Hybrid Vehicles in Perspective: Opportunities, Obstacles, and Outlook

John M. DeCicco

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SYNOPSIS

Hybrid electric vehicles (HEVs) are an important opportunity to address societal needs for higher fuel economy while meeting customer needs for performance, driving response, and onboard electricity. The technology encompasses a variety of designs that can be tailored to different targets for performance, efficiency, and operational characteristics at different levels of cost. Hybrid drive is synergistic with other technology developments. Load reduction measures are an important enabler of hybrid drive from powertrain mass and cost perspectives. Hybrid drive is itself an enabler of high efficiency engine options. When applied in isolation, the efficiency benefits are modest (15%–20%). However, when combined with other measures, the overall efficiency gains can be substantial, on the order of 100% for sophisticated implementations of HEV technology with advanced gasoline engines and reduced load platforms.

Cost will remain a major obstacle to HEVs for at least the next decade. Even mature high-volume electric drive componentry will involve a significant cost increment over conventional technology. Thus, use of hybrid drive will depend critically on its unique attributes and special elements of value that it can deliver. Competition from ongoing improvements to conventional powertrains will be another obstacle. For many applications, load reduction without hybridization, advanced spark-ignition engines and transmissions, and emerging electrical system technologies such as 12/42 volt alternators and integrated starter/generator systems can meet many requirements with better value/cost performance than hybrid drive. A key attribute of hybridization is that it provides a major efficiency boost while enhancing other useful vehicle attributes. Thus, another obstacle to widespread HEV applications is the lack of pressure to improve fuel economy.

A number of HEVs will undoubtedly be introduced by companies seeking to establish environmental and technological leadership, as with the recent Toyota and Honda products. Additional U.S. introductions may be stimulated by the California zero-emission vehicle (ZEV) program. What remains unclear is how long it will be before initial, limited introductions give way to more rapidly rising HEV market shares that would characterize mainstream technology diffusion. The European market, with its voluntary agreement on fuel economy, high fuel prices, and the differentiated vehicle taxation and access schemes in a number of countries, may be the place to watch for indications of when hybrid drivetrains achieve the value/cost crossover that will be the ultimate hallmark of success. In the United States, the outlook for HEV market share is likely to depend on the extent of future regulatory requirements to improve fleetwide fuel economy as a means of greenhouse gas emissions control.

[1] Present address: Senior Fellow, Environmental Defense <jdecicco@environmentaldefense.org>.

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INTRODUCTION

At the turn of the millennium, automotive technology finds itself in state of opportunity that is perhaps unprecedented over the 100$^+$ year history of the product. Late 20th century engineering capabilities are converging with the opposing forces of consumer wealth and environmental concern to foster a spate of creativity that makes for both great excitement and great uncertainty as the motor vehicle rides into the 21st century.

Perhaps the highlight of this new set of technological opportunities is hybrid electric drive. The prospect of building better powertrains that marry the energy and power density of petroleum fueled piston engines with the efficiency and responsiveness of electric motors has long intrigued engineers. However, the electronic systems and computerized design capabilities needed to execute such designs have proven elusive until only the past decade. Higher costs are inherent in a system that essentially combines two drive systems into one powertrain.

The question is, then, can enough value -- for meeting both customer needs and societal requirements -- be provided to justify the costs? A positive answer to this question can arise through a combination of falling costs and rising value. The answer for any technology, however, also depends on the status of competing solutions to the equation that makes the business case to invest in a given design approach. Moreover, strategic considerations come into play, in that early product deployment investments can be justified as a way to gain experience (including cost reduction) in anticipation of a greater value for the technology in the future.

Exploring these issues in order to assess the outlook for hybrid electric vehicles (HEVs) involves characterizing the technology and its benefits, examining the obstacles to its application, and synthesizing this information with an understanding of the market and non-market drivers that define the business context.

Technology Drivers

Even as automobilization diffuses around the world, the leading edge of automotive design still serves the needs and aspirations of northern/western upper middle classes in Europe, Japan, and the United States. These markets have different cultural and policy contexts, including widely varying regimes of fuel taxation. Nevertheless, vehicle technology is remarkably homogeneous. Diesel market share is the only notable difference, being higher in countries with higher fuel taxes generally or lower diesel taxes in particular. Other fuel economy differences are largely due to differences of mix (e.g., size, manual transmission share, etc.), rather than technological distinction.

In general, income-driven market forces pull technology evolution toward the traditional power and handling race; greater vehicle capacity, utility, and comfort; and increasing electronics content for communications, telematics, and entertainment. Aside from technology and fuels mandates limited to certain niches, emissions control needs are being met with ongoing refinements to gasoline and diesel engine cleanup technologies and fuel quality.

Thus, market needs, even constrained by conventional (non-greenhouse) pollution control requirements, appear unlikely to motivate near-term shifts to profoundly new technologies or fuels. The main rationales for developing advanced technology vehicles are various public concerns. Table 1 lists drivers and rationales associated with vehicle design attributes that a given technology solution might deliver. Customer amenities requiring higher on-board electric power are one such driver. Public health concerns are mainly addressed by a vehicle's criteria emissions performance. Safety is largely related to non-powertrain technologies, although there are, of course, safety concerns associated with any energy conversion and storage device. Some design attributes can address multiple drivers. For example, alternative fuel capability and higher fuel economy can both address emissions and energy security.

The technology drivers shown in Table 1 effectively define a new technology's value, which must be compared to its cost as illustrated in Figure 1 (given at end of paper). Any single driver, or even a subset of drivers, seems unlikely to compel significant technological change. It is the need for a good solution to all of the issues that can make the leap to hybrid drive worthwhile. Similar thinking motivates R&D on fuel cell vehicles (FCVs), which may compete with

Table 1. Drivers for Advanced Vehicle Technologies

Driver	Design Attribute	Rationale
Public Health	Criteria Emissions	Reducing criteria emissions to levels at which motor vehicles are no longer a major problem
Public Safety	Crashworthiness and Crash Compatibility	Save lives and reduce injuries
Global Warming and Energy Security	Fuel Economy	Higher end-use energy efficiency for cutting GHG emissions and reducing oil consumption
	Alternative Fuel Capability	Reducing oil dependence, diversifying energy resources, and cutting GHG emissions
Customer Amenity	High Power Source of Electricity	Onboard vehicle electrification, driving responsiveness, and other benefits

combustion hybrids as an ideal long-run solution. The fact that HEVs and FCVs share common components of electric drive can make hybrids a strategic pathway even if fuel cells become the powertrain "endgame." Since efficiency is a key benefit of hybrid drive, the need for higher fuel economy will be important in determining the prospects for widespread use of HEVs.

