HEV / PHEV Technologies

Paul Boskovitch

Chief Engineer

Advanced Technology Hybrid Systems

Ricardo Inc.

California Air Resource Board GHG Emissions HEV / PHEV Commercialization

Byron Sher Auditorium California EPA Headquarters Sacramento CA

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Ricardo has extensive experience in hybrid & electric vehicle technologies for over 10 years - many products now entering the market

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Ricardo Hybrids and Electric Vehicle → Passenger car / Commercial vehicles / Military applications

Micro   Mild   Full   PHEV   Range Ext EV   FC-HEV   Electric

Vehicle Systems: NVH / Chassis / Fuel / Exhaust / Brakes / Charger / Driver IP / Thermal / Packaging / Crash

Controls & Safety Systems   Electronics / High Voltage Systems / EMC   Battery Pack Systems   Calibration

Hybrid Transmissions & Drive systems

Hybrid applications: Gas and Diesel Engines

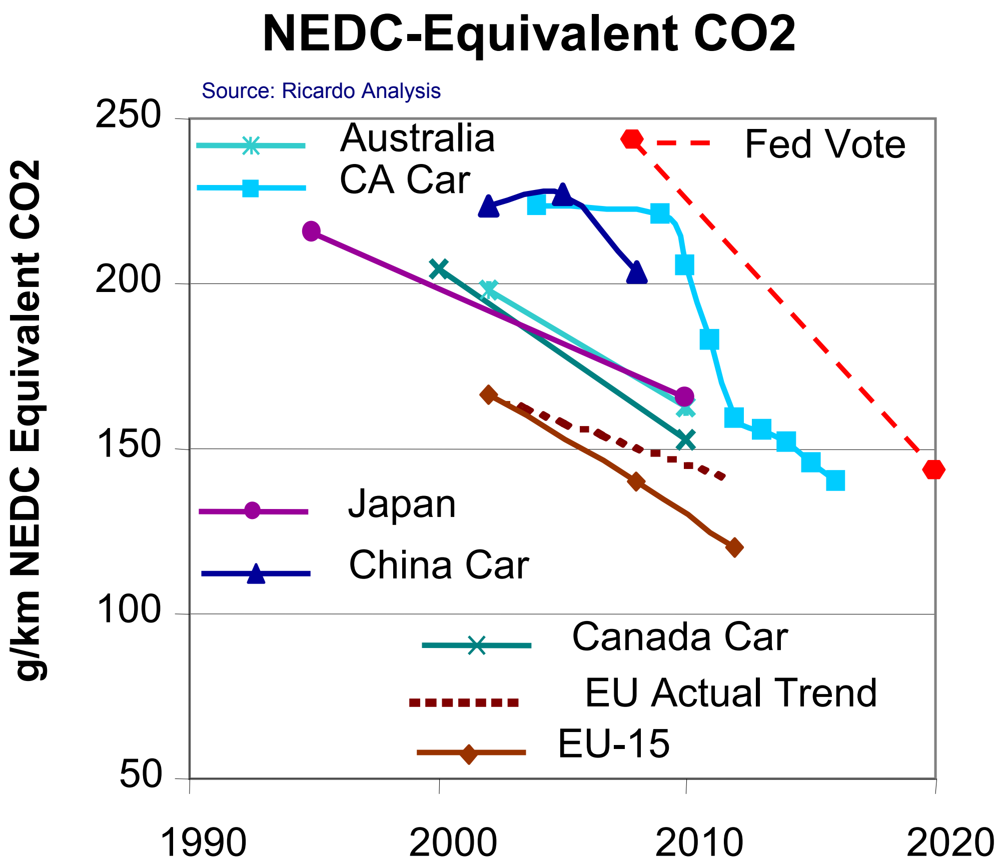
Emissions and OBD II

Production Release and support of Hybrid Products

Hybrid systems have found a niche and with a broader range of products being offered and with the 35 Mpg mandate; increased market penetration is expected.

