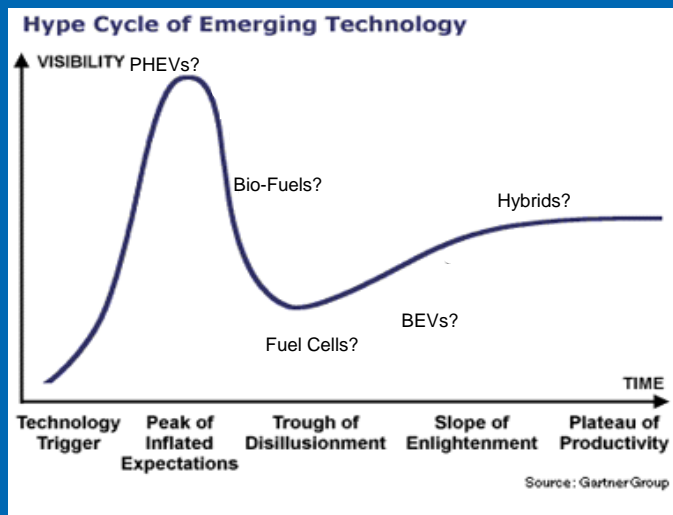


Electricity as a Low Carbon Fuel: A Comparison of Future Vehicle Technologies

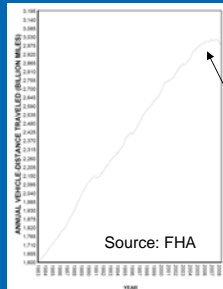
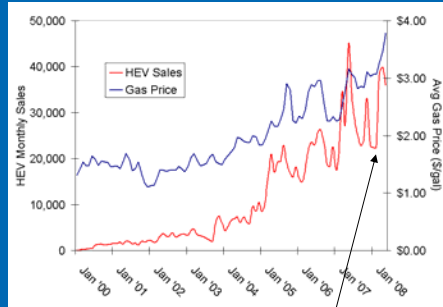
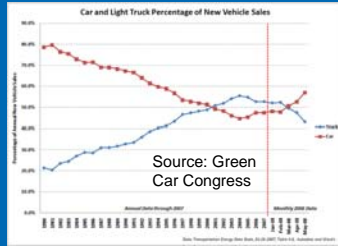
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Expectations for emerging technologies have a tendency to spiral out of control



How has the market responded to high fuel prices?
Looking forward, how will the market respond to CO₂ Regulation?



Hybrid vehicle sales have tended to track gas prices. *Is this trend changing?*

In the last year, vehicle miles have decreased markedly. *Is this due to a sluggish economy, or a larger trend?*



How will new technologies evolve over time?

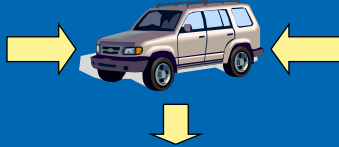
- **Efficiency:** Will advanced vehicle technologies maintain their efficiency advantage when compared to improved future “conventional” technologies?
- **Consumer Expectations:** Can alternative vehicles replicate the convenience, drivability, reliability, cargo space, etc of conventional vehicles? *Or offer alternative desirable attributes?*
- **Cost Competitiveness:** Is there a value proposition for the consumer?
- **Primary Energy Source:** Clean or dirty?



Evolutionary changes to conventional technology offer significant gains when compounded over many years...

Reduced Road Load

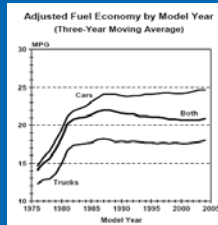
- Lightweight materials
- Improved aerodynamics
- Low rolling-resistance tires



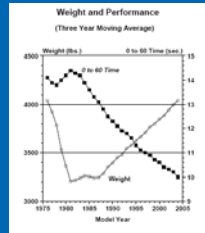
Powertrain Improvements

- Friction reduction, VVLT, cylinder cutout, GDI, etc.
- Turbo-charge
- New combustion cycles
- Improved transmissions
- Increased market penetration of diesel

But will these changes be deployed in a way that emphasizes fuel efficiency or performance?