The outlook for new technology is also shaped by the manner in which any issue is translated by the political process. Public health (air quality) concerns are the primary rationale for policy measures such as California's Zero-Emission Vehicle (ZEV) mandate and driving restrictions in some European cities. Concerns about global warming, petroleum dependence, and U.S. competitiveness motivated the Partnership for a New Generation of Vehicles (PNGV), which targets hybrid powertrains as a key technology for R&D investment. Such policies have accelerated the development of electric drive in general and HEVs in particular. Nevertheless, these existing policies have restricted reach. Subsidies might offset costs, but cannot really make the business case. As illustrated in Figure 2, there can be other reasons to deploy a technology before true value/cost crossover occurs: one can gain experience and claim leadership, for example. But the ultimate prospects for HEVs, as for any technology, depend on achieving the fundamental profitability that is possible when the product provides customer benefits that exceed manufacturer costs.

HYBRID OPTIONS AND BENEFITS

Technically, the quest for higher fuel economy is shaped by two major factors: how efficiently a powertrain converts fuel energy into useful power, and how sleek a vehicle is in terms of mass, streamlining, tire resistance, and auxiliary loads (the latter referring to power-consuming on-board services not related to the powertrain itself). On the other hand, vehicle functionality and comfort are shaped by various other factors, many of which run counter to higher fuel economy. Examples abound, from the way a torque converter sacrifices efficiency to provide better shift smoothness and responsiveness to the wide variety of features that add mass to a vehicle.

The gasoline engine is reasonably responsive and readily provides high power for meeting the performance specs so often highlighted in the market. But most driving requires only about 10%–15% of an engine's peak power, and gasoline engines are inefficient at low load. The need to match the infinite speed range of driving to the limited speed band under which a piston engine is reasonably efficient and responsive results in design choices that detract from the efficiency of both engine and transmission. As a result, gasoline vehicles typically have a net (tank-to-wheels) efficiency of under 20% under the U.S. EPA composite driving cycle. Diesel engines provide higher efficiency, but available control technologies do not allow light duty diesels to meet expected emissions standards, especially in California.

Electric motors, on the other hand, can be very efficient at low loads, as well as ultra-responsive due to high torque availability and electronic controllability. Moreover, electric motors can serve as generators so that, with a battery available to store power, an electric drivetrain can recover some of the energy that would otherwise be lost during braking. Other energy conversion devices (such as hydraulic motors coupled to mechanical storage devices) plausibly offer similar characteristics. However, virtues of compactness and controllability -- as well as synergy with on-board electrification -- favor electric drive in spite of the mass, size, efficiency, and cost burdens of electrochemical batteries.

A combination of factors has now, within a relatively few short years, brought hybrid electric drive from the realm of research and experimentation to that of commercial introduction. In no particular order of priority, these factors include:

- Expanding technical abilities, including advanced design techniques as well as electronics compact and robust enough for automotive environments.
- Increasing marketplace appreciation for attributes related to advanced technology and environmental friendliness.
- Auto industry awareness of the future need for higher fuel economy due to greenhouse gas emissions and petroleum dependence.
- The regulatory push of the California zero-emission vehicle (ZEV) mandate, serving to hasten the development of electrodrive technologies.
- The R&D focus of the PNGV, which itself is partly a foil against higher fuel economy standards.

Possibilities vs. Practice

In principle, hybrid drive can take many forms. These range from very mild hybridization (just a step beyond integrated starter/generator systems) to "series" hybrids that fully decouple the engine from the wheels. Some versions of the latter might merely use the engine as an onboard battery charger for a full-power EV drivetrain, providing some non-trivial pure electric driving range. The potential fuel economy improvements associated with HEVs range from relatively modest (15%–20%) to Amory Lovins' claimed multifold (300+ mpg) levels for "hypercars" (in which a key factor is radical mass reduction and streamlining rather than hybridization itself). Combining less radical but still very marked degrees of load reduction and a diesel engine, HEVs such as GM's Precept concept are capable of meeting the PNGV Goal 3 level of tripled fuel economy for a U.S. midsize sedan.

In practice, "parallel" configurations appear to be the designs of choice. Automakers are reluctant to fully decouple the combustion engine from the rest of the drivetrain. One reason is that batteries cannot provide adequate combinations of efficiency, performance, and gradability even when supplemented by an engine-powered generator. Examples of practical designs are provided by the first mass-produced HEVs, the Toyota Prius and the Honda Insight. Concepts presented by the PNGV and production-intent announcements, as for the Ford Escape HEV, also indicate directions for the technology.

Table 2 lists the Prius, Insight, and two hybrid vehicles announced by U.S. automakers. On the basis of simple comparisons, the range of fuel economy improvement is a factor of 1.2 for the Dodge Durango HEV to 1.85 for the Honda Insight. However, estimating the particular benefits of hybridization requires adjusting for weight, performance, and other differences in attributes that influence fuel economy. Some aspects of efficiency improvement are clearly a result of hybrid drive, such as idle-off and regenerative braking. However, it is difficult to separate part-load efficiency improvements of hybrid drive from various engine efficiency improvements also made in HEVs. Also, efficiency comparisons should entail performance adjustment, but traditional measures based on peak engine power to vehicle weight, or 0–60 mph time, may not do justice to the performance advantages of HEVs in everyday use. Despite some perhaps disturbing trends toward convergence, real-world driving is still quite different than what is embodied in a "drag-strip" metric such as 0–60 time. Toyota points out, for example, that the low- and mid-speed performance and responsiveness of the Prius are quite superior to those of a Corolla even though the 0–60 time is slower.

