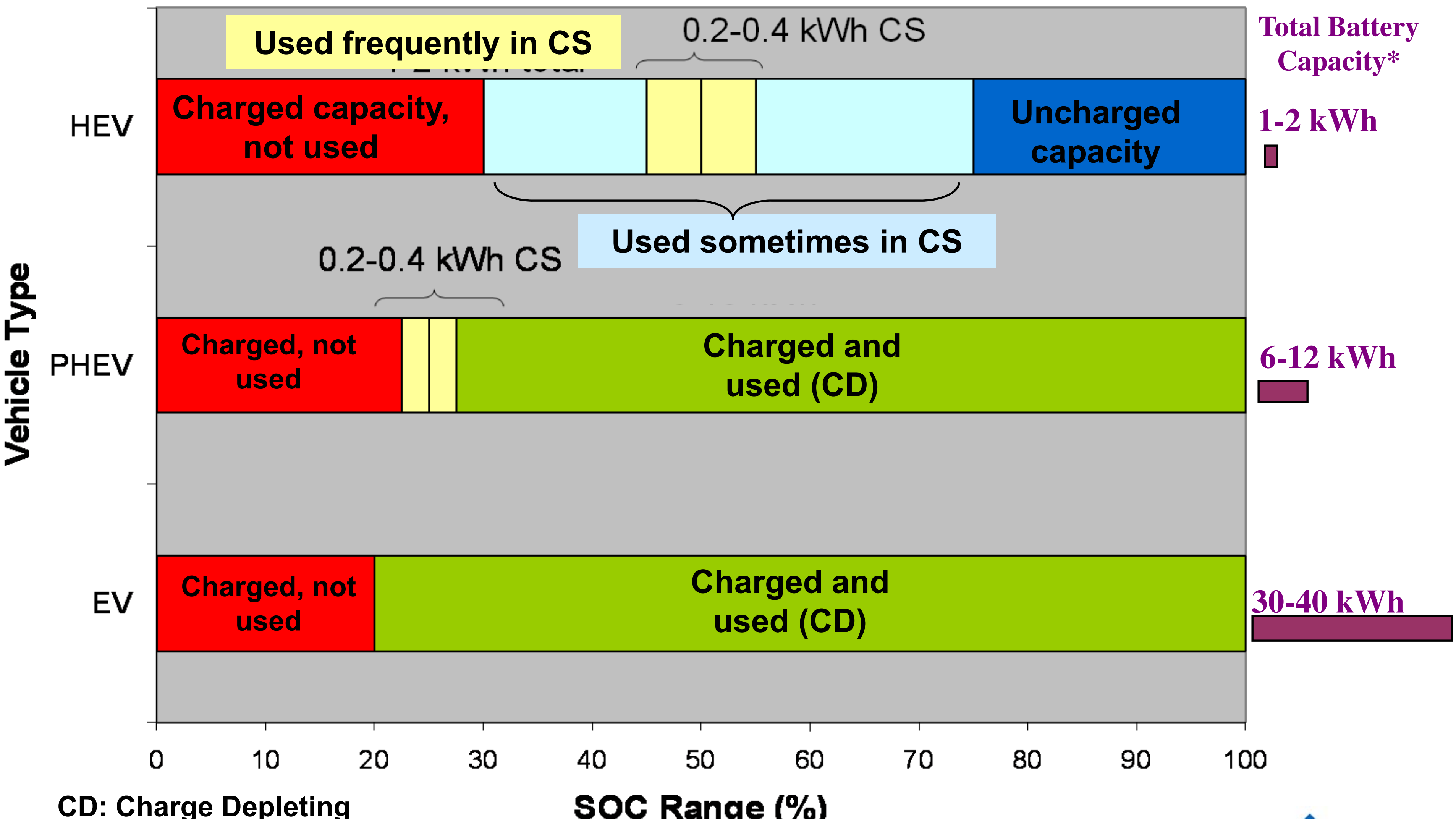
Kokam

Valence Technology

Iron phosphate based Li-Ion

A123 Systems

Battery Usage in EVs, HEVs, and PHEVs



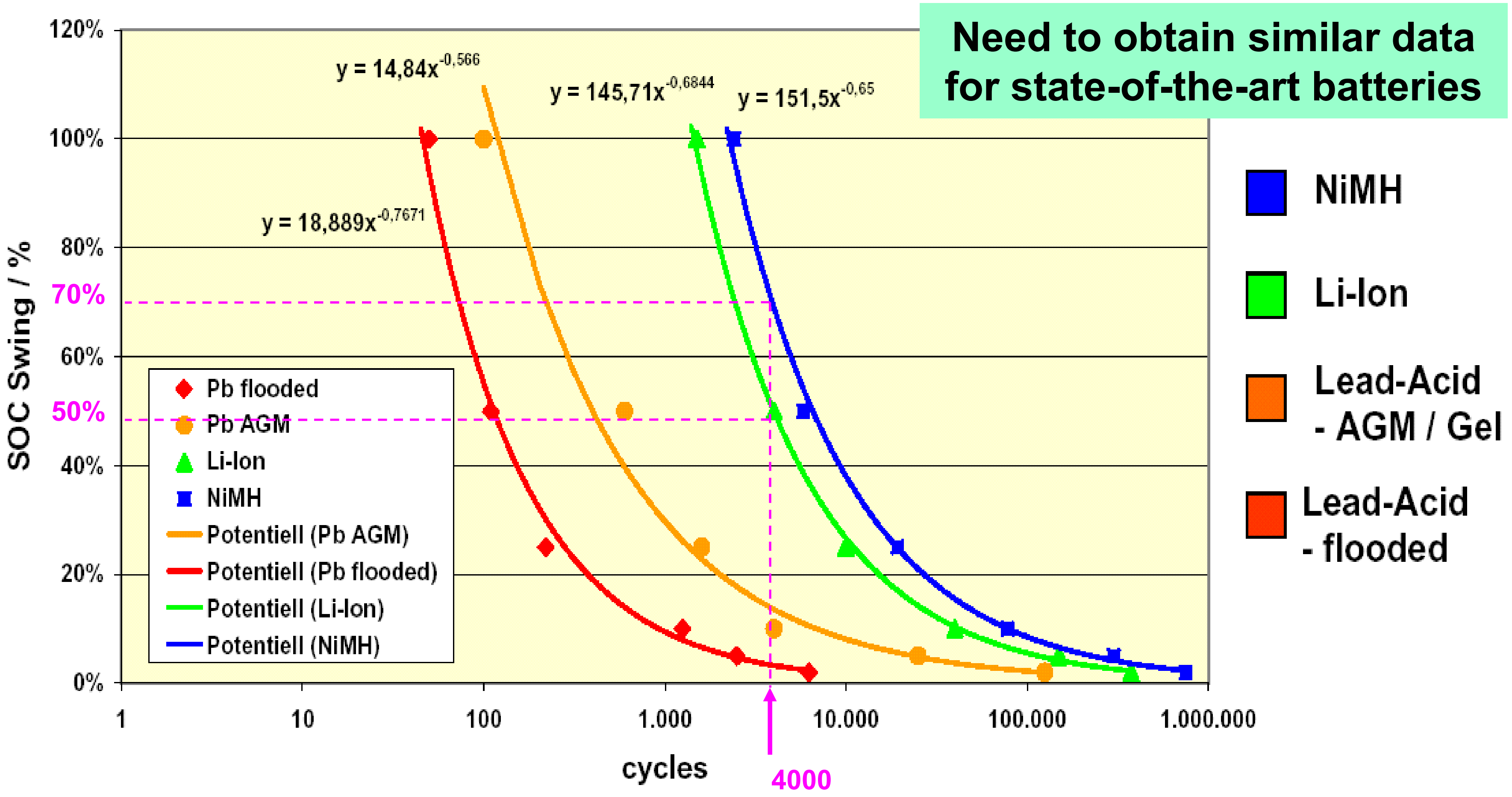
CD: Charge Depleting

CS: Charge Sustaining

*Battery capacity for a midsize car

