

HYBRID VEHICLES GO TO MARKET

Will Gas-and-Electric-Powered Automobiles Fit the Bill?

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The U.S. launches of the Honda Insight (Figure 1) and the Toyota Prius (Figure 2) have sparked interest in hybrid vehicles—vehicles powered by a combination of gasoline and electric battery pack—and their potential for meeting environmental and fuel efficiency goals. What is pushing the development of hybrid vehicles, what is the status of the designs, and what are the potential marketing barriers?

The primary barrier to widespread sales of hybrid vehicles is cost. In the United States, most customers do not value fuel savings enough to pay the current higher cost of hybrids, although a niche market may emerge. Mass market acceptance is likelier in Japan and Europe, which face higher fuel prices.

Nonetheless, government policies and incentives could boost acceptance of hybrids in the United States. Without incentives, mass-market sales of hybrids are less likely until successful development and market penetration in Japan and Europe reduce the cost.

Reducing Fuel Use

Sooner or later, vehicles must become more fuel-efficient or must run on alternative power sources. Crude oil supplies will not last forever. There is legitimate disagreement on how long crude oil supplies will last and at what level of supply the prices will rise, but this generation or the next probably will witness large shifts to alternative energy sources.

Not only is the supply of oil diminishing, but the rate of use is exploding as developing countries achieve the mobility of industrialized nations. Although there are alternative sources of oil—such as oil shale—these are likely to be even more expensive.

Adding to the argument are concerns about global warming. It is clear that the world is warming, although the role that the burning of fossil fuels plays is less clear—and quantifying the effect is even murkier. Reasonable steps to reduce fossil fuel use are prudent insurance.

Taking reasonable, cost-effective steps to reduce fuel use and carbon emissions offers many additional benefits. Customers benefit from reduced fuel costs. Society benefits from reduced pollution, with lower evaporative emissions and reduced emissions from fuel refining and distribution. Nations that

FIGURE 1
Honda Insight.



FIGURE 2
Toyota Prius.



import oil are particularly affected—for example, what was the cost of the Persian Gulf war, both in economics and in the impact on participants, or what is the economic cost of oil price shocks?

Barriers

Nonetheless, there are several barriers to improved vehicle efficiency and the use of alternative fuels:

1. Reducing fossil fuel use is a benefit to all of society more than to the vehicle purchaser as an individual. Experience with vehicle emission standards has shown that, despite widespread support for pollution controls, which have raised costs for everyone, few customers are willing to pay more individually for vehicles with lower emissions.

2. Vehicle purchasers respond rationally to the cost of fuel. Purchasers severely discount expected lifetime fuel savings because of the time value of money and the expected sale of the vehicle in a few years. Most customers are indifferent to technologies that enhance fuel economy—because the fuel savings are roughly offset by the higher cost of the technology, the net benefit is a wash. Given the many considerations affecting car purchases, it is not surprising that fuel efficiency ranks low (1).¹

3. Given customers' general indifference, investment in new fuel economy technology can be risky. Huge investments in research and development as well as tooling are necessary to bring new technologies to market; in addition, already scarce engineering expertise must be diverted from other projects. Then the manufacturer must hope that customers accept the technology.

4. Infrastructure, infrastructure, infrastructure! Most people have no desire to plan their lives and trips around fuel purchases and do not want a vehicle they can't refuel at the corner station. On the other hand, who will invest billions of dollars in new infrastructure for a product that no one is using? This chicken-and-egg problem is a huge barrier to alternative-fuel vehicles. Moreover, there is no consensus on which alternative fuel is best. Investing billions—perhaps hundreds of billions—of dollars in an infrastructure that may be abandoned in a few years when something better comes along is unthinkable.

5. There are multitudes of technology options:

- ◆ Should manufacturers work on incremental improvements to the gasoline engine?
- ◆ Compressed natural gas has many advantages, including lower CO₂ emissions, extremely

low criteria pollutant emissions, and reduction of the need for oil imports. Should the government work on an infrastructure for this alternative?

- ◆ Advanced diesels offer efficiency improvements, but can they meet upcoming emission concerns?

- ◆ What about making fuels from biomass, which may be able to use the current infrastructure?