Toyota Prius

The Toyota Prius was introduced in Japan in December 1997 with a rating of 28 km/liter (66 mpg) on the Japanese city cycle, claiming a 2x improvement over a similarly sized Corolla. Fuel economy is quite sensitive to driving cycle; hybridization sees its greatest benefits in the low-load, stop-and-go patterns of congested urban driving. U.S. EPA tests of the first-generation Japanese Prius found an average composite fuel economy of 49 mpg, a 65% improvement over the average 3000 lb weight class vehicle and a 45% improvement adjusted for performance (Hellman et al. 1998).

An et al. (1999) performed a modeling analysis using available specifications for the first-generation Japanese Prius and a 1997 Corolla. Separating the effects of hybridization from other measures, they estimated a 23% CAFE cycle benefit relative to a Corolla-like vehicle with performance adjusted downward (1.2 L engine and 14 s 0–60 time). However, efficiency benefits are quite sensitive to the assumed performance level, with a greater benefit from hybridization for vehicles having better performance. Adjusting the modeled HEV characteristics upward to match that of the standard Corolla (1.8L engine and 11s 0–60 time), An et al. found a 41% CAFE benefit.

Table 2 lists the U.S. version of the Prius, which uses second-generation hybrid componentry (also used in the new Japanese version). The Prius incorporates some load reduction, but not nearly as much as the aluminum-bodied Insight. It reflects improvements in packaging, modest materials changes, and reduced drag (C_D = 0.29). Thus, the similarly design Toyota Echo may make a better comparison than the Corolla. The two vehicles have similar interior volume: 89+12 and 87+14 passenger+cargo for the Prius and Echo, respectively. The Echo also has a state-of-the-art 1.5L

Table 2. Attributes of Some Early Hybrid Electric Vehicles

Attribute	Toyota Prius	Honda Insight	Ford Escape HEV	Dodge Durango HEV
Fuel Economy -- CAFE MPG	58	76	40	18.6
City / Hwy Label MPG	52 / 45	61 / 70	--	--
MPG Improvement Factor	1.4	1.85 (1.4)[a]	1.6	1.2
Performance Index, 0–60 time	12.5 s	12 s	9 s[b]	9 s[b]
Curb Weight, lbs	2765	1856	--	≈5000
Reference Vehicle	Echo 1.5L 4sp AT	Civic 1.6L 5sp MT	Escape 3.0L AT 4WD	Durango 5.9L AT 4WD
MPG: CAFE, City / Hwy	41, 32 / 38	40, 32 / 37	25, 20 / 24	15.6, 12 / 16
Curb Weight, lbs	2080	2200	3550	4900

(a) Author's approximate adjusted estimate for hybridization. (b) Assuming the claimed performance match to the reference vehicle. Sources: Automakers' new releases; press reports; Consumer Reports (2000).

engine with variable valve control (VVC), though the Prius incorporates several additional engine efficiency refinements. Compared to the Echo, the Prius offers efficiency improvements of 63% on the city cycle, 18% on the highway, and 42% on average.

Honda Insight

Honda provided a breakdown for the total 85% efficiency improvement for the Insight over a Civic Hatchback (an imperfect comparison, since the Insight is a two-seater while the Civic is a subcompact coupe). They attributed 30% of the MPG improvement to the Insight's streamlined, lightweight aluminum body, another 30% to the high-efficiency lean-burn engine, and the remaining 25% to the hybrid drive system. However, all of these items are synergistic. In particular, hybrid drive enables a number of key engine features that permit very high efficiency.

Although a fully adjusted comparison analysis has not yet been published, a rough idea of the net benefits of the Insight's hybrid mechanism can be had by subtracting, from the 85% total benefit, 30% for load reduction plus half of the 30% engine efficiency contribution (i.e., attributing a 15% fuel economy improvement to VVC and engine friction reduction techniques). This approach leaves approximately a 40% (1.4x) efficiency benefit attributable to hybridization, including its contributions of idle-off, regeneration, and the additional increases in part-load efficiency enabled by the hybrid mechanism.

Prototypes and Efficiency Prospects

Also listed in Table 2 is the Ford Escape HEV, the first production-intent hybrid sport utility vehicle for the U.S. market. Although only limited specifications have been released to date, the targeted 40 mpg composite fuel economy implies an efficiency improvement factor of 1.6. The Escape's powertrain is based on the DESIREE power-split system developed at Volvo, making it seem closer in concept to the Prius rather than to the Insight or Ford's PNGV "low storage requirement" (LSR) hybrid concept. However, the Escape HEV might incorporate additional measures, perhaps other refinements in the 4-cylinder engine and probably some further weight reduction measures.

For the Durango HEV, DaimlerChrysler has stated a 20% fuel economy improvement relative to the 5.9L V8 4WD version of the Durango, which is the most powerful now on the market. The road-coupled hybridization used in the prototype is clearly "mild," so this value may represent the lower end of what to expect from HEV technology. Also, the Durango HEV does not appear to incorporate any special load reduction or engine efficiency measures that could interact with the electric hybrid system to provide greater synergies.

Not listed here are the PNGV concept vehicles, which show greater degrees of fuel economy improvement (relative to their class) than the few commercial HEVs and near-commercial prototypes. The recent (early 2000) versions of the PNGV concepts are the GM Precept, Ford Prodigy, and DaimlerChrysler ESX3; all are midsize sedans claimed to approach or meet the Goal 3 level of roughly 80 mpg. However, it is difficult to make inferences from these concepts, since many design issues needed for production are yet to be confronted.

In terms of the general potential for fuel economy improvement, analyses for the U.S. Department of

Energy were summarized by the Interlaboratory Working Group (IWG) report on technologies for controlling greenhouse gas emissions. IWG (1997, 5.12) gives a 28%–43% range for the fuel economy benefit of hybrid drive when applied in a gasoline vehicle, and a lower range of 10%–23% when applied in a diesel vehicle. IWG notes, however, that DOE's HEV R&D program targets a doubled fuel economy, based on developing more advanced versions of all key components (batteries, motors/controllers, etc.).

Academic analysts have also projected greater fuel economy improvement, as high as 2x, from hybridization alone. Such estimates, and perhaps the DOE 2x R&D targets, may not fully account for real-world vehicle program requirements or contributions from conventional powertrain refinements and other design synergies. Such issues can confound HEV analysis. For example, mechanical efficiency improvements (e.g., operational and design techniques that reduce average engine friction) identified for HEVs can also be obtained to a non-trivial degree by more conventional means.