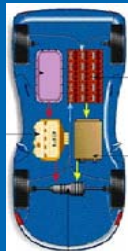
Source: EPA



HEVs have the potential to reduce cost while improving their efficiency benefits relative to conventional ICEs

Cost Reduction Opportunities

- Increased production volumes
- Improved controls may enable simplified architecture
- Advances in battery technology



Efficiency Improvement Opportunities

- Improved controls enable operation in the high efficiency regime
- Improved integration of motor with wheels increases effectiveness of regenerative braking
- Evolutionary improvements in battery, motor, power electronics, and auxiliaries

Important Challenges

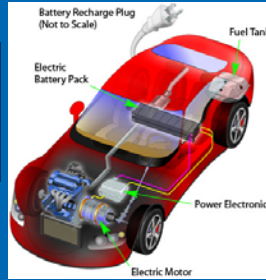
- The longevity and fault-tolerance of lithium-ion batteries
- High accessory loads (e.g. A/C) significantly reduce HEV fuel economy
- Limited benefit under steady state, highway driving conditions



PHEVs must overcome a number of technical hurdles to be successful in the present market context -- in particular battery cost and durability.

PHEV Design Opportunities

- Boosted HEV or Extended Range EV?
- All-electric driving or Blended?
- Advanced control strategies



Battery Issues

- Durability: Can batteries meet the rigors of a PHEV duty cycle
- Safety
- Will cheaper li-ion chemistries emerge?

Other Challenges:

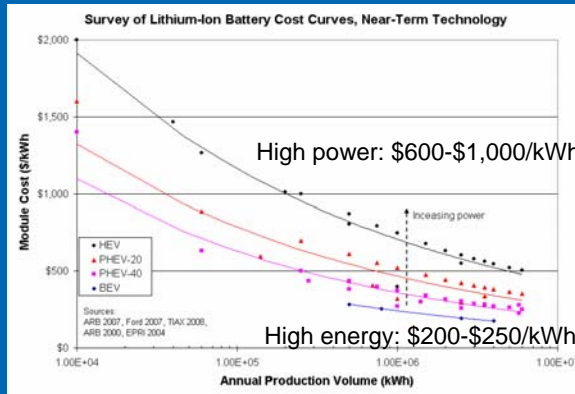
- Heating and cooling
- Cold Start Emissions
- Charging
- GHG Impacts
- Driveability
- Packaging

However, none of these challenges appear insurmountable

1. Picture Source: www.nrel.gov



Cheap, long-lasting lithium-ion batteries are the key enabling technology for a transition to an electrified fleet

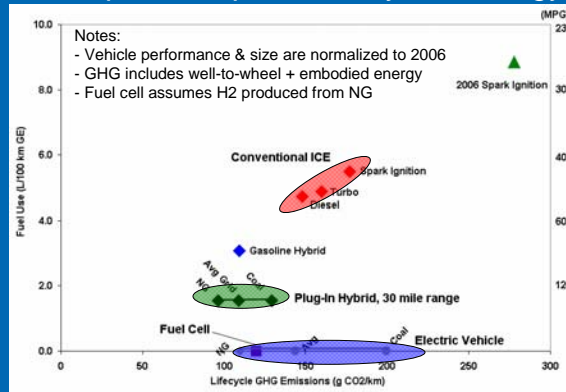


Battery Pack Characteristics (~1-2M kWh/Yr)		
Vehicle	Size (kWh)	Factory Cost
HEV	1.0	\$1,000
PHEV-10	3.6	\$1,500
PHEV-30	8.2	\$3,000
PHEV-60	16.5	\$4,500
EV (200 mi)	48	\$12,000

High volume production can drive significant cost reductions, but new, cheaper lithium-ion chemistries are needed to approach price-parity



In 2030-2035, the PHEV is projected to offer a 67% reduction in GHG emissions and an 85% reduction in onboard fuel use compared to present-day technology

