PHEVs: the Technical Side

A talk at PG&E’s Pacific Energy Center, February 23, 2006
CO2 figures updated April 29, 2006

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PHEVs: the Technical Side

Background: Gasoline Vehicles

Gasoline (Otto cycle) vehicles:

- Burn oil, a limited, non-renewable resource
- Emit 8.9 kg CO2/gallon (http://www.eia.doe.gov/oiaf/1605/factors.html)
- Emit other pollutants, somewhat cleaned up but still causing smog
- Only 12-15% efficient (tank-to-wheels) despite 25-30% peak efficiency! (http://www.chevron.com/products/prodserv/fuels/bulletin/fuel_economy/)
- Well-to-wheels efficiency: 10-13%, assuming 85% well-to-tank
- Gasoline contains approx. 114 kBtu/gal = 33.4 kWh/gal (same reference)

Major sources of extra inefficiency:

- Idling
- Friction losses at high engine speeds
- Pumping losses at low power output
  - The "compression braking" you use downhill is actually always occurring except during full acceleration
  - This is the main reason larger engines lead to poorer mileage
- Compression limited by octane rating

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Background: Diesel Vehicles

Diesel vehicles

- Emit 10.2 kg CO2/gallon (14% more than gasoline)
- No extra pumping losses at low power
  - Larger engines have less disadvantage, though still heavier
- Diesel fuel weighs 10% more per gallon than gasoline
  - It contains correspondingly more energy, oil, and carbon
  - De-rate Diesel mpg by 10% for true economy vs. gasoline
- Higher compression, thus higher combustion efficiency (35-40% peak efficiency, maybe 45% with turbo)
- 15-20% efficient (13-17% well-to-wheels), 25-30% more than Otto
- High particulate emissions
  - Due to major efforts, may soon meet existing California requirements (CA still has smog problems)
  - No known way to meet PZEV/future emission levels that many hybrids already meet

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Background: HEV Efficiency Improvements

Strong gas/electric hybrids (HEVs)

- Can increase overall efficiency by 50-100%, to 18-30% (peaks similar to Diesel)
  - Well-to-wheels is around 15-26%, assuming 85% well-to-tank
  - Diesel hybrids would have only slightly higher overall efficiencies
- Larger increase in city than highway driving

City driving improvements:

- No idle (up to 15%)
- Regenerative braking recaptures energy otherwise wasted, and uses it to help accelerate the vehicle
  - Up to 50% captured & reused => up to 30-50% improvement

Improvements to both city and highway efficiency

- Engine downsizing, due to acceleration assist
- Change from Otto to Atkinson/Miller cycle engine
  - Greatly reduces low-power pumping losses
  - Low torque; unusable without electric acceleration assist
  - Much of the gains of Diesel engines, but at lower cost
- Operation of engine largely at efficient speed/power combinations
  - Due to flexibility of electric assist and oft-used continuously variable transmission (CVT)
- Rapid throttle responses are electric
  - Engine responses can be slower, not requiring extra spurt of fuel

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Background: Further HEV Efficiency Notes

Vehicle weight mainly affects city driving, via

- The energy required to accelerate the vehicle and climb hills
  - Dominant during stop & go and/or hilly driving
  - A strong hybrid can recover and reuse up to 50% of this energy
    - A hybrid's improved efficiency Is more pronounced in hilly country
    - Reducing a hybrid's weight is a less effective economy measure
- Rolling resistance
  - Dominant during steady low-speed driving
- Aerodynamics has little effect

Vehicle aerodynamics mainly affects highway driving

- Aerodynamic drag is dominant
- Vehicle weight has little effect except during hill climbing

City vs. highway efficiency (mileage)

- Gasoline (Otto): much worse city due to low-power pumping loses
- Diesel: slightly worse city; acceleration energy not recovered
- Strong hybrid: better city because acceleration energy recovered
- Electric & PHEV: similar to strong hybrid
  - Better yet in mountains due to more capacity to recover energy during descent

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PHEV Replacement of Liquid Fuel with Electricity