With these considerations in mind and in light of data on early HEVs, a range of 20% – 50% seems reasonable for the fuel economy improvement attainable through hybrid drive. This range reflects the different characteristics of different hybrid configurations, as well as the performance, cost, and value particulars selected by designers for a given application. Implicit in such numbers is the efficiency offset associated with batteries, due to the mass penalty and losses in power conversion, storage, and retrieval. What may not be fully reflected, since HEV technology is still quite new, is the potential for future technology improvements that might yield higher efficiency benefits in the long run.

COST ISSUES

A hybrid vehicle is inherently more costly than a combustion engine vehicle since the added costs of batteries, motors, and power electronics exceed the cost offsets from replacements or simplifications of other components (such as engine, transmission, starter/alternator). The ultimate issue is, of course, whether and when the customer and regulatory value of a hybrid package makes the higher cost worthwhile.

Batteries

Batteries are not quite the bane of HEVs that they are of pure EVs, but they remain a burden in terms of both cost and mass. The high-power storage requirements for HEVs are quite different than the energy storage requirements for a pure EV. Battery developers can trade off specific energy (kWh/kg) for specific power (kW/kg). Hybrid-oriented batteries typically have a power-to-energy ratio about ten times higher than batteries oriented to provide range for a plug-in EV. HEVs are likely to need only 2–3 kWh of battery capacity, compared to the order of 30 kWh needed for a pure EV (the Toyota Prius has a 6.5 Ah, or roughly 2 kWh, battery pack). Although a battery is not the only possible high-power storage device, it is the only one that now seems likely to be feasible and potentially affordable.

Lead-acid batteries have advantages of familiarity and low cost, but a disadvantage of short life. High-power lead-acid batteries might cost about $10/kW retail-equivalent (Williams and West 1999). Although peak-power optimized designs would differ from the common starter batteries of today, this cost level is consistent with existing starter batteries, considering only first cost. An auto parts store gives a retail price of $60 (with trade-in) for a 600 amp battery (7.2 kW peak), suggesting a cost of $8/kW. However, this value is only a first cost. The typical lead-acid lifetime of 3–4 years suggests a lifecycle (10–12 year) cost roughly three times higher, as well as issues of customer inconvenience.

Nickel-Metal Hydride (NiMH) seems to be the battery technology of choice for initial HEVs, as for the Toyota and Honda vehicles, in spite of costing much more than lead-acid. Lifetime considerations loom large, since automakers wish to avoid components needing periodic replacement. Lithium-based batteries show future promise (they are used on the Nissan Tino HEV concept, for example), but are still plagued by durability problems. EEA (1998) estimates the retail-equivalent cost of the 21 kW NiMH battery used in the Toyota Prius at $1550, implying a cost factor of $74/kW. EEA projects that these costs could drop by a factor of two at higher volume. CARB (2000) suggests similar or slightly better cost reductions. Nevertheless, even $30/kW is still quite high for a supplemental device in any kind of powertrain, given that the retail-equivalent cost of a complete conventional powertrain is only $50/kW. Even if battery lifecycle costs fall as low as $10/kW, this cost factor still compounds those of the other electric drive components needed for HEVs.

Motors and Controllers

At this point, motor and controller costs are also high due to low volume and limited experience with versions optimized for vehicle applications. EV proponents count on economies of scale to lower these costs to tolerable levels. For example, Sperling (1996) projected a halving of costs if volumes implied by the California 10% ZEV mandate are reached. (Ten percent of California's new car and light truck sales would be about 150,000 vehicles.) Although HEVs have reached mass production status, they are still low volume products. Even as the Toyota Prius ramps up to 30,000–40,000 units per year globally (for all three markets, Japan, North America, Europe), its volume will be an order of magnitude lower than that of a typical automotive program.

Figure 3 summarizes the results of some published assessments of motor and controller costs, expressed in terms of electrodrive system peak power rating. For parallel HEVs, the lower power ratings are most relevant. The higher line reflects the estimates of OTA (1995), which used EEA as the consultant and assumed permanent magnet (PM) motors (AC induction system costs would be somewhat lower). The University of California Institute of Transportation Studies (ITS) results, summarized by Delucchi (1999), also assume PM motors but incorporate learning-based cost reductions. Vyas et al. (1998) of Argonne National Laboratory (ANL) report long-term, high-volume cost estimates similar to those of ITS. At the low end, these estimates place motor and controller system costs in the range of $25–$35 per kW.

Time to Learn

Although these costs could be acceptable for future vehicles, it will take time and experience for such levels to be reached. EEA (1998) estimated a retail-equivalent cost of about $5,000 for the 45 kW hybrid drive system of the Toyota Prius, or $111/kW. Combined with the estimated $74/kW for the battery, the result is roughly $200/kW for total electrodrive system costs. Nevertheless, given the rapid pace of development and proprietary nature of leading-edge work, it is difficult to know where such technology stands in terms of a learning process and actual current costs.

Early stages of new technology commercialization involve R&D learning, which tends to be more rapid than that associated with scale economies alone. However, the Japanese automakers have a strong tradition of "learning by doing," part of their lean-production paradigm. Toyota has noted that the U.S. Prius represents a second generation of their hybrid system, reflecting a number of refinements and a roughly factor-of-two reduction in cost.

An illustrative analysis can bound how long it might take for electric drive component costs to fall. Pegging the starting level at $200/kW for a global volume of 25,000 units per year (approximate year 2000 volume for the Prius), Figure 4 illustrates several rates of learning with a rather ambitious ramp-up of electric drive system production. The scenario has volume roughly doubling every two years, reaching 100,000 units per year by 2005, 1 million units per year by 2010, and 4 million by 2015. Declining cost curves are shown for three levels of learning: slow (10%), moderate (20%), and fast (30%). Assuming a moderate learning rate -- costs falling 20% for each doubling of cumulative production -- suggests that a $30/kW level would not be achieved until roughly 2015. Such a cost level might be a long-run asymptote based on targets for combined battery, motor, and controller componentry.

