House Appropriations Subcommittee on Energy and Water Development

Overview Hearing: Gas Prices and Vehicle Technology

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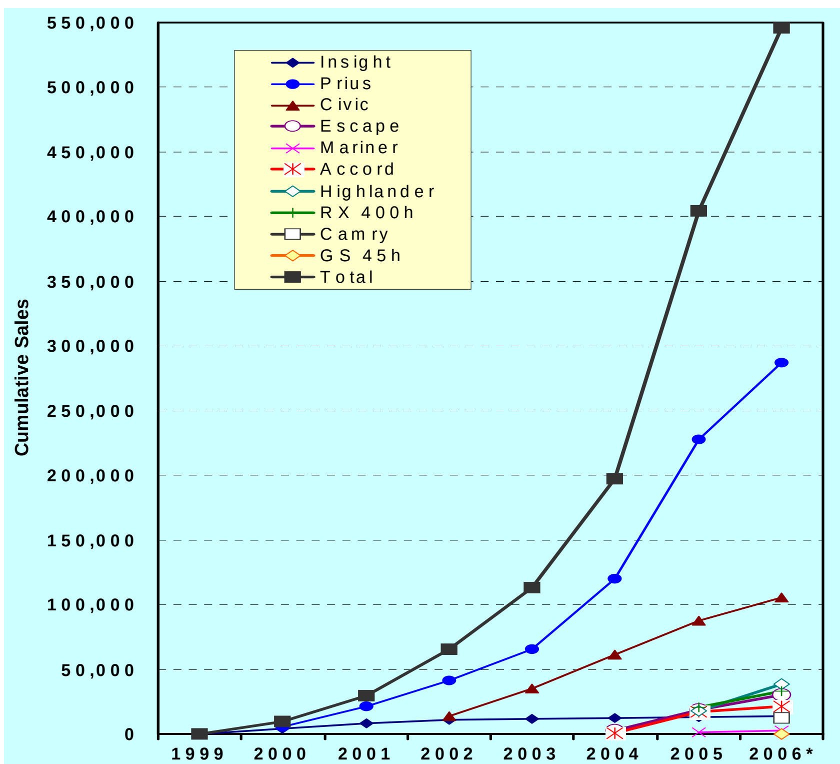
Testimony of Don Hillebrand, Ph.D.
Director, Center for Transportation Research
Argonne National Laboratory

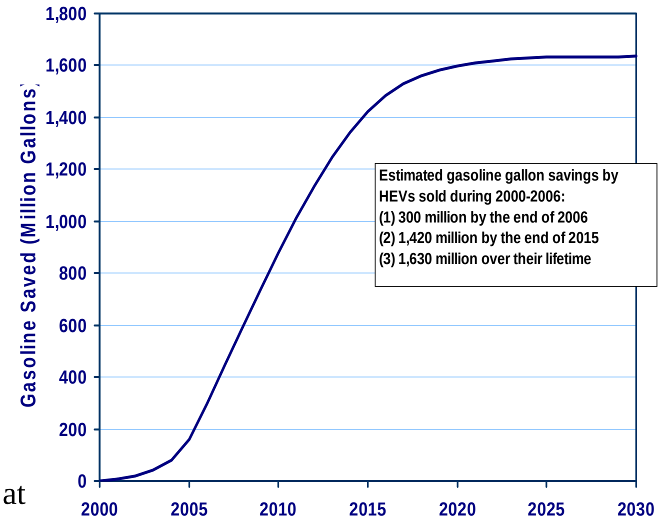
In the last 25 months there has been a dramatic development in automotive and vehicle technology in North America. This development relates to the rapid adoption of hybrid and particularly plug-in hybrid electric vehicle (PHEV) technology programs by the Nation's automakers. There are plans for the introduction of dozens of versions of plug-in hybrid conversions based on an array of existing vehicle platforms. This is occurring for a variety of reasons, including sustained government funding of automotive technology development programs, tough clean-air standards that are challenging to wider deployment of diesels, the existence of the night time "trough" in electricity usage, the successful creation of improved battery chemistries, the creative and innovative spirit of small American businesses, and perhaps foremost, the rapid increase in U.S. fuel prices and growing and sustained dependence on imported oil.

While the reasons for the sudden interest in plug-in hybrids are many, it is clear that we are in the midst of a revolution in automotive technology similar to the expansion of the auto industry during its infancy at the start of the last century.