- ◆ Then there is the Holy Grail: fuel cells. Can all the engineering challenges be resolved? How long will it take? Can the costs come down to reasonable levels? What about hydrogen storage or onboard reforming?

So many questions, but so few answers!

Hybrid Compromise

Why hybrids? Hybrids are expensive, they could be upstaged by fuel cells, and they use fossil fuels. Why bother?

Hybrids can be looked at as a compromise. Efficiency and emissions may not match those of a hydrogen fuel cell, but fuel cell development has a long way to go. In addition, hybrids can match the overall efficiency of a fuel cell that uses onboard reformers to produce hydrogen (2).²

Gasoline hybrids avoid the emission problems of diesels as well as the range problems of electric vehicles. Hybrids offer greater improvement in efficiency than is likely through incremental engine improvements—especially since engine improvements also can apply to hybrids. A more important advantage is that hybrids can use the current infrastructure.

Hybrid Powerplants

There are several different kinds of hybrid systems. The two basic configurations are serial (Figure 3) and parallel (Figure 4).

Serial Configuration

In the series hybrid, the engine connects directly to a generator, which supplies the motor and recharges the battery. In theory, the advantage is that the engine can run in more efficient operating zones and can be shut off when not needed. Because converting the engine output into electricity before driving the motor creates substantial inefficiencies if

¹The cited reference includes an excellent discussion of why customers are largely indifferent to fuel efficiency technology.

²According to the reference cited, hybrids with advanced internal combustion powertrains even may be as good as fuel cells with onboard hydrogen storage, unless the hydrogen for the fuel cell is produced from nonfossil energy sources or from fossil sources with carbon sequestration.

the engine is the primary power source, the serial configuration usually includes a small engine that provides a range boost to a large battery pack.

This configuration has low emission levels, but requires a large, heavy battery pack, significantly increasing cost and reducing energy efficiency and vehicle performance. In addition, the motor must be large enough to meet acceleration needs.

Parallel Configuration

The parallel hybrid uses an engine and a motor, both connected directly to the drivetrain. The biggest challenge with a parallel system is integrating the two power sources. The major advantage is the large gain in efficiency, even with a relatively small, light battery pack.

Innovative Approaches

Engineers can be creative in applying these concepts to vehicles. The two hybrid vehicles recently introduced in the United States, the Honda Insight and the Toyota Prius, both have chosen innovative hybrid techniques.

Toyota Prius

Instead of choosing between series and parallel systems, Toyota has developed a new type of hybrid combining some of the advantages of both systems.³ The Prius powertrain is based on the parallel type, but allows series-like operation with a separate generator to optimize engine efficiency (Figure 5).

Toyota's hybrid system is relatively complicated and heavy, requiring a power split device and an extra generator and inverter (the two inverters are in a single package). However, it offers great flexibility in engine operation and calibration. The system also acts as a continuously variable transmission, eliminating the need for a conventional transmission.

Honda Insight

Honda took a different approach for the Insight (3). Honda's Integrated Motor Assist (IMA) system locates a high-torque, high-efficiency DC brushless motor between the engine and the transmission (Figure 6). This 10 kW motor is only 60 mm (2.4") thick and connects directly to the engine's crankshaft. It supplies up to 36 ft-lb of torque during acceleration and acts as a generator during deceleration to recharge the battery pack. This is a simple, elegant method for packaging a parallel hybrid system and minimizing the weight increase.