Any such scenario is, of course, highly uncertain: the starting point, learning pathways, and asymptotic costs are all poorly known. The purpose is not to project particular costs in a particular time frame, but rather to indicate that learning curve arguments -- which underpin technology proponents' arguments about near-term prospects for electric drive vehicles -- also suggest that ample time must be allowed for experience to be gained. Thus, widespread deployment will only be possible if high costs, compared to conventional vehicles, can be borne for many (hundreds of thousands) vehicles for a number of years. Bearing these costs would entail some combination of (a) strategic pricing; (b) value-based designs that package the costly components to provide new customer amenities; and (c) government subsidies.

OUTLOOK

The outlook for any new technology depends not only on its own cost and value, but also on the capabilities of competing technologies that can meet market and policy needs. Both types of determinants are subject to various influences that can change the outlook as a result of decisions by automakers, consumers, and policy makers.

Competing Technologies

Hybrid vehicles face different form of competition over different time horizons. In the long run, HEVs may look outmoded compared to fuel cell vehicles. At present, however, conventional powertrain technologies, plus both conventional and advanced load reduction technologies, may offer lower cost ways to achieve higher fuel economy. Analyses of this potential are reviewed in Greene and DeCicco (2000), who summarize recent studies of both conventional and advanced technologies. Given sufficient lead time, a MPG improvement factor of up to 1.8 could be achieved at relatively low cost (5% or less of vehicle price) by means of incremental technology changes (DeCicco and Ross 1994). Table 3 summarizes the range of improvements identified for near- and long-term horizons, as a way to put the benefits of HEVs in perspective.

Table 3. **Hybrid Drive in Context: Complementary and Competing Technologies for Light Vehicle Fuel Economy Improvement**

TECHNOLOGY TYPE	FUEL ECONOMY IMPROVEMENT*
Load Reduction	
Mass (materials substitution, packaging)	10% – 30%
Aerodynamics	4% – 10%
Other	4% – 8%
Conventional Powertrain	
Variable Valve Control (VVC)	12% – 16%
Other Spark Ignition Engine Refinements	5% – 10%
Direct Injection Spark Ignition (DISI)	5% – 23%
DI Compression Ignition (DICI/diesel)	20% – 30%
Improved Transmissions	6% – 14%
Integrated Starter/Generator, Engine Start/Stop	3% – 6%
Hybrid Powertrain	20% – 50%
TOTALS (adjusted for interactions)	
Mid Term (2010 – 2015)	40% – 80%
Long Term (2020 – 2030)	100% – 200%

* Gasoline energy-equivalent, relative to a U.S. average mid-1990s light vehicle at 25 mpg (9.4 L/100km).
Source: Author's synthesis of technology assessments by ACEEE, DOE, and NRC.

Load reduction without downsizing -- through use of lightweight materials, streamlining, improved tires, more efficient accessories -- has a key role to play. It is an important enabler of many advanced powertrain designs. Most concept cars featuring electric drive technologies are built on platforms demonstrating marked mass reduction (30%–50%). Load reduction also competes with advanced powertrains, since it facilitates higher fuel economy and lower emissions with internal combustion engines.

Refinements to stoichiometric, spark-ignition engines and improved transmissions can go some distance toward meeting future fuel economy needs. Beyond these improvements, lean combustion aftertreatment and cleaner gasoline could expand the reach of "conventional" technology. Although adequate aftertreatment for diesels has not yet been demonstrated, a combination of resurgent interest in the technology and increasing regulatory pressure to address NO_X and fine PM may stimulate breakthroughs sufficient to make the diesel a contender for light duty vehicles over the next decade or so.

As noted earlier, the need for higher onboard electrical power capacity is another technology driver, and one which can favor hybrid electric drive. However, other approaches exist for meeting this need. Refinements to conventional alternators and the use of step-up converters can raise capacity to the 6 kW range. Migration to a 12/42 volt systems can provide greater power and flexibility. Use of an integrated starter/generator can enable engine start/stop or "idle off," pushing powertrain electrification to a level just short of the mildest forms of hybrid drive. Start/stop would also provide fuel economy benefits on the order of up to 6% (net of other conventional powertrain refinements that also attack part-load inefficiencies). In short, this set of more modest, less costly technology changes can both facilitate a move to hybrid drive while at the same time delaying such a move by addressing many of the same design requirements.

Commercialization Influences

The value/cost framework introduced earlier provides a way to think about the HEV outlook in light of both competing technologies and market drivers. While one can project 5, 10, 15 years out based on present circumstances, what is most critical is the evolution of factors, both internal and external to the market, that influence the cost/value equation. As shown in Figure 2, today's situation finds the technology being deployed in advance of profitability. Since HEVs offer such promise, there is interest in how the business case can be further accelerated.

One way to improve the value/cost equation is, of course, to lower the costs (Figure 5). R&D is a mechanism to do this. As noted earlier, the R&D stimulated (directly and indirectly) by the PNGV has been a factor that has helped bring the technology to where it is today. Expanded R&D efforts, both public and private, could further help to lower costs. Production experience itself can lower costs. This is one factor that motivates Toyota's and Honda's efforts to begin limited deployments of HEVs.

Other ways to accelerate the business case are strategies that enhance the value of the new technology (Figure 6). It is hard for consumers to value something unfamiliar, so marketing tailored to special attributes of the technology is clearly important. Innovative designs can be worked into an appealing package of options. For hybrids, since the fuel economy benefit is but weakly valued, creating new packages of amenity around the technology will be a way to increase its value. In markets with high fuel prices, such as Europe and Japan, one should find a greater value being placed on any fuel efficient technology. In the end, successful sales and customer satisfaction are perhaps the ultimate value enhancers; once such factors come into play, the technology can really begin to take off.

Market-based cost reduction and value enhancement strategies are primarily the role of the industry. Policy makers can help, for example, through R&D funding that contributes to lower costs, as well as subsidies that can complement the industry's own strategic deployment efforts. There can also be governmental or other third party roles for enhancing the value side of the equation. Such strategies include public information that highlights relevant attributes (high efficiency, environmental friendliness) or calls attention to the new technology itself. Market creation programs (fleets, other means of demand aggregation) can also help establish a customer base on which broader sales experience can be built.