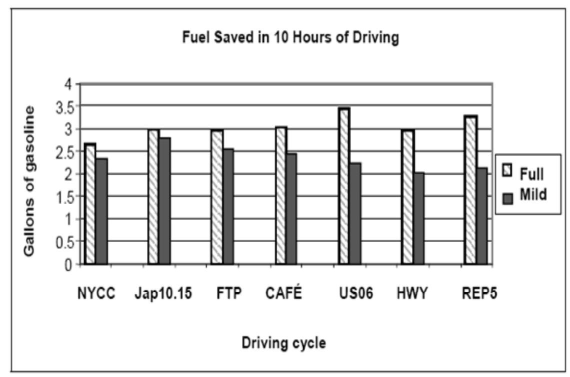


Cumulative U.S. hybrid sales – Source J.D. Power and Associates

The first modern hybrid vehicles were developed through U.S. government research programs in the early 1990's. There was no commercialization because of low fuel prices, lack of battery technology, and immature power electronics development, all of which contributed to make the vehicles expensive and inefficient. In the late 1990's, Toyota produced the first successful hybrid using new nickel metal hydride batteries (NiMH). Toyota currently manufactures its hybrid vehicles in Japan and exports those vehicles to North America.



The world hybrid-vehicle market, estimated at 504,000 vehicle sales in 2007, is projected to grow at an average rate of 30% over the next four years and could reach 2 million units by 2015. This growth is dramatic in automotive terms and the competition between manufacturers is intense. Toyota produces more than 80% of the hybrids sold in the U.S., and this situation is not likely to change soon. Ford and GM have both produced viable hybrids, but the production of these is slowly ramping up because of limitations on materials and high costs. The GM 2-mode hybrid is arguably the world's most advanced, but the Toyota system is more mature and available. Ford has a hybrid system similar to Toyota's system, but they have publicly stated that they were severely hampered by a lack of access to battery technology and high battery costs.



From Argonne Hybrid Electric Vehicle Technology Assessment, 2001

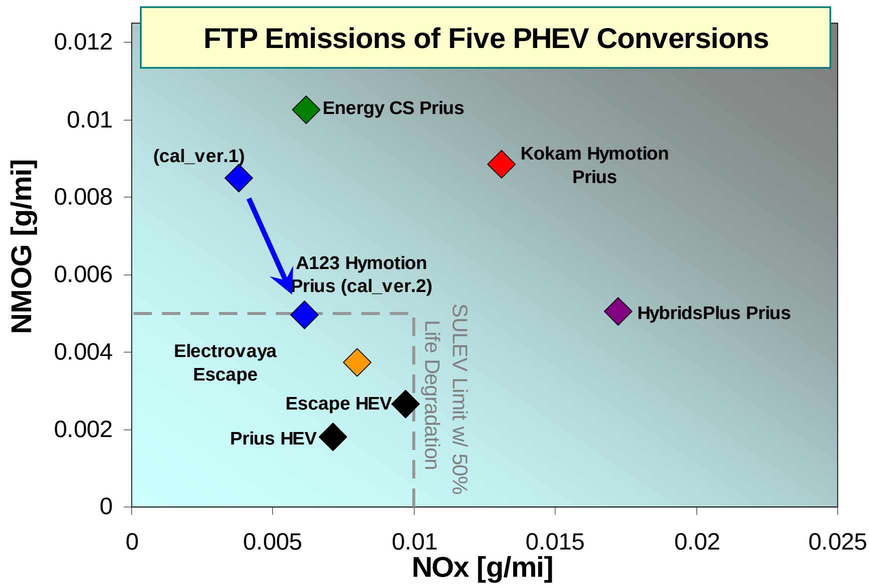
The potential for hybrid technology to reduce fuel usage is high. Hybrids can improve fuel economy up to 25%, and testing to this point indicates that plug-in hybrids can further improve fuel economy substantially. The measured fuel economy of plug-in hybrid prototypes at Argonne has exceeded 100 mpg, and there is potential for further improvement. This number sounds a bit sensational, and I am hesitant to use fuel economy when talking about plug-in hybrids, but suffice it to say that the plug-in hybrids have great potential.