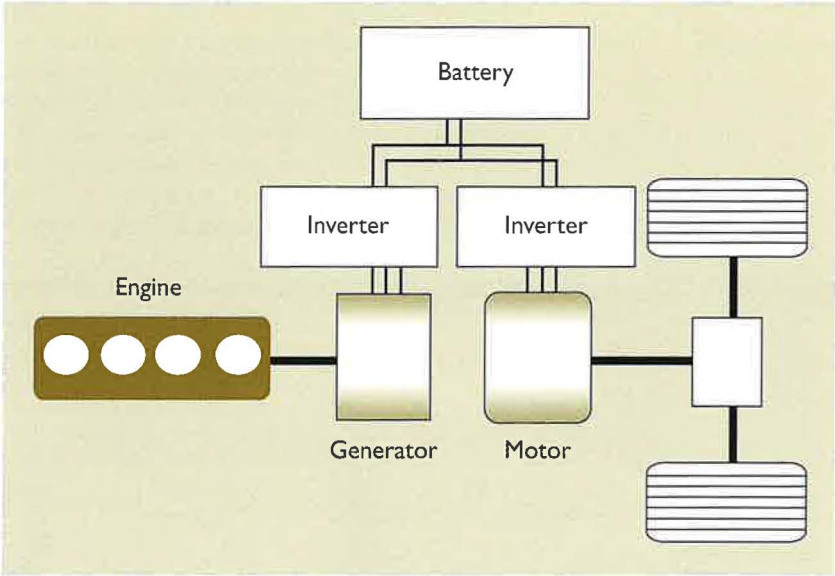


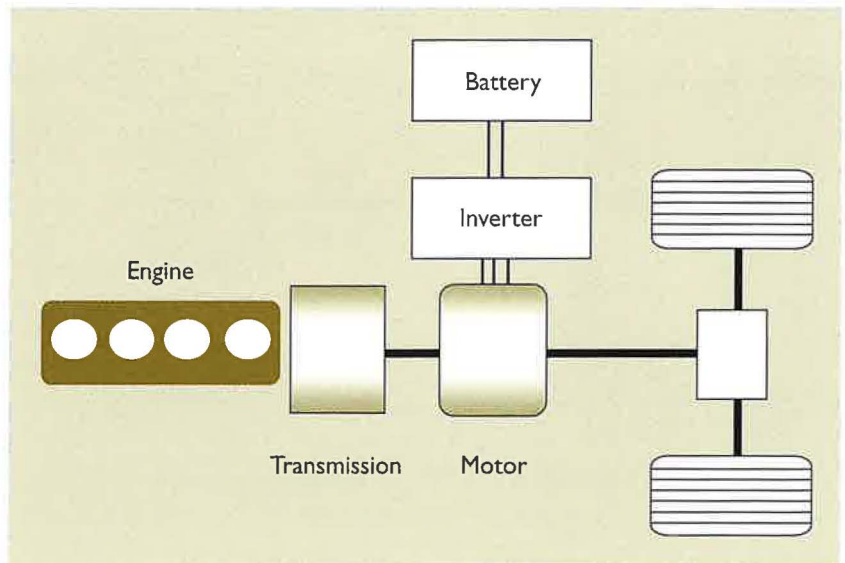
FIGURE 3 Series hybrid.

Operating Characteristics

Basic operating characteristics shape the design of any hybrid system. The greatest demands on horsepower and torque occur when accelerating and climbing grades. Minimal power can maintain a vehicle's speed on a level road. With an electric motor to provide a power boost to the engine when appropriate, a smaller, more fuel-efficient gasoline engine can be used (Figure 7).

In addition, the motor can capture energy normally lost in deceleration and braking and use the energy to recharge the battery—a process referred to as “regenerative braking.” Finally, the powerful electric motor can restart the engine far more quickly

FIGURE 4 Parallel hybrid.



³Prius information based on a presentation by Dave Hermance of Toyota, “Toyota Hybrid System Concept and Technologies,” October 1999.

than a conventional starter motor and with minimal emissions impact, allowing engine shut-off at idle.

Both models use relatively small battery packs. The Insight's nickel-metal hydride (NiMH) battery pack is rated at about 1 kW-h of storage and weighs about 22 kg (48 lb). The battery pack on the Prius is larger, but no more than twice the size of the Insight's battery pack. These lightweight battery



FIGURE 7 Honda Insight high-efficiency engine with integrated electric motor.

packs help to maintain in-use performance and efficiency while supplying most of the hybrid system benefits. The larger motor and battery on the Prius allow limited acceleration and cruising at light loads on electricity only.

Both the Prius and the Insight incorporate improvements in engine efficiency, in addition to the downsizing allowed by the hybrid system. The Prius uses a low-friction, Atkinson cycle 1.5-L engine. The Atkinson cycle uses a longer expansion stroke, extracting more energy from the combustion process to boost efficiency.