- Significant publicity for Hybrid and Plug-In Hybrid vehicles. Some of the ways to deliver lower vehicle CO2, displace petroleum, “green” marketing/brand/image….
- Vehicles marketed on fuel savings and environmental benefits
  - Overall “cost of ownership” dominated by higher initial price and re-sale value
  - Purchased for “environmental Image” - reduced C02, reduced oil consumption
  - Path to sustainable energy
- Wide variety of hybrid configurations possible – which one is best?
  - Must provide market relevant benefits (improved: GHG emissions, FE)
  - Must be attractive to the consumer – style/fashion / image remain key elements
  - For mass market, they must be profitable to manufacture
- What are the drivers that will increase hybrid sales volumes to mass market?
  - Broader range of hybrid model selections
  - **Federal state and local requirements (CARB, CAA 2008, 35 Mpg 2020…)**
  - Lower cost (components) due to higher volumes
  - Battery technology improvements
  - Optional selections of hybrid configurations
  - Ease of implementation in existing vehicle platforms

Most Countries adopting low carbon targets for road transport, emphasis on energy security and climate change



- Europe is leading the world with an average 1.6% per year improvement over the last decade
- California, Canada, Australia, China and Japan all have legislation or agreements relating to vehicle fuel economy or CO_2
  - Generally set at 3% per year
- US EPA to initiate a regulatory process for improved fuel economy through the Clean Air Act by 2008
  - Senate vote for 35 mpg by 2020
  - This represents over **4% per year** reduction in fuel consumption
- In Europe, the commission have now proposed that legislation will be introduced requiring fleet average CO_2 to be reduced to 130 g/km by 2012
  - This represents a major economic challenge for the entire automotive sector
- Japan has also set targets for fuel economy in 2010 and have been the first to introduce fuel economy legislation for heavy duty vehicles (15% reduction from 2002 by 2015)

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Hybrids combine two power sources, one of which can regenerate & store energy when the vehicle slows down. Usually these are an IC engine and an electric motor/generator with energy storage. There are many permutations…

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- **Stop / Start and Micro Hybrid**
  - Belt-drive starter/alternators or automated starters
  - Fuel saving: 3-10% - but up to 20% in heavy traffic
  - Best for: Urban delivery vans, Gasoline city cars
- **Mild Hybrid**
  - Small motor supplementing down-sized engine
  - Fuel saving:15 -25% - half or more from engine down-sizing
  - Best for: Cost-effective gasoline family vehicles with mixed usage.
- **Full Hybrid**
  - 1 or 2 Electric motors of significant power.
  - Electric drive capability
  - Many different arrangements of engine & motors
  - Fuel saving: 30-50% - with some benefit shown at high speed cruise. (transient response)
  - Best For: Family or premium vehicles (inc SUVs) with tendency to urban use.

-20% in City

4.0 l/100 km

3.7 l/100 km

Plug-In Hybrids and Extended Range EVs have different operating characteristics and performance capabilities.

Plug-in hybrid PHEV(10,20,30,40)

- Common characteristics:
  - Minimize on board fuel usage over drive cycle
  - Battery discharges to depletion limit
  - Operates as charge sustaining HEV at depletion limit
  - Requires external charging to restore upper limit SOC and to realize optimum FE benefit
- Blended / Urban Capable (PHEV10 → PHEV30)
  - Conversion PHEV - Blended depletion operation over drive cycle
  - Urban capable PHEV – EV capable of full performance over urban cycle
  - Extended electric drive operation
  - Engine on transition is required for full performance
  - Full vehicle performance maintained at depletion limit
- Full Capability Performance PHEV40
  - Capable of full Electric vehicle performance over drive cycle
  - Transition to charge sustaining at depletion limit
  - May have reduced performance during charge sustaining operation
  - With engine on may operate in Series, direct drive, combination

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Hybrid vehicles with Series or Parallel layouts require different battery requirements