Since key drivers for advanced technologies are, however, the external needs as shown in Table 1, another government role is regulatory policy. In essence, regulations impose new rules of the game that impact what is valued in a product from a societal perspective. Figure 7 illustrates this type of policy influence, which can also take the form of incentives. These measures artificially enhance the value side of the equation in order to compensate for market limitations related to emissions and fuel consumption. Again, with higher fuel taxes in Europe and Japan (not all of which are energy policy instruments), along with differentiated vehicle taxation schemes favoring higher efficiency, one would expect to find a "value line" for HEVs that is higher than what would be found under current U.S. conditions.

Another way to get a technology into the marketplace is to mandate it. Figure 8 shows the situation when a technology is put into production even when its value exceeds the cost. Aside from an external need (such as air quality), mandates can be justified as a way to generate experience so that market-based cost reductions and value enhancements can come into play sooner than otherwise. Many view the California ZEV mandate has having stimulated R&D which has lowered the costs of electrodrive technologies in general. However, the extent of such influence and whether it is well targeted are unclear; the opportunity cost of mandating a deficient technology can be high. For pure EVs, the cost and value still seem rather far apart. Partial ZEV credits are being considered as a way to accelerate the deployment of HEVs, for which the cost burdens and value limitations are less severe.

The different influences of mandates and performance-based standards are compared in Figure 9 (the relative timing is purely arbitrary in this illustration). Mandates can get a technology built with greater certainty, although how it fares in the market may be uncertain. Performance standards can accelerate the case for a new technology as a way to solve a new "problem" now imposed on the designer, e.g., to provide higher fuel economy than dictated by market factors alone. However, a particular design solution is not proscribed. In the case of HEVs, for example, a less costly way of providing the desired performance may be available. Nevertheless, a regulatory influence related to a special attribute of the technology -- such as high fuel economy -- is likely to accelerate deployment if the cost/value fundamentals are such that the business case is otherwise close to being made.

CONCLUSION

The hybrid electric vehicle has reached its current position of market emergence through a combination of factors, including advancing technical capabilities as well as new customer expectations and public policy needs. How it progresses in the market will depend on how these factors evolve. Because the value of a new technology depends on so many complex issues, it is difficult to quantify when and in what forms hybrid drive will cross the threshold of value exceeding costs, at which point true diffusion can begin.

A variety of influences can accelerate the commercialization of electric drive, which is seen as crucial for addressing environmental concerns in the years ahead. The importance of further R&D is widely appreciated; what is unclear is the proper balance and focus of government research versus private efforts.

In the U.S. context, it is recognized that the PNGV has aided the development of electric drive technologies. However, so has the California ZEV mandate, which was premised mainly on stimulation of the auto industry's private R&D efforts. Indeed, the mandate was itself partly triggered by GM's own private R&D initiatives that yielded the Impact battery-electric concept car in January 1990. Yet it is notable that the first hybrids to reach market are from Toyota and Honda, who do not participate in the PNGV. Of course, PNGV was partly motivated as a way to both postpone and prepare for higher fuel economy standards. Thus, the line between policy influences is not always sharp. Given that an efficiency boost is a key feature of hybrid drive, higher market-wide requirements for fuel economy would serve to raise the value of this technology as a design solution.

In Europe, the combination of higher fuel taxes, efficiency-correlated vehicle taxation schedules, and voluntary agreements to improve fuel economy serves to raise the value of technologies offering higher efficiency. However, lenient emissions standards permit greater use of diesels and direct injection gasoline engines. Therefore, while the market value of fuel economy is higher in Europe than in the United States, so is the competition HEVs face from conventional options. Nevertheless, it would seem that this greater overall pressure for higher fuel efficiency, along with similar consumer desires for on-board power consuming amenities, will make Europe the place to watch for a true HEV market to take hold.

In any market, public information, promotion, and market creation activities can also enhance the value of new technology and speed up the commercialization process. What is clear at this point is that major commitments are being made to hybrid electric vehicles, with the desire for environmental and technological leadership being a key motive. Yet this factor is one that is impossible to quantify, even though it appears to be the most important factor that has moved HEVs from R&D to the showroom to date. How all of these factors will interact with the basic business equations based on customer value and production cost will make for a fascinating story as the market for HEVs unfolds over the coming decade.

REFERENCES

An, F., F. Stodolsky, and D. Santini. 1999. Hybrid Options for Light-Duty Vehicles. SAE Paper No. 1999-01-2929. Warrendale, PA: Society of Automotive Engineers.

CARB. 1994. Technical Support Document, Zero-Emission Vehicle Update. Staff Report. Sacramento, CA: California Air Resources Board. April.

CARB. 2000. Advanced Batteries for Electric Vehicles: An Assessment of Performance, Cost and Availability. Report by the Battery Technology Advisory Panel. Sacramento, CA: California Air Resources Board. May.

DeCicco, J., and M. Ross. 1994. Improving Automotive Efficiency. *Scientific American,* p. 52-57, December.

Delucchi, M.A. 1999. Motor Vehicle Lifecycle Cost and Energy Use Model. Davis, CA: University of California, Institute for Transportation Studies.

EEA. 1998. Technology and Costs of the Toyota Prius. Report to the U.S. Department of Energy. Arlington, VA: Energy and Environmental Analysis, Inc., July.

Greene, D.L., and J.M. DeCicco. 2000. Engineering-Economic Analyses of Automotive Fuel Economy Potential in the United States. Oak Ridge, TN: Oak Ridge National Laboratory. February.

Hellman, K.H., M.R. Peralta, and G.K. Piotrowski. 1998. Evaluation of a Toyota Prius Hybrid System (THS). Ann Arbor, MI: U.S. Environmental Protection Agency, August.

IWG. 1997. Scenarios of U.S. Carbon Reductions. Prepared by the Interlaboratory Working Group (IWG). Washington, DC: U.S. Department of Energy, Office of Energy Efficiency and Renewable Energy. September.

OTA. 1995. Advanced Automotive Technology: Visions of a Super-Efficient Family Car. Washington, DC: U.S. Congress, Office of Technology Assessment. September.