Battery Cycle Life Depends on State of Charge Swing

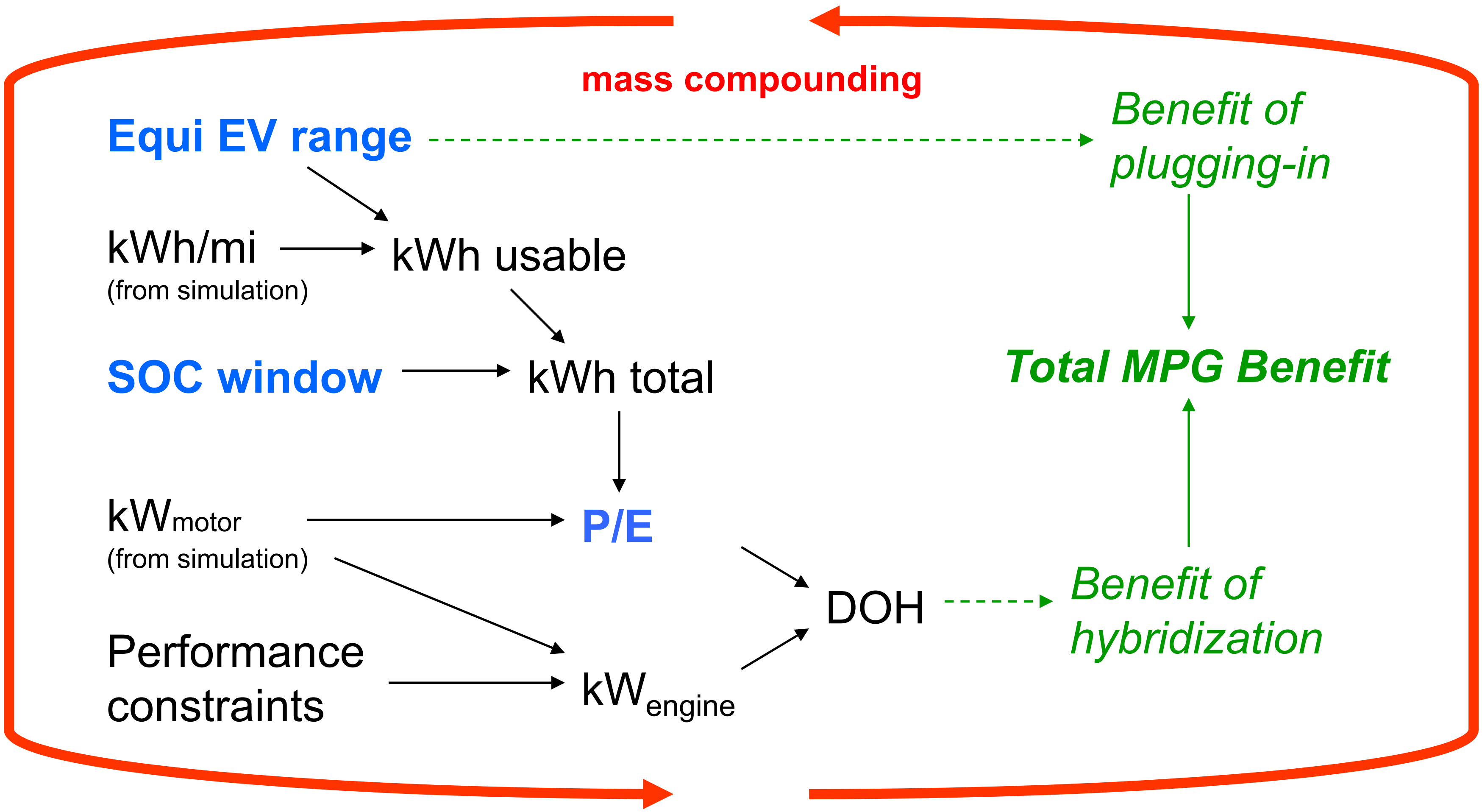
- PHEV battery likely to deep-cycle each day driven: 15 yrs equates to 4000-5000 deep cycles
- Also need to consider combination of high and low frequency cycling



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

Battery Sizing Depends on:

EV range, vehicle (mass, aerodynamic, etc.), drive cycle, strategy



DOH = degree of hybridization

Source: Tony Markel and Andrew Simpson, Milestone Report, National Renewable Energy Laboratory, Golden, CO, September 2005.