- Most normal daily driving can be electric (EPRI: 74% of all PHEV-60 miles)
  - EV range can be tailored to user/fleet needs
  - Early adopters will be those with an even higher percentage of EV mileage
- Renewables (other than grown fuels) usually produce electricity
  - States like California require a higher percentage of renewables each year
  - Night-time charging coincides with highest windpower production
    - There is enough wind available in the U.S. to supply all transportation energy needs
    - Farms can double their income by leasing wind turbine sites on a tiny percentage of their land
  - 50-75% source-to-wheels efficiency vs. 12-20% maximum for hydrogen
    - 100% electricity used vs. 66% H2 via electrolysis (http://www.halfbakery.com/idea/Efficient_20Electrolysis_3f)
    - 80%+ existing advanced battery & charger vs. 40% maximum fuel cell or 23% H2 HEV ICE
    - 70-100% motor and electronics (incl. regenerative braking savings) (not relevant for H2 ICE)
    - 93% grid efficiency vs. 77% H2 compression & transportation (http://link.aip.org/link/?JERTD2/124/173/1)
- Well-to-wheels fossil fuel efficiency: 18-44%
  - Vs. Otto-cycle 10-13%, H2 13-19%, HEV 17-26% using 75% efficient natural gas reforming)
  - 35-70% generation efficiency (old vs. new plants, http://www.grist.org/news/powers/2003/11/06/assets/)
  - 93% grid efficiency
  - 55-67% electric propulsion efficiency (including regenerative braking energy recovery)
- Energy security and emissions
  - Only 2% of electricity is generated from oil in the U.S.
  - Emissions of sulfur and some other pollutants are capped (cannot increase with increasing production)
  - Carbon emission caps are pending in Eastern states and being considered in California
- Cost of electricity is equivalent to $0.50-1.00 per gallon of gasoline!

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Greenhouse Gas Emissions: EV vs. Gasoline

18 mpg	Auto at average 2004 new auto EPA rating of 20.8 mpg, less 15% for real-world driving
28 mpg	Projected average auto if it were built as a strong hybrid (35% additional mpg)
45 mpg	2004+ Prius, EPA rating, 51 mpg, at estimated real-world average
3 mi/grid-kWh	Estimated average EV efficiency of fleet of PHEV vehicles, 333 grid-Wh/mi
3.82 mi/grid-kWh	Measured EV efficiency of CalCars' first PRIUS+, 262 grid-Wh/mi

CO2 Emissions:

Vehicle: Source of Energy	Average auto vs. projected average EV		Average auto vs. PRIUS+ (EV)	Prius (gasoline) vs. PRIUS+ (EV)		Projected hybrid auto vs. projected average EV	
	grams/mi	% of gasoline	% of gasoline	grams/mi	% of gasoline	grams/mi	% of gasoline
Gasoline	494	100%	40%	198	100%	318	100%
EV from Renewables	0	0%	0%	0	0%	0	0%
EV from Idaho 2004	0	0%	0%	0	0%	0	0%
EV from PG&E 2005	67	13%	11%	52	26%	67	21%
EV from CA 2004	79	16%	13%	62	31%	79	25%
EV from U.S. 2050	125	25%	20%	98	50%	125	39%
EV from U.S. 2010	167	34%	26%	131	66%	167	52%
EV from U.S. 2004	205	41%	33%	161	81%	205	64%
EV from U.S. 1996	221	45%	35%	174	88%	221	70%
EV from MI 2004	226	46%	36%	178	90%	226	71%
EV from Modern coal	323	65%	51%	254	128%	323	102%
EV from ND 2004	524	106%	83%	412	208%	524	165%

See last slide for references.