Sperling, D. 1996. The Case for Electric Vehicles. *Scientific American,* pp. 54-59, November.

Vyas, A., R. Cuenca, and L. Gaines. 1998. An Assessment of Electric Vehicle Life Cycle Costs to Consumers. SAE No. 982182. Warrendale, PA: Society of Automotive Engineers.

Williams, K.R., and J.G.W. West. 1999. Fuel Cell Systems: New Developments & Vehicle Integration. Presented at *Commercializing Advanced Vehicle Propulsion Systems 99,* Vancouver, BC, March. Portland, Maine: Intertech Conferences, Inc.

Value/Cost Crossover for New Technology

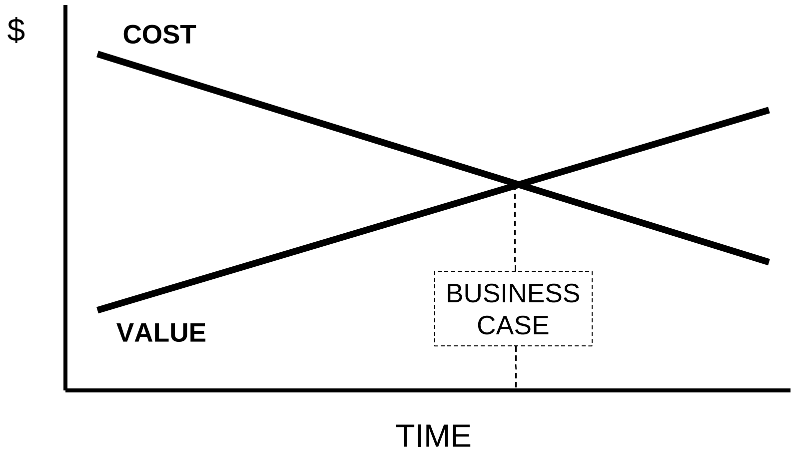

Figure 1

Reasons to get ahead of the game in hopes of future profitability

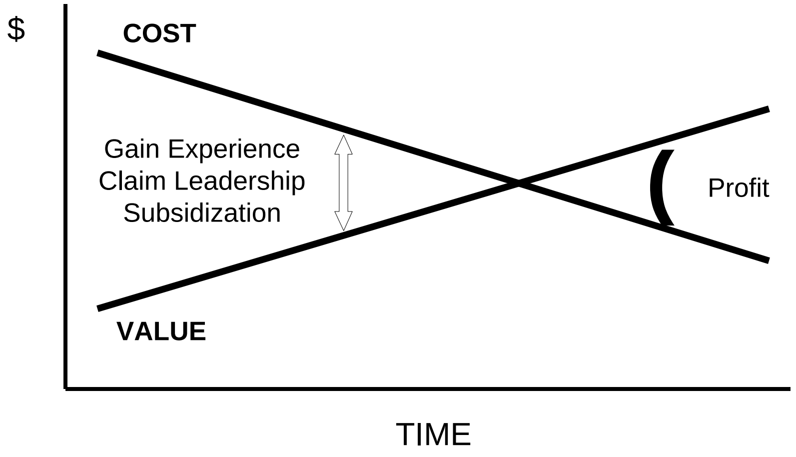

Figure 2

Mass Production Cost Estimates for Electric Drive Motor/Controller Systems