The downside is that the Atkinson cycle generates a relatively low peak horsepower. This is acceptable on the Prius because the electric motor can provide a power boost during acceleration. However, if the battery is depleted—for example, on an extended hill climb with four passengers—performance reduces substantially.

The Insight uses a conventional Otto cycle engine, but incorporates many different strategies to improve efficiency. Honda's variable valve technology (VTEC) boosts the engine's peak horsepower and allows more engine downsizing. The 1.0-L, 3-cylinder engine also incorporates lean-burn operation, low friction, and lightweight technologies to maximize fuel efficiency. Despite the small engine size, the Insight is able to sustain performance with a depleted battery, because of the high power to weight from the VTEC engine.

Combining Features

The Prius and Insight have used different powertrain technologies to achieve similar efficiency

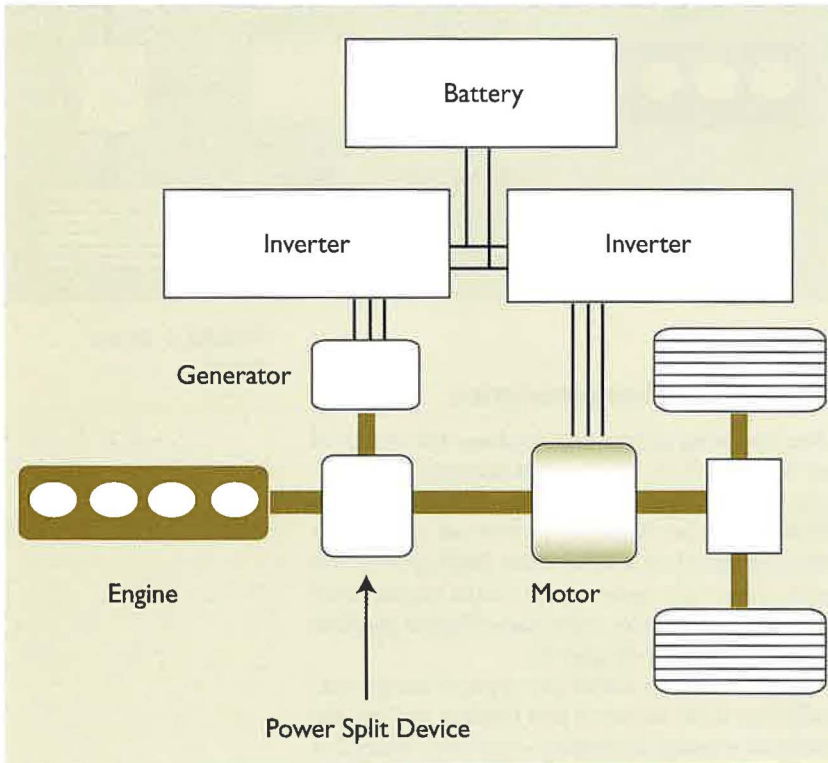


FIGURE 5 Toyota Prius powertrain.

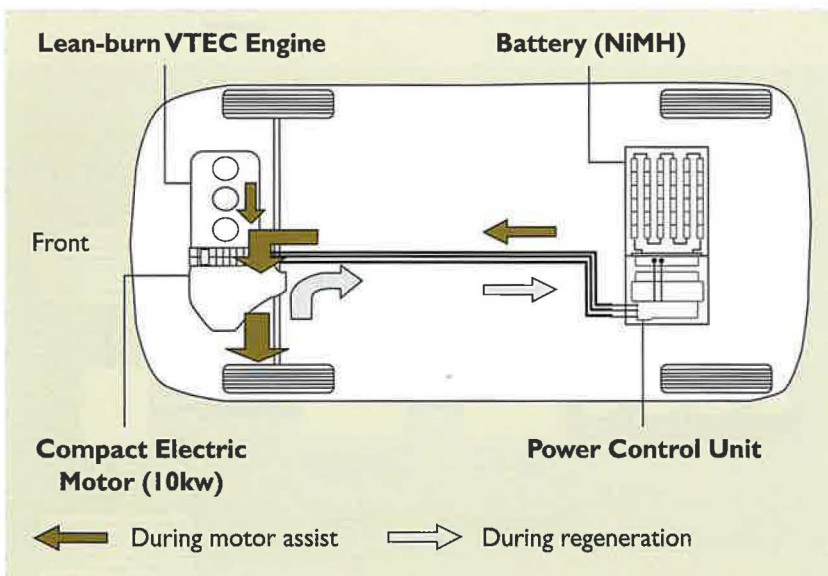


FIGURE 6 Honda Insight powertrain.

goals. One important lesson is that different types of hybrid systems may achieve similar environmental performance. There are an infinite number of ways to combine hybrid components to create a practical hybrid electric vehicle.