Example of Battery Requirements for Plug-in Hybrid Vehicles

	Characteristics at EOL (End of Life) [1]		Long-Term[2]
Systetm Targets	Maximum System Production Price @ 100k units/yr	$	**$3,500**
	Calendar Life, 40°C	Years	**15**
	Maximum System Weight	kg	**125**
	Maximum System Volume	Liter	**85**
	SOC Range	%	**70**
Charge Depleting HEV Mode	Equivalent Electric Range	miles	**40**
	Available Energy for CD Mode, 10 kW Rate	kWh	**12**
	CD Life / Discharge Throughput	Cycles / MWh	**4000 / 50**
	Total Energy (at 10 kW rate)	kWh	**17**
	Maximum System Recharge Rate at 30°C	kW	**1.5 (120V/12A)**
Charge Sustaing HEV Mode	Peak Pulse Discharge Power (10 sec)	kW	**40**
	Peak Regen Pulse Power (10 sec)	kW	**25**
	Available Energy for CS (Charge Sustaining) Mode	kWh	**0.3**
	Minimum Round-trip Energy Efficiency (USABC HEV Cycle)	%	**90**
	Cold Cranking Power at -30°C, 2 sec - 3 Pulses	kW	**5**
	CS HEV Cycle Life, 50 Wh Profile	Cycles	**300,000**
Battery Limits	Max. Current (10 sec pulse)	A	**300**
	Maximum Operating Voltage	Vdc	**400**
	Minimum Operating Voltage	Vdc	**>0.55 x Vmax**
	Maximum Self-discharge	Wh/day	**50**
	Survival Temperature Range	°C	**-46 to +66**
	Unassisted Operating & Charging Temperature Range	°C	**-30 to +52**

1. These categories are similar to the ones proposed for USABC charge-depleting electric vehicles and FreedomCAR charge-depleting power-assist HEVs
2. Typical numbers, final USABC numbers could be found in http://www.uscar.org/commands/files_download.php?files_id=118

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

- Energy Storage/Battery
  - Cost
  - Life
    - Shallow and deep cycles
    - Calendar
  - Safety
  - Packaging
  - Thermal Management
- Power Electronics
- Vehicle cost

Cost-Benefit Analysis

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Plug-In Hybrid Fuel Economy

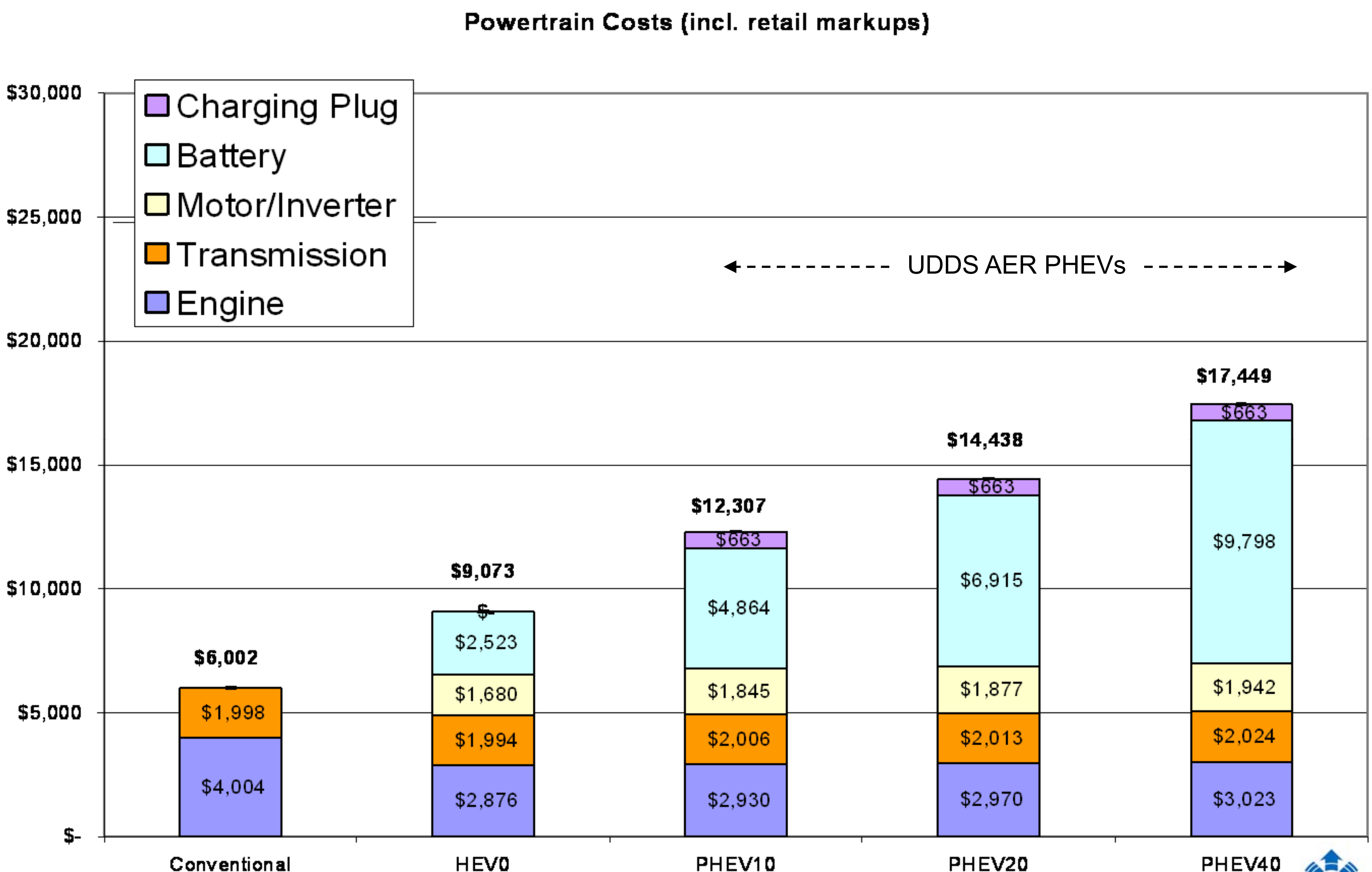
Predicted fuel economy and operating costs for midsize sedan[1]