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PHEV Efficiency Improvements over HEV

Main advantage: Electricity used in place of most liquid fuel

Increased regenerative braking

- Enough battery capacity to accept energy from long descents
  - Significant savings in mountainous areas

Increased engine downsizing (strong PHEVs only)

- Engine need handle only maximum steady-state load
  - Engine can be ½ the size of those in existing hybrids without reducing performance
  - Battery must have enough reserve capacity to provide the climbing energy throughout a 70 mph mountain climb (e.g. 0 – 7000 ft. altitude)
  - Or strong trailer towing capability can be realized if no further downsizing
- Saves weight and space for use by the battery
- Improves HEV-mode mileage
  - Smaller engine
  - All but hill-climbing and all-out acceleration can be electric, allowing the engine to be run only at its most efficient power and speed

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The PRIUS+ Performance

Project	Battery Manuf.	Battery Model	Chem -istry	Eff Ah	EV mi	Mix mi*	Added lb	In-range Mpg*	Orig Mpg	City HEV Mpg	Comments
World's 1st	BB Battery	EVP20 -12	Lead-acid	12	10	20	300**	80	45	-10% due to extra weight**	OEM battery not removed; hilly Marin terrain
EDrive	Valence	U1-12XP	Li-ion	36	30	60	200	100	50	Unchanged due to lower impedence	Flat Los Angeles driving
Electro Energy	Electro Energy	N/A	NiMH	30	24	48	250	90	45	Unchanged due to lower impedence	Project nearly complete
Another Li-ion	Enax	N/A	Li-ion	33	27	54	100	90	45	Increased due to even lower impedence	Anticipated

* Mixed city & highway driving (also uses around 130 Watt-hr/mi electricity)

** OEM battery pack unused but not removed, adding ~75 lb

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PRIUS+: Demonstrated PHEV Operation

What the various PRIUS+ vehicles demonstrate:

- With very minor modification, currently mass-produced strong hybrids can become effective (though not optimized) PHEVs
  - An added EV-only button, already available in Europe & Asia
  - A replaced battery and replaced or fooled battery management computer
  - An added charger that plugs into a 120VAC, 15A outlet
  - No change at all to any other hybrid system hardware or software
- No new technology is required for practical PHEVs
  - Currently mass-produced hybrids contain everything but the charger and larger deep-discharge battery
  - Current battery technology can do the job
    - Our Electro Energy PRIUS+ is beginning to demonstrate a capable NiMH pack
    - The EDrive and HyMotion conversions demonstrate capable Li-ion packs

Limitations

- Pure electric (EV) operation only up to 34 mph
  - 20-40% electric assist at higher speeds
- Limited pure electric power (engine automatically starts if more requested)
  - 33 hp, yields very moderate acceleration
- Once the engine starts, it can’t be stopped until warmed-up
- CalCars’ lead-acid battery has serious low-temperature problems

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A Prius' Real PHEV Capabilities

Possible performance with no mechanical and minor electrical changes

- Changes required
  - Double the size of the DC:DC upconverter between battery and motor electronics
  - Change the (proprietary) hybrid control software to recognize and optimize PHEV operation
- EV operation at all speeds
  - Engine would have to spin above a speed somewhere between 42 & 60 mph
    - Only 1000 rpm necessary, causing a little added drag
    - No gasoline use necessary
- Sufficient EV power for most driving needs
  - 67 hp at low to moderate speeds, progressively less at higher speeds
  - Sufficient acceleration for all but jackrabbit starts (then the engine starts)

It is believed that other strong hybrids on the market have similar potential PHEV capabilities

- The Ford Escape hybrid (up to 94 EV hp, no DC:DC converter to resize)
- The hybrid versions of Toyota's Camry, Highlander, and Lexus SUV

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PHEV Batteries

- NiMH batteries are used in all mass-produced hybrids, and in the EV-1 and RAV4EV
  - They have a track record of very low failure rates and long lifetimes in all vehicles
  - Projected volume production pricing for high energy (vs. more expensive high power HEV) NiMH batteries make them practical
- Li-ion batteries have already been announced for next-generation mass-produced hybrids
  - They have twice the specific energy of NiMH at around the same cost
  - There are existing solutions for potential safety and longevity problems
- Coming soon
  - Nanotechnology Li-ion cells by Toshiba, A123, Johnson Controls, and many others
  - Evercel NiZn, used in Oxygen mopeds and Segways (lower cost)
  - Firefly graphite-foam plate lead-acid (>NiMH performance at much lower cost)

What is needed now is:

- Battery qualification and incorporation by auto manufacturers
- The risk-taking required to warrant battery life in the first vehicles
  - Due to insufficient (nearly zero) real-world experience in PHEVs
  - National requirements: 8 years or 100,000 miles (CA: 10 years or 150,000 miles)
- Mass-production of PHEVs (starting with modifications of current strong hybrids)
- The cost savings of high volume production and continued refinement

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PHEV Energy Requirements

Electric generation capacity

- 2004 U.S. total generation: 3717 tWh (http://www.eia.doe.gov/emeu/aer/pdf/pages/sec8_5.pdf)
- 2004 U.S. capacity: 938 gW (http://www.eia.doe.gov/emeu/aer/pdf/pages/sec8_43.pdf)
- Average unused capacity: 54% = 505 gW (higher at night but some out of service)
- Average charge requirements per PHEV: 1.5 kW (max from 120V, 15A outlet)
- Average unused capacity can simultaneously charge 337 million PHEVs

If all ground vehicles were suddenly PHEVs

- As hybrids, they could average at least 50% more efficient, saving 33% of ground transportation fuel
- 67% of the reduced fuel requirement could be electric (74% for PHEV-60, EPRI study #1000349, 2001)
- Total ground transportation oil savings: 78% (33% + 45% EV (67% of remaining))
- PHEV electric energy requirements
  - 136 billion gallons of gasoline + 42.5 of Diesel fuel used in 2004 = 179 giga-gallons (http://www.eia.doe.gov/emeu/aer/pdf/pages/sec5_32.pdf)
    - 3 mi/Wh (333 Wh/mi) vs. real-world 18 mpg => Approx. 6 kWh required to go as far as a gallon
    - Equivalent to 1.07 tWh
    - 45% of this needed to displace 67% of 33% more efficient vehicles’ fuel: 483 tWh
  - 2004 U.S. electric generation: 3717 tWh/year
  - Added generation requirements: 13%
  - 10 times 2004 wind production: 142 tWh/year = 29% of above PHEV requirements

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Background: Ethanol and Biodiesel

Upside

- Ethanol/gasoline flex-fuel vehicles cost only ~$150 extra to manufacture
  - Can burn anything from pure gasoline to 85% ethanol (E85)
  - Retrofitting existing vehicles is difficult because proprietary engine management software must be changed
  - At this price and retrofit difficulty, why are all new gasoline vehicles not already flex-fuel?
- Biodiesel can be run in existing Diesel vehicles
  - They then run cleaner

Downside (except cellulosic ethanol and thermal depolymerization biodiesel)

- Fuel production competes with food production & rainforests for land
  - U.S. corn used for ethanol was previously sold on international markets
  - South American rainforests are now being cut down to supply Europe with biofuel carbon offsets!
- Barely higher energy output than input
  - Due to fertilization, cultivation, etc. energy inputs

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Background: Ethanol and Biodiesel

Cellulosic ethanol

- Can be made from farm and urban plant wastes like corn stalks & cobs, forest brush, and weeds like switchgrass and water hyacinth
  - Carbon neutral!
  - May form a market for forest brush so trees need not be cut to pay for removal
  - Enough feedstock available for up to 30% of ground transportation requirements before competing with food and/or forests for land (http://www.whitehouse.gov/stateoftheunion/2006/energy/index.html#section3)
- First full production plant going online in Italy this fall

Thermal depolymerization biodiesel

- Can be made from meat production wastes like turkey parts, and waste plastics
  - Carbon neutral?
  - I believe far less raw material is available than for cellulosic ethanol
    - Therefore, this will be lumped with cellulosic ethanol for the rest of the talk
- First pilot plant is online next to a turkey processing plant in Carthage, MO

There is enough U.S. biofuel feedstock available to supply around 30% of U.S. ground transportation (ground-trans) energy without competing for land with food production and/or forests

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Cellulosic Ethanol and PHEVs Together