However, any similarity between the Prius and the Insight ends with powertrain performance. In developing the Insight, Honda identified three key areas to improve overall efficiency:

1. Improve the efficiency of the powertrain,
2. Reduce vehicle weight, and
3. Reduce drag and friction.

Honda's development of advanced technologies to reduce the Insight's weight as well as drag and friction have increased fuel efficiency under all types of driving conditions (Figure 8).

Energy Achievements

Both the Prius, which seats four adults, and the two-seat Insight have improved fuel economy impressively. The Insight has recorded the highest fuel economy label values ever for a gasoline vehicle, 61 mpg in the city and 70 mpg on the highway. The Prius values are 52 mpg in the city and 45 mpg on the highway.

It is also interesting to examine the fuel economy ratings of comparable vehicles. The closest comparison to the Insight is the Honda Civic 3-door hatchback. The closest comparison to the Prius is the Toyota Corolla. Table 1 compares the label values for the 2000 model year.

Although Toyota did not focus on weight reduction technology in the Prius, the complex, sophisticated hybrid system produced an impressive improvement in city ratings. The lack of load reduction, however, is apparent on the highway. Because the highway cycle is mostly steady-state operation, hybrid systems and regenerative braking offer little benefit. On the highway, therefore, the reduced-displacement, highly efficient Insight engine, combined with extensive load reduction, yields greater fuel economy.

Potential Benefits

Hybrids also offer potential reductions in emissions. The lower fuel consumption reduces upstream emissions from the production and distribution of gasoline. The higher efficiency increases the range and reduces the evaporative emissions from refueling. Hybrids also can reduce engine-out emissions of nitrogen oxides (NOx). NOx formation correlates with engine load—

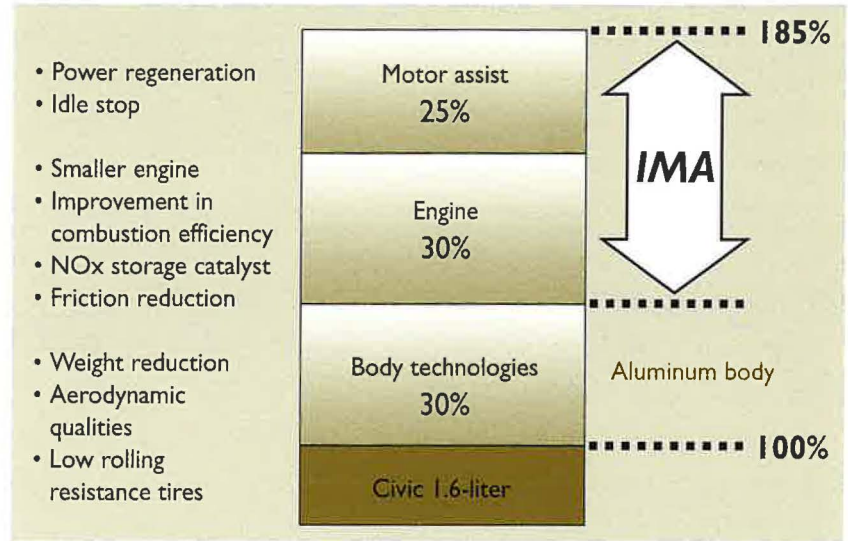


FIGURE 8 Honda Insight low fuel-consumption technologies.

engines generate more NOx during acceleration than when cruising. By reducing the load on the engine during acceleration, the hybrid system correspondingly reduces NOx formation.