Batteries | **Hybrid vehicle battery requirements**

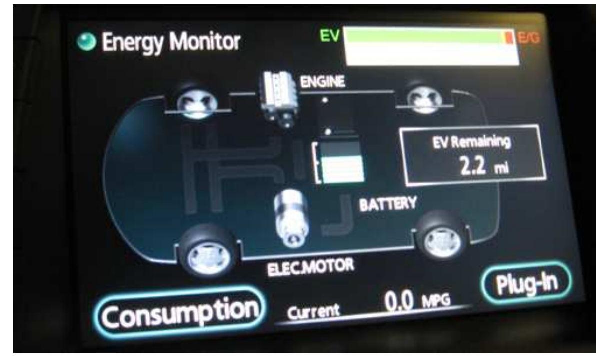
- Capacity is less important with HEVs compared with PHEVs since the engine also provides capacity
  - battery can be much smaller, saving weight
  - battery may still be required to provide the same instantaneous power as the PHEV battery from time to time
  - smaller battery must deliver much higher currents when called upon
- Wide range of batteries is required to accommodate the range of HEV configurations as well as vehicle performance requirements:
  - Series Hybrid - engine and motor / generator sources electric power to drive the vehicle and charge the battery.
    - Electrical system provides a variable speed transmission
    - Electric motor provides the full driving power
    - Battery requirements similar to EV
  - Parallel Hybrid - engine and/or motor drive wheels
    - battery capacity may be as low as 2 KWh
    - must deliver short duration power boosts (up to 40C for acceleration and hill climbing)


Toyota Prius Ni-MH Battery Pack

Plug-In Hybrid Electric Vehicles require higher capacity batteries and deliver hybrid functionality with extended all electric range.

Batteries	Plug-In Hybrid vehicle battery requirements

- Higher capacity batteries required to extend range
  - A typical electric car uses around 250 – 350 Watt-hours per mile.
- Battery must be capable of regular deep discharge (~70% - 80% DOD) operation
  - Designed to maximize energy content and deliver full power even with deep discharge to expected cumulative electric range.
  - Routinely receives a full charge and often reaches 20% – 30% SOC
  - Needs to operate at more than 5C during acceleration and braking if full re-generative capacity used
- Needs a Battery Management System (BMS) and thermal management
- Enters Charge sustaining HEV mode during drive cycle.
  - Typical voltage > 300 Volts.
  - Typical capacity 4 kWh< Capacity < 15kWh
  - Typical discharge current up to 1C rate continuous and 5C peak for short durations.



Toyota Plug-In energy monitor

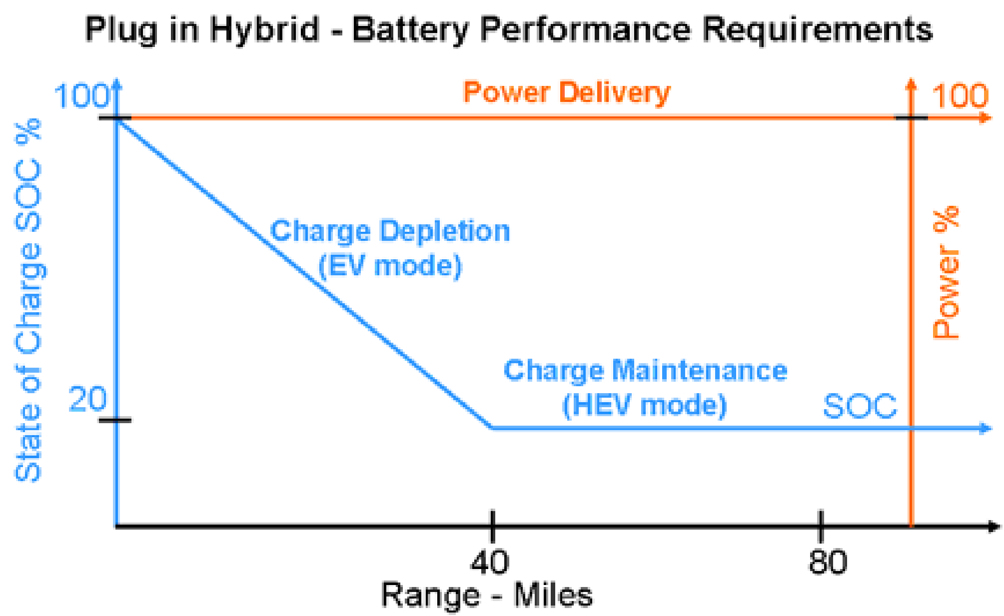
'**C**' is the rated capacity of a cell or a battery. The charging & discharging current of a cell is expressed as a multiple of C. (Example: The 0.1 C current for cell with rated capacity of 1.4 Ah is 140 mA).