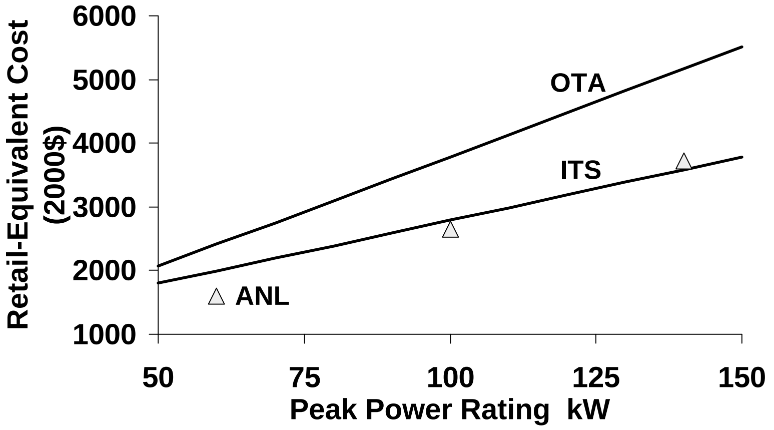

Figure 3

Illustrative Learning Curve Cost Reductions for Hybrid Electric Powertrains

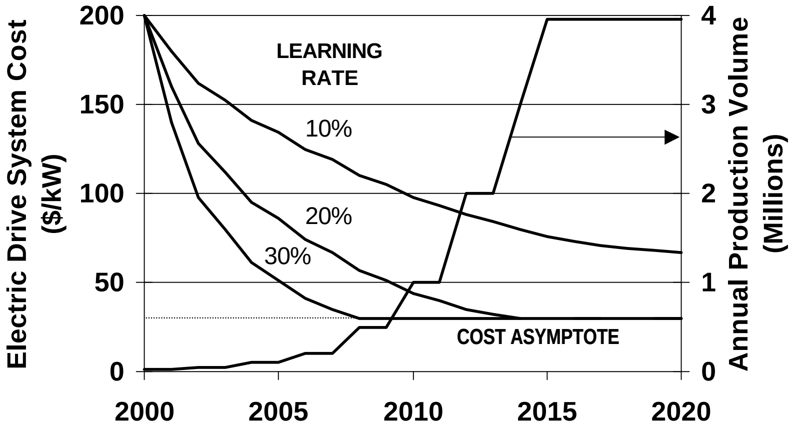

Figure 4

Accelerating the Business Case: Cost Reduction Strategies

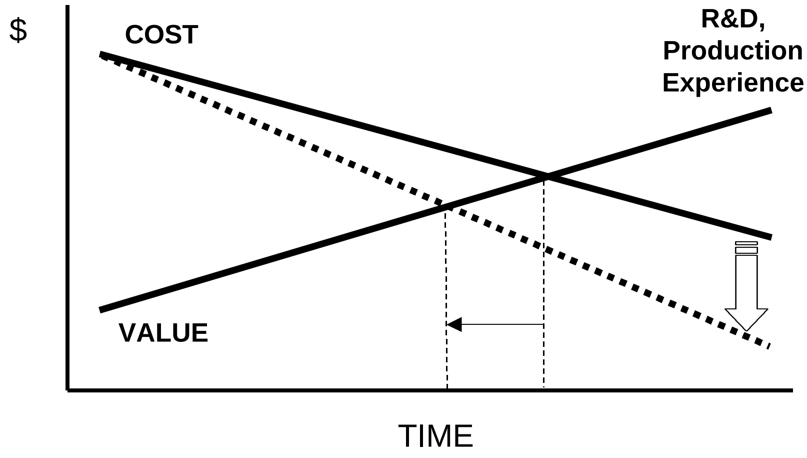

Figure 5

Accelerating the Business Case: Value Enhancement Strategies

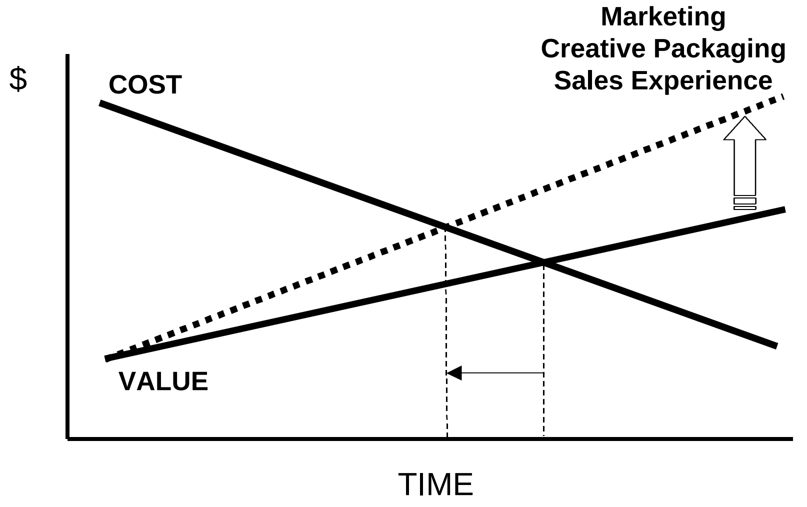

Figure 6

Accelerating the Business Case: Non-Market (Regulatory) Value

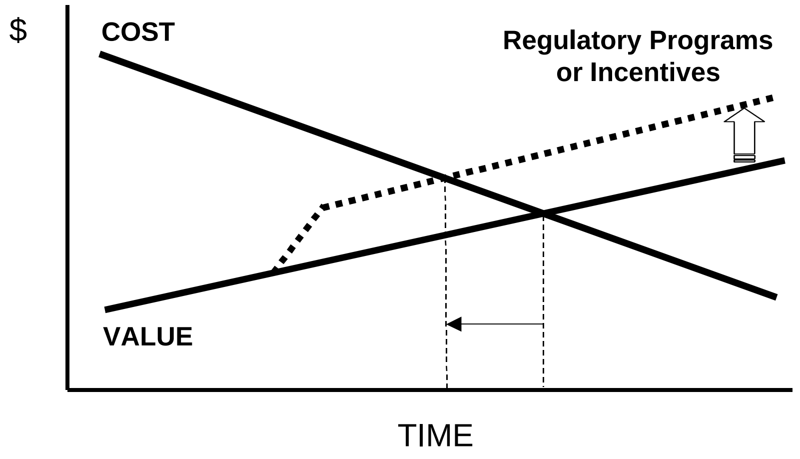

Figure 7

A technology mandate might bend the cost/value curves to speed up crossover

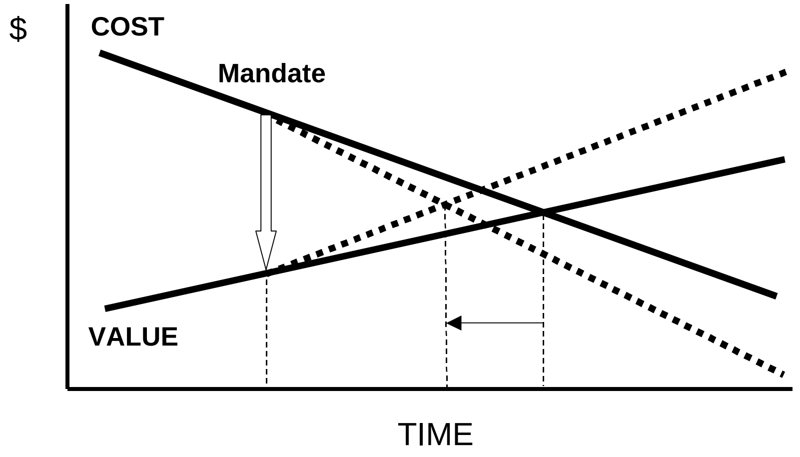

Figure 8

Performance-Based Regulation vs. Technology Mandate

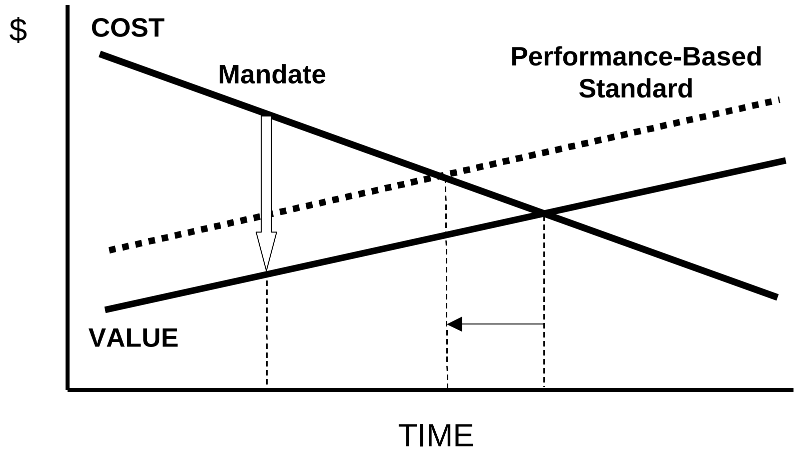

Figure 9