Hybrids offer customers many desirable features. One is that hybrids use gasoline or diesel fuel, which do not require new infrastructure. The customer benefits from lower fuel costs, extended range, and fewer trips to the gas station. Hybrids have good synergy with other fuel economy technologies and help reduce emissions.

Of equal importance is that the hybrid has little impact on the vehicle's operation—hybrid vehicles drive and operate like conventional vehicles. Manufacturers can design the hybrid's motor to boost performance instead of reducing engine displacement. This performance-oriented concept still could realize significant fuel savings from hybrid operation and regenerative braking, resulting in an environmentally sound supercharger.

TABLE 1 Hybrid Fuel Economy Improvement

	City	Highway	Combined
Insight	61	70	65
Civic 3-door M5	32	37	34
Insight improvement	91%	89%	91%
Prius	52	45	48
Corolla A4	29	37	32
Prius improvement	79%	22%	50%

TABLE 2 Hybrid Vehicle Comparison

Status	Model	CAFE mpg	Improvement ^a
Commercial	Honda Insight	76	91%
Commercial	Toyota Prius	58	50%
Prototype	Ford Escape SUV	40	40–70%
Prototype	Dodge Durango SUV	19	20%
Prototype	GM SUV	35	20%
Prototype	GM full-size pickup	20	15%
Prototype	Ford Prodigy - PNGV diesel	70 ^b	155%
Prototype	DC ESX3 - PNGV diesel	72 ^b	162%
Prototype	GM Precept - PNGV diesel	80 ^b	191%

Notes: PNGV = Partnership for a New Generation of Vehicles; DC = DaimlerChrysler

^aBaseline for Escape is 24 mpg (V6) to 29 mpg (4-cyl); baseline for PNGV is 28 mpg (based on typical midsize car)

^bGasoline-equivalent mpg

Emerging Prototypes

New hybrid prototypes also are emerging. Table 2 compares the manufacturer claims for new prototype vehicles with the production values for the Insight and Prius. The table presents corporate average fuel economy (CAFE) values instead of fuel economy label values.⁴

The General Motors (GM) sport utility vehicle (SUV) improves fuel efficiency by only 20 percent, but has added a 32-hp electric motor without downsizing the engine. Therefore performance levels are much higher than for the nonhybrid version. The figures for the two big trucks (Durango and GM pickup) also look out of line; however, because the base fuel consumption is high, the fuel savings are large. Moreover, the trucks include no other improvements except the hybrid system and engine downsizing. This demonstrates the possible synergies when hybrids are combined with engine and load improvements.

Coming to Market

Recent announcements indicate that manufacturers are considering hybrid systems in a variety of vehicles.

⁴The Environmental Protection Agency discounts the city test by 10 percent and the highway test by 22 percent when calculating fuel economy values, so the combined fuel efficiency based on the label values presented in Table 1 is approximately 15 percent less than the CAFE values in Table 2.

◆ Toyota has designed the compact Corolla and midsize Camry to carry hybrid systems in the future and is investigating minivan and SUV applications (4).

◆ Toyota also has announced production of a hybrid electric minivan for the Japanese market (5).

◆ Honda recently announced a hybrid version of the Civic four-door sedan to be sold in Japan in 2001 and in the United States sometime next year.

◆ Ford plans to put a hybrid system into a 2003 model year Escape, a small SUV (6, 7).

◆ DaimlerChrysler will offer a hybrid in its Durango SUV in 2003 (8).

◆ GM already is selling hybrid bus systems and plans to sell hybrid versions of its full-size pickup truck and a Saturn SUV in 2004 (9).

The use of hybrid systems has no inherent limitations as long as the packaging, weight, and cost issues are managed.

Market Response

Traditionally, customer distrust of a new technology slows market penetration. But sales of the Insight and the public's reaction have surprised Honda. Originally, the company targeted sales of 4,000 Insights in the first year. Instead, production has had to increase to keep up with the surprising demand for a two-seat vehicle priced at \$20,000.

Even more interesting is the publicity—the Insight has generated positive feedback and buzz exceeding expectations. The Prius also has been popular—some buyers report a 3-month wait. With the recent spate of hybrid announcements, the level of interest in and knowledge about hybrids should ensure continued development and introductions by manufacturers.