Battery requirements for plug in hybrid vehicles are a combination of EV and HEV charging/discharging cycles

Batteries | **Plug-In Hybrid (PHEV) vehicle battery requirements**

- Batteries for plug in hybrid vehicles must satisfy conflicting performance requirements:
  - EV batteries usually optimised for high capacity
  - HEV batteries usually optimised for high power
- PHEV Batteries need to operate with variable depth of discharge:
  - EV battery operates to high discharge (DOD) for long range
  - HEV operates at a shallow DOD for long life.

- The plug in hybrid is designed to be used as
  - Blended depleting electric
  - EV for urban cycle
  - EV full performance
  - HEV when charge is depleted or for highway driving:



The PHEV battery is thus expected to perform both as an EV and as an HEV

Plug-in hybrids show large potential though high battery costs are currently limiting their financial feasibly

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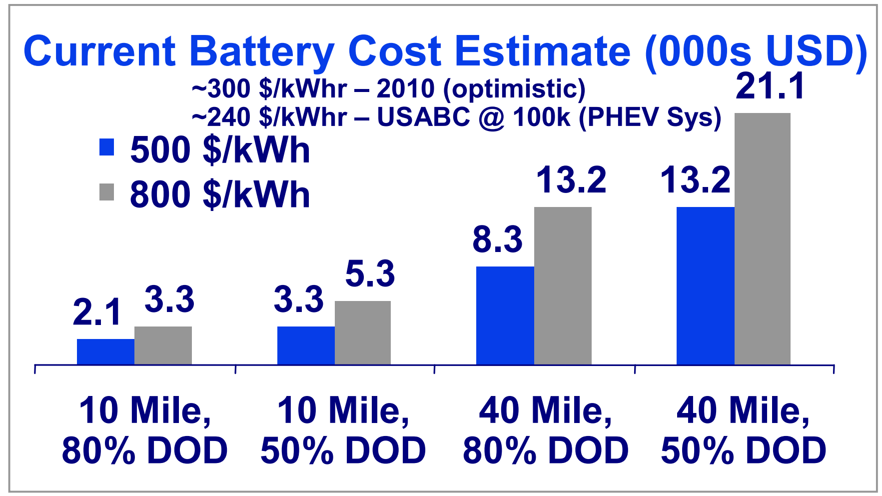
- Plug-in hybrids offer reduced CO2 when operated on low carbon electricity (e.g. coal with carbon sequestration, renewable or nuclear)
- Significant plug-in interest in the US
  - Potential to reduce dependence on imported oil/petroleum products
  - Electricity supply from domestic fuel sources
  - US - 35 Mpg 2020 fleet requirement
- Batteries charged using off-peak electricity
- Battery sized for range of 10-40 miles (15-60 km) - gasoline fuel for longer distances
- Key hurdle is the energy storage technology
  - **Cost:** Currently up to ~$20k US for battery
  - **Size:** Limited package space in pass cars
  - **Durability:** Replacement cost major issue



Note: battery cost is a **contentious** subject, driven by differing views on materials costs, rate of technical improvement, permissible depth of discharge (DOD), range, etc.