The U.S. imports 60% of its oil; 70% of its oil is used for ground-trans

- Domestic production is rapidly decreasing; world production may be peaking
- If all ground vehicles were suddenly strong hybrids
  - They could be at least 50% more efficient than existing vehicles, saving 33% of ground-trans fuel and 33% of CO2 emissions
  - Total oil savings: 23%, far less than imports
- If all ground vehicles were suddenly PHEVs (from previous page)
  - Total ground-trans savings: 78% of oil and 61% (73% by 2010) of CO2
  - Total oil savings: 55%, slightly less than import requirements, but not for long
- If all ground vehicles were suddenly flex-fuel, with sufficient cellulosic ethanol refineries
  - 30% of current ground-trans energy could be ethanol (and biodiesel) without competing with food production or forests, reducing CO2 by 30%, too
  - Savings relative to total U.S. oil consumption: 21%
  - Flex-fuel strong hybrids could save
    - 63% of ground-trans oil and CO2
    - 44% of all U.S. oil
- If suddenly all vehicles were flex-fuel PHEVs
  - Ground-trans liquid fuel requirements would be 20% of today’s
  - Sufficient biofuel feedstocks would be available to meet current & near-future needs without competing with food or forests
  - Using E85, ground-trans oil use would be cut 97%!
  - Total oil use, changing only ground-trans, would be cut 67%!
  - Ground-trans CO2 would be cut 81% (93% by 2010)

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Additions and Conclusions

Domestic biofuels and PHEVs together can supply essentially all U.S. ground transportation energy

- Reducing ground-trans oil requirements by 97%
- Reducing ground-trans CO2 emissions by 81% (93% by 2010)

Neither can accomplish enough individually, but with an all-out effort

- In 2-5 years, all new gasoline vehicles could be flex-fuel
- In 12-20 years, most existing vehicles would then be flex-fuel
  - For 21% total oil consumption and 30% ground-trans CO2 reductions
- In 10-15 years, all new vehicles could be flex-fuel PHEVs
- In 20-30 years, most existing vehicles would then be flex-fuel PHEVs
  - For 97% total oil consumption and 93% ground-trans CO2 reductions
- Until feedstock limits are reached, cellulosic ethanol production could probably begin and grow fast enough to keep up with E85 demand
- PHEV penetration might occur quickly enough to begin reducing liquid fuel requirements just before biofuel feedstock limits are reached
  - Otherwise, more gasoline will temporarily need to be blended into the fuel
- These savings will be reduced by simultaneous increases in total miles driven

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Greenhouse Gas Emissions: EV vs. Gasoline

CO2 emissions from burning gasoline:

8900 g/gallon

CO2 emissions from electric generation:

0 g/kWh	Renewables	Solar, wind, etc.
0 g/kWh	Idaho 2004	Best state, reference 3, 1996 figures scaled to 2004 U.S. total
200 g/kWh	PG&E 2005	PG&E flyer: 16-18 Mtons for 80 tWh => 182-205 g/kWh
236 g/kWh	CA 2004	Reference 3, 1996 figures scaled to 2004 U.S. total
375 g/kWh	U.S. 2050	EPRI projection, reference 4
500 g/kWh	U.S. 2010	EPRI projection, reference 4
615 g/kWh	U.S. 2004	References 1 & 2
664 g/kWh	U.S. 1996	Reference 3
679 g/kWh	MI 2004	Reference 3, 1996 figures scaled to 2004 U.S. total
1573 g/kWh	ND 2004	Worst state, reference 3, 1996 figures scaled to 2004 U.S. total

References:

1 2004 U.S. CO2 emissions from electric generation (2.444 x 10**15 grams): http://www.eia.doe.gov/cneaf/electricity/epa/epat5p1.html

2 2004 U.S. net electric generation (3.971 x 10**12 kWh): http://www.eia.doe.gov/cneaf/electricity/epa/epat1p1.html

3 1996 Electric carbon (multiply by 3.67 for CO2) emissions, U.S. & by state: http://weber.ucsd.edu/~carsonvs/papers/932.doc, pg. 34
(reproduced and sorted on next worksheet, with added column for C EPRI projection, reference 4

4 EPRI projection: http://www.greencarcongress.com/2006/02/epridaimlerchry.html