UDDS Cycle Charge Depletion Operation	Average Depleting MPG	Average Battery Usage [Whr/mi]	CD range [miles]	Usable Energy [kWhrs]	Petroleum Displacement Factor [%]	Charge-Sustaining MPG
Valence Hymotion Prius	178	126	24	2.9	61.4%	66.4
A123 Hymotion Prius	160	129	25	3.1	59.9%	64.4
EnergyCS Prius	139	131	34	4.5	55.2%	62.2

HWY Cycle Charge Depletion Operation	Average Depleting MPG	Average Battery Usage [Whr/mi]	CD range [miles]	Usable Energy [kWhrs]	Petroleum Displacement Factor [%]	Charge-Sustaining MPG
Valence Hymotion Prius	122	98	33	3.2	47.5%	64.0
A123 Hymotion Prius	101	113	31	3.4	45.5%	55.0
EnergyCS Prius	103	103	50	4.9	43.6%	58.1

Argonne Advanced Powertrain Research facility testing results for PHEV conversion vehicles

Another issue of concern is the level of emissions from PHEV conversions. Testing of conversions has indicated that the PHEV vehicles can meet SULEV emissions. The chart at right shows test results from Argonne's Advanced Powertrain Test Facility. It indicates that development of PHEV control systems can lower emissions and bring PHEV conversion vehicles into compliance.

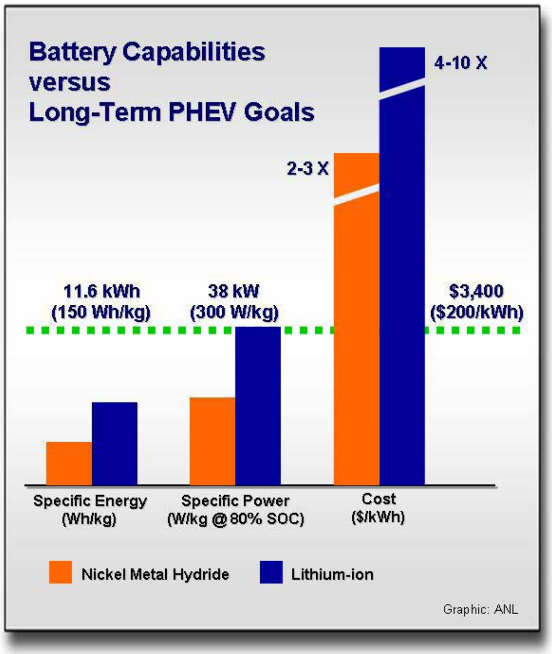


In all cases, whether hybrids or plug-in hybrids, the batteries are the key enabling technology, and lithium ion battery chemistries are the leading candidate for solving automotive battery issues. The U.S. is dominant in the development of battery materials and chemistries, although many of the fundamental breakthroughs in battery technology have been subsequently licensed overseas. The DOE battery research programs have spawned small businesses and pushed applied development of promising battery chemistries to a high level. A plethora of small companies have grown out of universities and research centers and these companies are pushing the edge of battery technology. National laboratory programs for battery development and testing continue to be successful, but the U.S. is behind the rest of the world in the adoption of battery manufacturing capability. Many small American battery companies build their factories in China. NiMH automotive technology was initially developed in the U.S., but has been commercialized by Panasonic and Sanyo and is mainly manufactured in Japan and Korea, and is available on most Toyota hybrids.

Lithium-ion advantages over NiMH and other battery chemistry:

Lithium-ion (Li-ion) batteries are considered the front-runner for PHEVs because of the higher specific energy and power compared to NiMH. Li-ion cells with cobalt cathodes hold twice the energy of a nickel-based battery and four-times that of lead acid. Li-ion is a low maintenance system, an advantage that most other chemistries cannot claim. There is no "memory" and the battery does not require scheduled cycling to prolong its life. Li-ion does not have the sulfation problem of lead acid that occurs when the battery is stored without periodic topping charge. Li-ion has a low self-discharge and is environmentally friendly, hence disposal is of minimal concern. Li-ion battery energy density is 1.8-times of NiMH and power density 2.5-times, thus vehicles can go further with Li-ion. For the last ten years, Li-ion battery technology and applications have progressed significantly – the amount sold in 1995 was \$3.389 billion and then in 2004 it reached \$42.1 billion (a 12-fold increase).

The chart at right compares the capabilities of Li-ion and NiMH batteries to the long-term PHEV battery goals and illustrates the substantial improvements in energy and cost required. Although specific energy of Li-ion is roughly twice that of Ni-MH, it must double to provide energy to meet the PHEV 40-mile electric range goal. Specific power is not a limitation. Cost is the greatest concern for Li-ion; it is estimated to be 4 to 10-times that required to be competitive.