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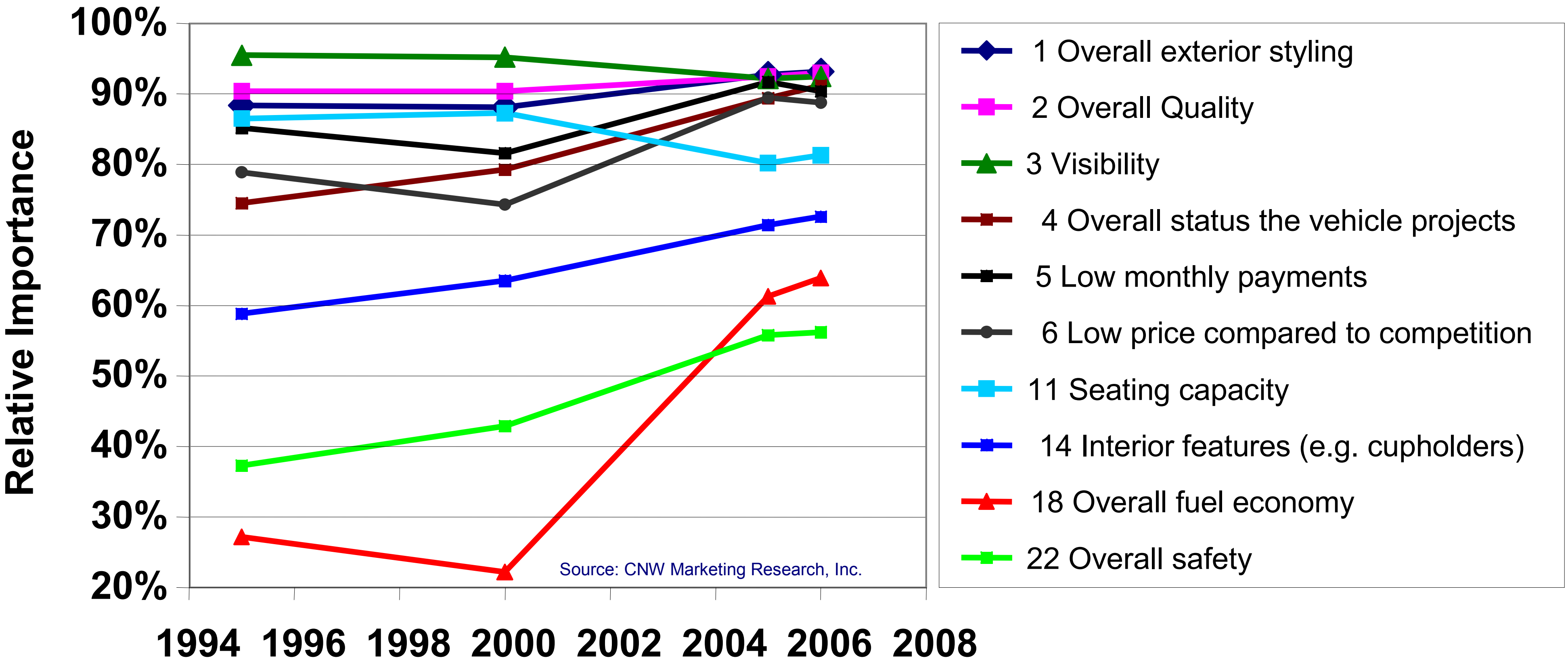
Higher US fuel prices have increased consumer interest in fuel economy but this must be kept in perspective…