Vehicle Type	Gasoline Fuel Economy	Electricity Use	Annual Energy Use	Annual Energy Cost	Recharge Time[3]
Conventional	27 mpg	---	564 gal.	$1360	---
Hybrid-Electric	36 mpg	---	416 gal.	$1000	---
Plug-In Hybrid 20mi range	51 mpg	0.09 kWh/mi	297 gal. and 1394 kWh[2]	$716 + $125	< 4 hrs
Plug-In Hybrid 40mi range	69 mpg	0.16 kWh/mi	218 gal. and 2342 kWh[2]	$525 + $211	< 8 hrs

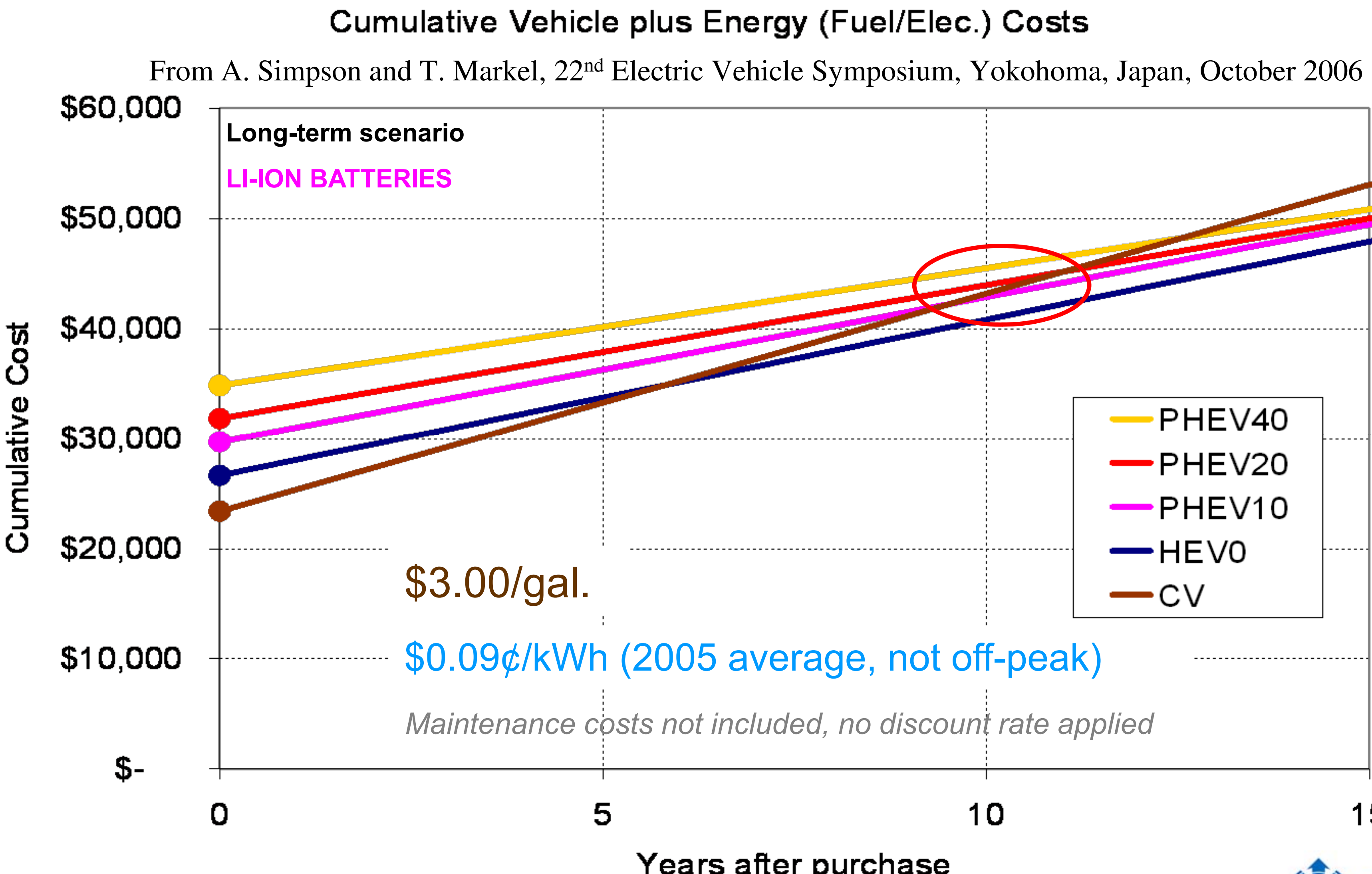