Cycle life using a PHEV duty cycle has not been evaluated for either battery, but NiMH performs sufficiently well in hybrid (power assist) applications to allow Toyota and GM to offer an 8-year, 100,000-mile warranty. Tests of Li-ion using a hybrid power assist cycle have demonstrated up to 300,000 shallow cycles; PHEVs could require up to 3,000 deep discharge cycles as well.

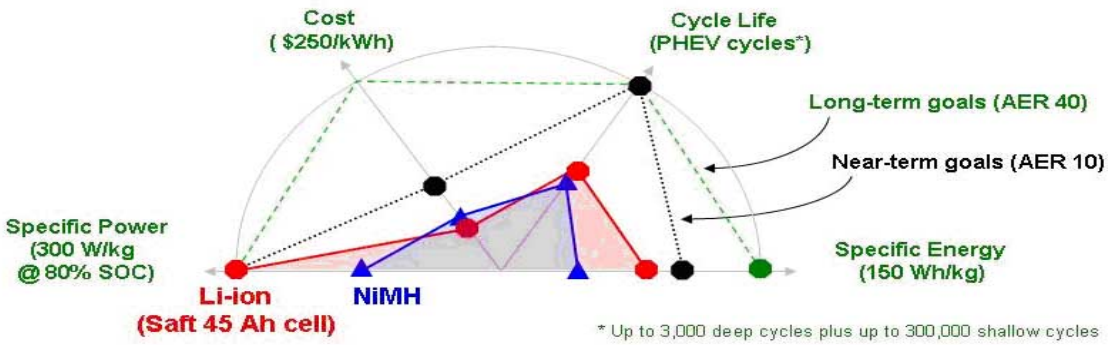
Cost – The lack of a high-volume manufacturing facility for high-energy automotive batteries is considered a major factor in the cost gap since Li-ion uses low-cost and abundant materials compared to NiMH. In addition, it should benefit from the material refinements and production maturation in the high-volume consumer electronics market.

Life **–** A combination of energy and power fade are anticipated challenges for Li-ion because a PHEV duty cycle includes high power assist at low state-of-charge (SOC) in addition to the high energy demand for electric range over the 15-year life of the vehicle. Li-ion batteries have demonstrated acceptable life for shallow cycle hybrid applications, but battery life typically falls off dramatically with deep discharge cycling.

Low-Temperature Performance **–** Li-ion exhibits significant discharge and regenerative power reduction at temperatures less than -20ºC.

Tolerance of Abuse and Safety **–** Li-ion batteries used in consumer electronics are not intrinsically tolerant of abusive conditions such as short circuits, overcharge, over-discharge, crush, or exposure to fire and/or other high-temperature environments.

Availability of Lithium – The primary sources of lithium are located outside of the U.S. and the question has been posed whether or not this is a limiting factor for Li-ion battery production. This does not appear to be a matter of immediate concern, but it needs to be more fully explored.



Source – DOE PHEV Program Plan

Li-ion battery advantages for PHEVs:

- Higher power and energy
- Lower number of cells
- Lower heat generation
- Lower metal cost per kWh
- Higher usable state-of-charge (SOC) range
- Higher operating temperature range
- Lower long-term cost

Safety issues with Li ion:

Li-ion battery high energy density comes at a price. Manufacturing methods are more critical the denser the cells become. With a separator thickness of only 20-25µm, any small intrusion of metallic dust particles can cause great problems. Appropriate measures are needed to achieve the desired safety performance. Li-ion batteries are nearing their theoretical energy density limit and battery manufacturers are beginning to focus on improving manufacturing methods and increasing safety. Li ion battery safety concerns include:

- High energy and prone to shorting;
- The electrolyte is flammable;
- Electrodes need to be thin, increasing the chance of shorting;
- Short-circuiting a Li-ion battery can cause it to ignite or explode; and
- Inherent instabilities of lithium means the cell has the potential for thermal run-away (the temperature rises quickly to the melting point of lithium causing a violent reaction).

Because of the inherent instability of lithium metal, research has shifted to a non-metallic lithium battery using lithium ions. Although slightly lower in energy density, the lithium-ion system is safe, providing certain precautions are met when charging and discharging.

Li-ion battery manufacturing:

Many countries have recognized that battery manufacturing capability is the key to automotive manufacturing competitiveness, but the U.S. companies have generally not concentrated on the manufacture of batteries.