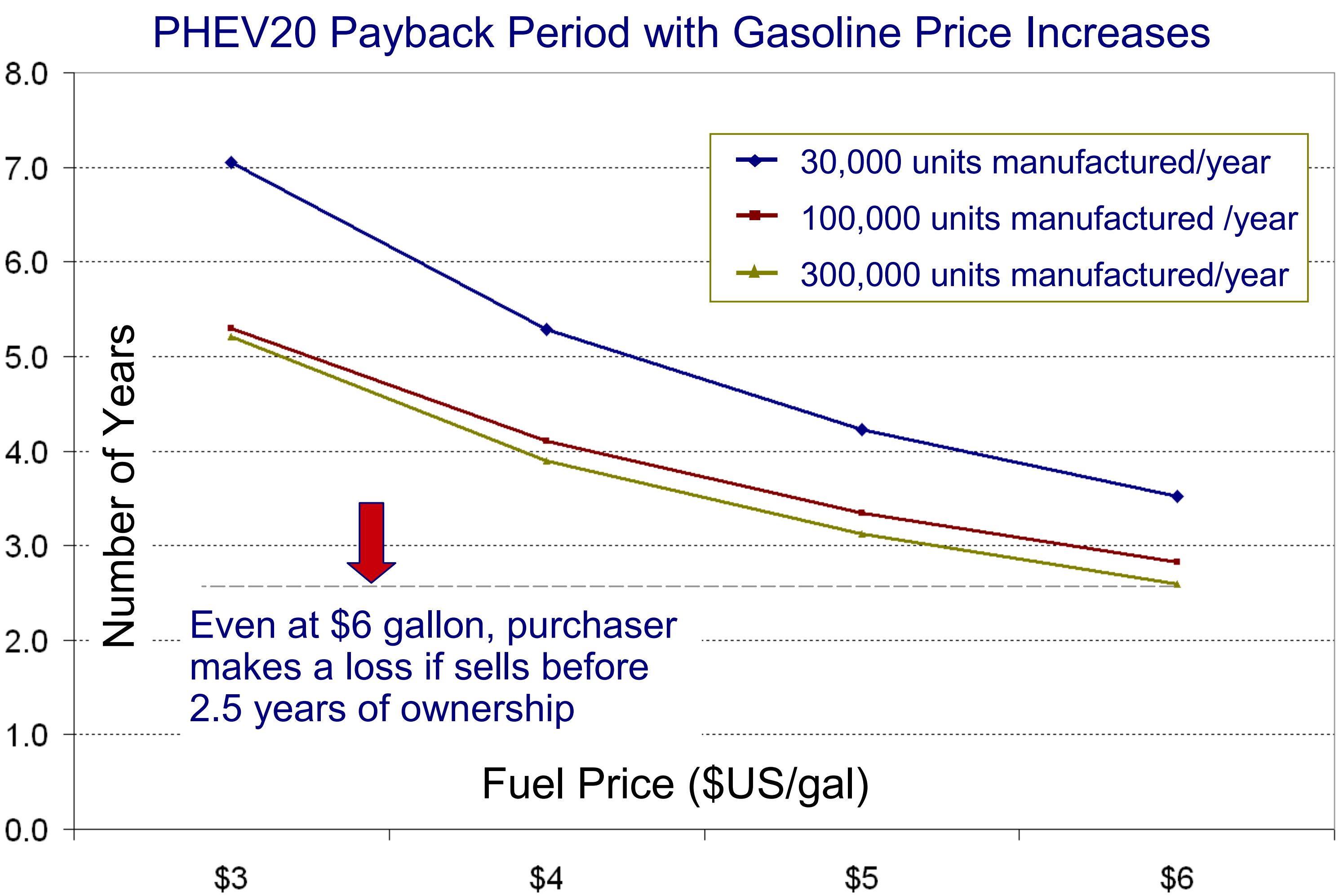
- Consumer surveys in the US show that fuel economy is now a higher priority in the decision to purchase a vehicle:



- When shopping for a new vehicle, people rank good gas mileage only slightly higher than cup holders.... But after they buy the car, gas mileage becomes a customer satisfaction issue. People always want better gas mileage ...They resent spending money on gas

KURANI, K. S. & TURRENTINE, T. S. (2002) Marketing Clean and Efficient Vehicles: A Review of Social Marketing and Social Science Approaches. UCD-ITS-RR-02-01. Institute of Transportation Studies, University of California, Davis.

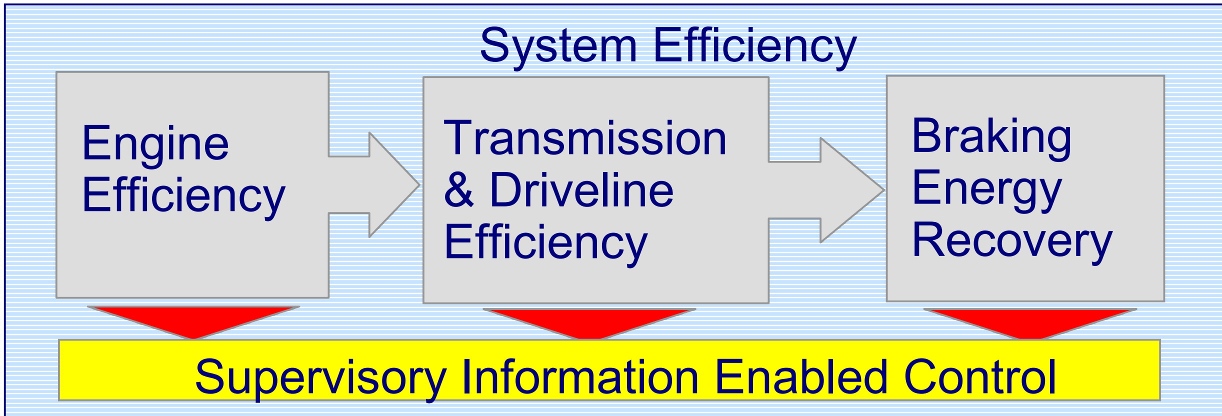
Plug-in hybrid electric vehicles can be competitive on cost if fuel prices continue to rise and battery costs fall.