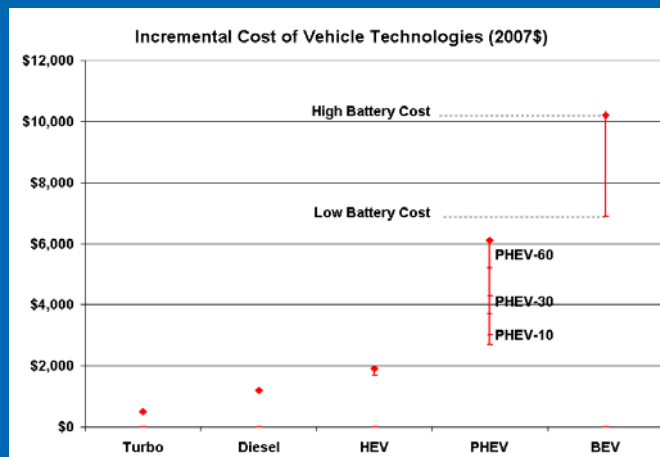


Source: Kromer & Heywood 2007

However, the projected GHG benefits are modest compared to future HEVs without significant de-carbonization of the electric grid



The PHEV incurs significant additional cost compared to the HEV



However, it offers EV-like benefits without the high cost and range limitations of the electric vehicle; it also offers other attributes that may be attractive to consumers, such as all-electric driving.



The plug-in hybrid has a great deal of potential as a mid- to long-term option for reducing petroleum and GHG emissions

- Significant, but not revolutionary, improvements to battery technology are needed to facilitate success in the market.
- In the near-term, CO₂ benefits may range from a modest positive to a modest negative (+/- 15%) compared to the HEV, depending on charging regime.
- Continued reduction in the grid's carbon footprint over time will increase this benefit.
- The PHEV is particularly attractive in comparison to fuel cell and electric vehicle technology, offering similar benefits with lower cost and less infrastructural risk in the mid-term.



Thank you for your attention.

Questions?

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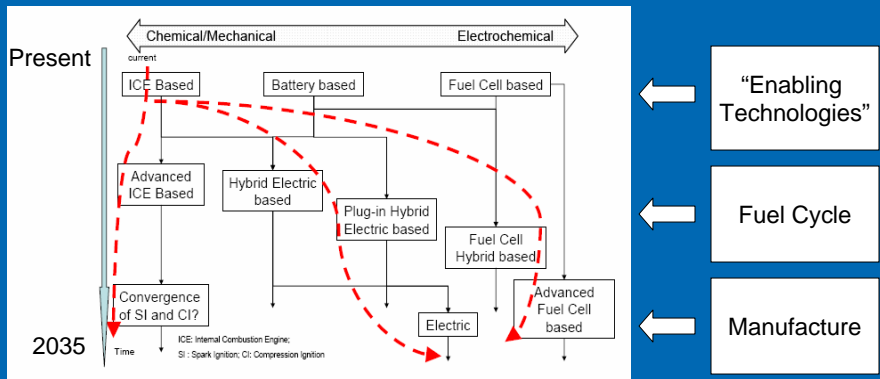
Battery

	Units	HEV	PHEV-10	PHEV-30	PHEV-60	BEV
Energy	<i>kWh</i>	1.0	3.6	8.2	16.5	48
Battery Wt	<i>Kg</i>	10	32	60	120	333
Specific Cost	<i>\$/kWh</i>	\$750	\$420	\$320	\$270	\$250
Battery Cost	<i>\$</i>	\$900	\$1,500	\$2,800	\$4,600	\$12,000

Criteria	Risk		
	HEV	PHEV-30	BEV
Safety	Low	Low	Low
Specific Energy	Low	Low	Medium
Specific Power	Low	Low	Low
Durability	Medium	High	Medium
Cost	Medium	High	Very High



How do lifecycle energy use and CO₂ emissions of future vehicle technologies compare?



Source: Bandivadekar 2008

Technologies were normalized to the performance and size of a 2005 Toyota Camry; fuel consumption was estimated from software models