Japan: Japan recognizes advanced battery technology as the key driving force behind competitiveness and hence views it as an issue of "national survival." The Japanese government is very supportive in funding research programs and its program couples superior manufacturing with excellent materials and systems development. Japan is the world's leading battery manufacturer and want/needs to maintain leadership in this technology. Japan used to supply 50% of the nickel cadmium batteries in the world, and for NiMH batteries, it supplies more than 70 percent. For Li-ion batteries, Japan plans to supply about 60% and wants to maintain a market share of 60-70 percent. At the current time, for hybrid vehicles, Toyota uses about 94% of NiMH batteries. The other six percent is Ford in the U.S.; however, about two-thids of that is from Japan. Basically, Japan is the only supplier for the whole world. Therefore, it is planning to leverage its position to become the leading supplier of Li-ion batteries for vehicles.

China: China is the planned location for many new manufacturing facilities. Their battery manufacturing methods are labor intensive, and at this time not well refined; however, China will quickly develop capability and will maintain lower production costs. Naturally, the American companies are attracted to this location.

Korea: Korea has low-cost aggressive companies, but is more a follower than a leader on chemistry and materials. In Korea, there is a government directed national project from 2004 to 2009 funded at about $84.7 million, or about $16.95 million per year. The project is trying to develop a super high-capacity Li-ion secondary battery (a rechargeable battery), as well as developing super capacitors.

Germany: Germany has announced "The German Battery Alliance" with intent to develop a homegrown battery manufacturing capability. The program will look at all aspects of battery development and is funded by the German government. This was driven by requests from the German auto industry for access to battery technology for hybrids. The project's objective is to substantially increase the energy and performance density of Li-ion batteries and to accelerate the possible use in production. Around €420M (about $600 million) will be invested in the initiative by participating industrial partners and the Federal Ministry for Education and Research.

United States: The U.S. is a leader in battery materials and chemistry development and also leads battery start-up activities and innovation. The major problem with the U.S. is that it lacks manufacturing or prototyping capability. Manufacturing capability does not occur overnight. Battery manufacturing know-how and capability are developed over time and require huge capital investments. Toyota has invested substantial funding in developing the capability to develop and design batteries. Estimates of costs vary, but studies indicate that Toyota pays one-third less for their batteries than do the American-owned companies. There are many reasons for this, but one is that Toyota has developed the requisite design and manufacturing infrastructure, and hence is a generation ahead in manufacturing technology and experience. Asian-based battery makers have marked advantages based on the large investments they have made in the manufacturing process. No matter how good the chemistry, one needs manufacturing skill to produce commercial batteries. Li-ion batteries are complicated devices that are prone to overheat, leak, and fail, no matter what chemistries they use. Superior design can minimize the chance of these faults occurring, but if you don't have advanced manufacturing methods you cannot make high-quality, durable, and safe commercial batteries.

Beyond manufacturing, the two biggest concerns with lithium ion are safety and cost. While lithium ion battery safety is a concern, the problems are solvable, meaning that the limiting factor to PHEV introduction will likely be cost. Estimates of battery cost range from roughly $3,000 to $12,000 for the expected 40-mile plug-in battery (PHEV-40). At these levels the major hurdle to introducing plug-in hybrid technology is that the projected fuel dollar savings are considerably lower than the cost of depreciating the battery over its useful life. In other words, there is no payback.

To make this cost/value shift positive, we either need to lower battery costs, to develop longer battery life, or we need larger differences between gasoline and electricity costs. This gap can be closed with the slow evolution of technology, or can be accelerated with government policies such as tax policies, R&D tax credits, or incentives. Additionally, government supported research focused on PHEVs and battery development should include scale-up technologies, systems development, battery recycling, and research on access to battery raw materials. From the automakers point of view, with batteries not ready for commercial introduction, the business risk of introducing a plug-in hybrid is tremendous. Especially because automotive battery warrantees are for the “life-of-the-car”. Specific, focused North American battery manufacturing incentives could spur further advancement. Perhaps a SEMATECH-like program focused on developing a manufacturing capability might help jump-start a homegrown battery manufacturing industry in North America.

Summary Recommendations:

Government should continue support for research and development, provide incentives for conventional hybrids to accelerate growth of market share, and consider added incentives for plug-in hybrids. Government R&D funding for advanced vehicles should better reflect the likelihood of success and be configured by the need for short term results. A sustained effort to develop battery manufacturing capability will be equally important. In either case, as we develop new vehicle technologies to displace oil consumption, the battery will be the key enabling technology. Ultimately, we have not accomplished much if we transfer a dependence on imported oil, for an addiction for foreign batteries.