1) Assumes 15,000 miles annually, gasoline price of $2.40 per gallon, electricity price of 9c/kWh
2) Note that average US household consumes 10,700 kWh of electricity each year
3) Using 110V, 20A household outlet

Powertrain Costs Comparison – Long Term

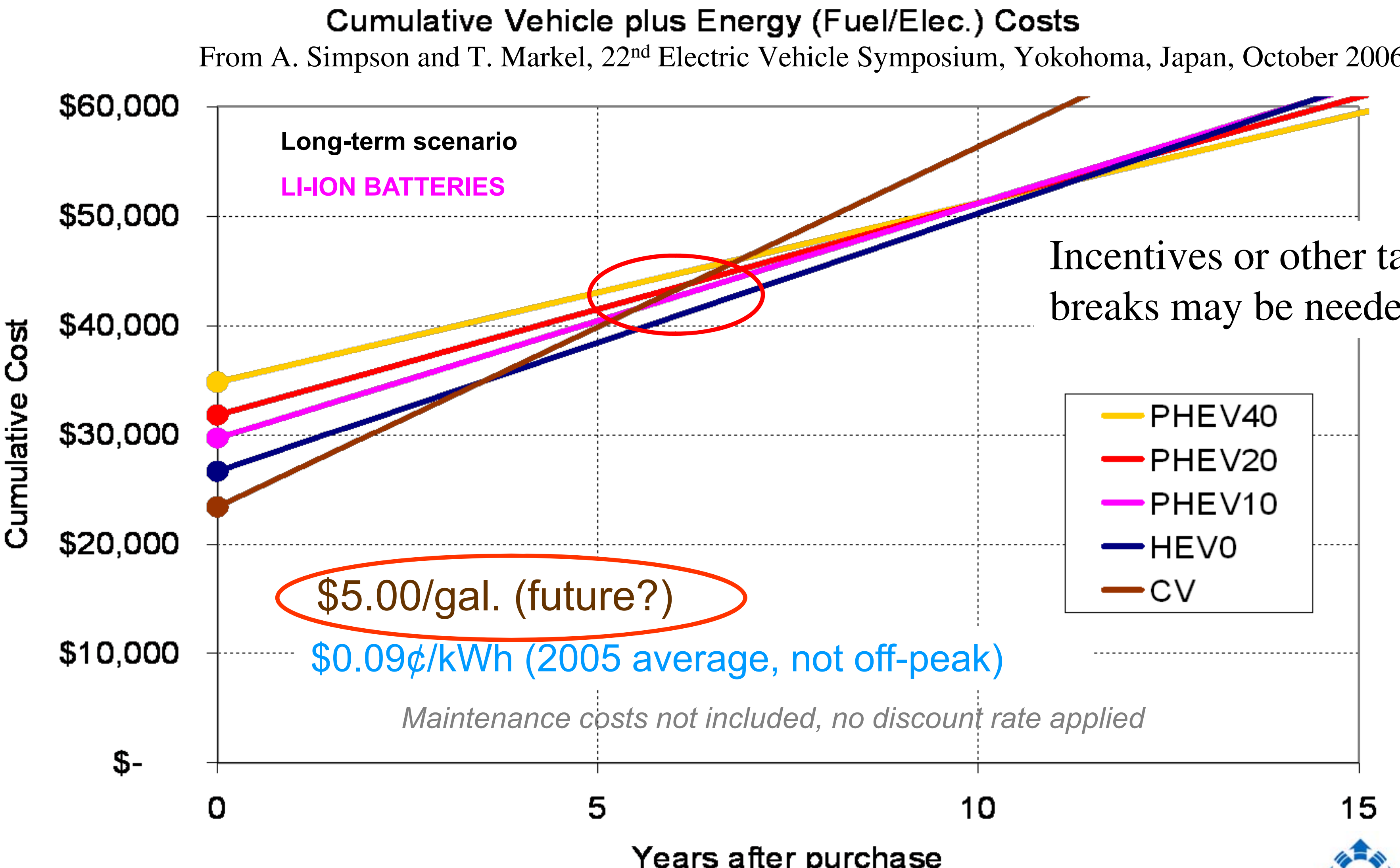
From A. Simpson and T. Markel, 22nd Electric Vehicle Symposium, Yokohoma, Japan, October 2006