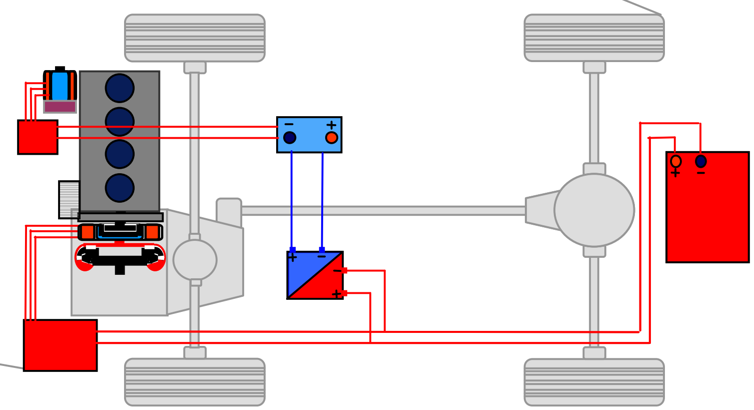
- At US$3/gallon, the PHEV20 payback period is 5 - 7 years
- At US$6/gallon PHEV20 payback occurs in 2.5 – 3.5 years
- New vehicle purchasers do not recover costs at current fuel prices
- High EU fuel prices should make PHEV’s more attractive in Europe?

- PHEV20 payback period is much less sensitive to electricity price increases. A 400% increase in electricity price (4c to 20c/kWh) = extra 2 year payback period

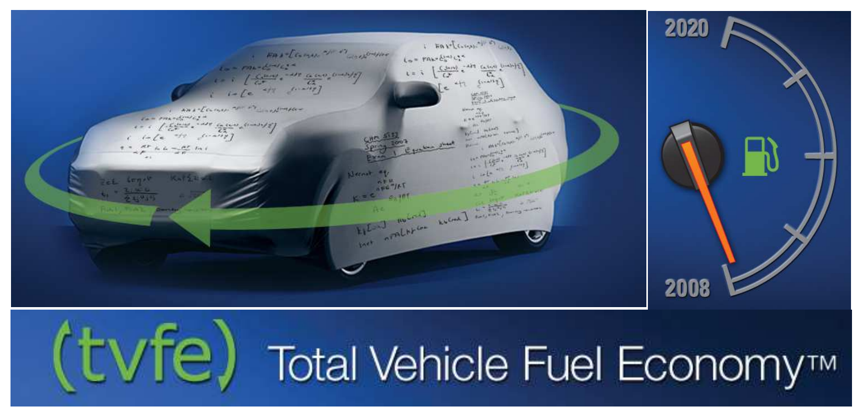
A successful powertrain must be optimized as a system for each application - this includes engine systems, transmission, drivelines, vehicle installation & control integration



Vehicle Systems Integration



- Systems Integration requires:
  - Broad powertrain capability and knowledge
  - Advanced system simulation tools
  - Knowledge of component and subsystem interactions
    - Explore configuration issues
    - Develop control strategies
  - Analytical system optimization techniques



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Requirements for effective deployment of HEV & EV include cost & weight reduction of batteries together with very effective system engineering

- Hybrid and Plug-In Hybrid electric vehicles will offer a significant contribution to lower carbon transport if cost competitive products can be delivered
  - Niche products have little effect on carbon emissions
  - Mass market always dominated by economics
- HEV / PHEV systems are significantly more complex than conventional powertrains
  - System engineering is the key to success
  - Sophisticated control systems are required to optimize energy and power flows
- At current Battery technology levels:
  - Plug-in (PHEV10, PHEV20) electric vehicles can be reasonably adapted to existing vehicle platforms.
  - Plug-in (PHEV30, PHEV40) requires more extensive vehicle modifications
  - Range extended EV are purpose built to optimize EV drive performance.
- Plug-in hybrid electric vehicles may offer best compromise if:
  - Battery cost can be reduced
  - Electricity energy price remains significantly lower than liquid hydrocarbons (including bio-fuels)
  - Electricity increasingly produced from renewable low carbon sources
- Cost and weight reduction must not compromise battery safety or durability