Hybrids and Fuel Cells

Some experts contend that resources would be better spent on developing fuel cells, probably the most promising long-term fuel option. Hydrogen fuel cells have virtually no emissions and are extremely efficient. Large-scale production of hydrogen would probably use natural gas, which would reduce dependence on fossil fuels. In the longer term, hydrogen may be produced from solar energy or biomass fuels.

However, fuel cell developers still have many problems to solve, such as

- ◆ Reducing cost and size,
- ◆ Improving onboard hydrogen storage density significantly, and
- ◆ Proving durability.

Even if these problems are solved, infrastructure remains a major issue. Fuel cells, therefore, will be a long time in development.

Hybrids can help fill the gap until fuel cells and their infrastructure are ready. Hybrids even may become the preferred technology until nonfossil sources of hydrogen are available, depending on the assumptions for modeling life-cycle greenhouse gas (GHG) emissions and advances in engine technology (2). Hybrids also are a useful hedge if fuel cell development meets an unexpected barrier. Finally, hybrid vehicles can provide a good path to fuel-cell vehicles; fuel-cell systems may incorporate some of the hybrid technologies.

Cost Considerations

The bottom line is that there is only one significant impediment to hybrid systems—cost. Packaging issues—such as finding space for the motor, battery pack, and power electronics—as well as the issues of additional weight, are secondary.

Hybrid systems are not cheap. Manufacturers are reluctant to discuss the cost of hybrid systems, making it difficult to determine a realistic cost. Toyota and Honda do not make money on the Prius or the Insight. The development costs are spread over relatively low sales; these costs also include many technology advances in addition to the hybrid system.

DaimlerChrysler's hybrid Durango will cost about \$3,000 more than the standard model (8) and Ford also expects its hybrid to add about \$3,000 to the price of the Escape (6). Peugeot recently "set a target of making the cost of stepping up to hybrid power no greater than the amount motorists are now prepared to pay for the switch from petrol to diesel" (10).

Also increasing costs are long-term maintenance and replacement issues. One of the reasons Honda put the Insight into production was to gain experience with the in-use durability of the hybrid components. Although it will take a few years to gather these data, the maintenance and repair costs should prove reasonable.

The electric motor and power electronics should be durable, despite concerns based on experience with electric vehicles. Battery deterioration mostly occurs at the lowest 20 percent and the highest 20 percent of the charge. Electric vehicles, which already suffer from limited range, cannot avoid these conditions. The battery on the Insight, by contrast, is controlled to stay in the middle 60 percent range, allowing a much longer battery life—Honda expects the battery on the Insight to last the life of the vehicle. If the battery must be replaced, the cost is still far less than an electric vehicle battery, because the hybrid battery pack is much smaller.

Finally, manufacturers cannot produce hybrid vehicles that require constant replacement of components—consumer expectations of quality and durability would not tolerate this. If initial problems occur, manufacturers will improve the components to meet customer expectations.

Customers' View

But what are customers in the United States and overseas willing to pay in exchange for fuel savings? A critical assumption is that customers discount fuel savings. Most customers in the United States only consider the first four years of fuel savings and heavily discount even these savings. In other words, customers only value the fuel savings for approximately the first 50,000 miles. The same 50,000-mile assumption may apply also to overseas customers, who drive less per year but may value the fuel savings more.

The next assumptions involve the fuel savings, which are calculated from both the baseline fuel economy and the hybrid benefit. The baseline fuel economy is a function of vehicle size, which varies greatly; therefore it is best to produce estimates for several different vehicles.

The hybrid benefit is not as straightforward—the improvements listed in Table 2 range from 15 percent to 196 percent. Most of the vehicles in Table 2 incorporate features in addition to the hybrid system, such as weight and load reduction, engine efficiency improvements, and dieselization. A reasonable value for just the effect of the hybrid system and the corresponding engine size reduction is probably about 30 percent to 40 percent over combined cycles. Table 3 also includes sensitivity cases of 20 percent and 80 percent (for hybrids combined with moderate engine and load improvements).