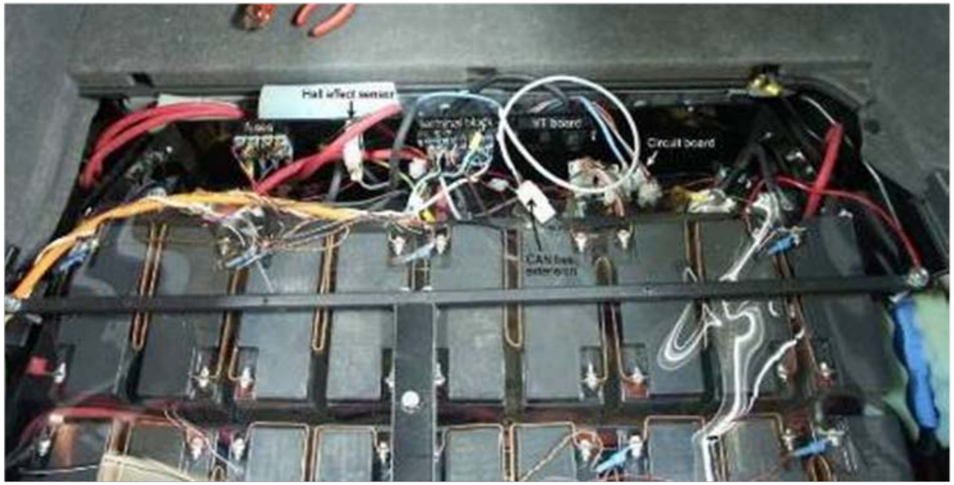
Payback time of PHEVs Relative to HEVs depends on the initial battery cost and fuel cost



Both Higher Gas Prices and Lower Battery Costs Required for PHEV to Payback Relative to HEV



Concerns with Battery Packaging and Management



Concluding Remarks

- PHEVs could displace petroleum consumption with domestic and renewable electricity.
- Batteries with low power to energy ratios are needed for PHEVs.
- Widening of the battery's usable SOC window while maintaining life will be critical for reducing system cost and volume, but could decrease the life.
- 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.
- Battery requirements for PHEVs are demanding: low cost, wide T operation, wide SOC operation, both shallow and deep cycles.
- PHEVs make economic sense with lower battery cost and higher gasoline prices, otherwise other incentives or tax credits needed.
- The key barriers to commercialization of PHEVs are battery life, packaging, safety, and cost.

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