The final factor is fuel cost. Table 3 lists two cases: \$1.50/gallon (United States) and \$4.00/gallon (Europe and Japan). The formula for calculating the fuel savings in Table 3 is:

$$\left[\frac{50,000 \text{ miles}}{\text{baseline mpg}} - \frac{50,000 \text{ miles}}{\text{base mpg} * (1 + FE \text{ inc})} \right] * \text{fuel cost}$$

where *FE inc* is the fuel economy increase.

Compared with Ford's and DaimlerChrysler's \$3,000 estimated cost increase for hybrid vehicles, the results are sobering. The fuel savings over the full life of the vehicle (approximately three times the values in Table 3), combined with the benefits discussed earlier, would likely justify the cost of hybrid systems from a societal point of view.

However, the typical customer would not want to pay an additional \$3,000 for the hybrid fuel savings, especially in the United States. Japan and

TABLE 3 Customer Value of Hybrid Fuel Savings for the First 50,000 Miles

Fuel economy increase	Fuel cost	Small car (40 mpg)	Midsize car (27 mpg)	Large truck (16 mpg)
20%	\$1.50/gal	\$313	\$463	\$781
	\$4.00/gal	\$833	\$1,235	\$2,083
40%	\$1.50/gal	\$536	\$794	\$1,339
	\$4.00/gal	\$1,429	\$2,116	\$3,571
80%	\$1.50/gal	\$833	\$1,235	\$2,083
	\$4.00/gal	\$2,222	\$3,292	\$5,556

Europe may have a substantial market for hybrids even at \$3,000 in added cost because of the higher fuel prices; a majority of customers probably would be more willing to purchase a hybrid vehicle if the added cost could be reduced to \$1,500 or \$2,000.

In the United States, some customers who drive a lot or who highly value the hybrid vehicle's benefits may be willing to pay the additional \$3,000. Nonetheless, hybrids will not break into the mainstream U.S. market unless the cost comes down or some sort of market assistance or incentive program becomes available.

Looking Ahead

Transition Technology

Fuel cells have great promise, but developers still have many issues that will take a long time to resolve. Hybrids offer a promising transition technology until then, since they can use the current infrastructure, reduce fuel consumption substan-

tially, and reduce emissions modestly. Hybrids can push development of batteries and motors, which will be useful for fuel-cell vehicles, and also can serve as a hedge if fuel-cell vehicles do not perform as planned.

Sales

In the next five to ten years, a gradual increase in hybrid sales in the United States is likely. The breakeven point for a hybrid powertrain system in 2003 is about \$3,000. Although this cost is too high for the U.S. mass market, enough customers will desire the hybrid features to keep the market growing.

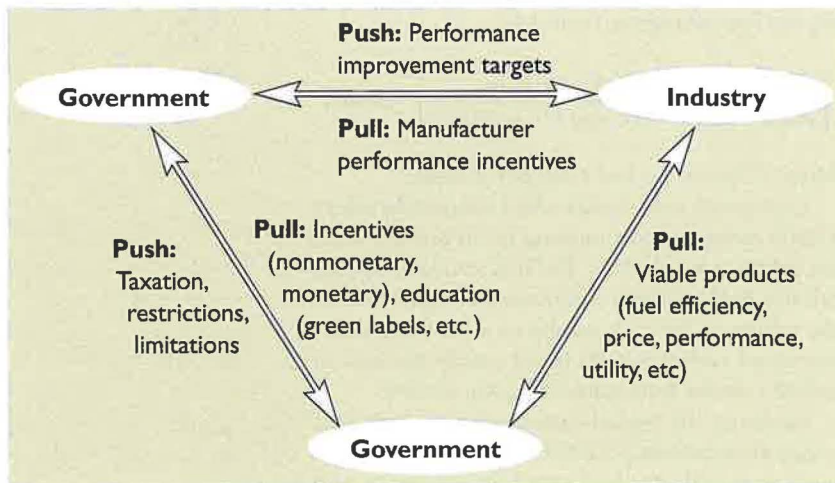
Hybrid sales are likely to increase much faster in Europe and Japan, due to the higher cost of fuel. This will lead to higher volume production and further development, both of which will reduce the cost worldwide. U.S. sales will increase as the cost comes down.

Fuel Efficiency

Forward-thinking manufacturers realize that fuel efficiency must improve. Concerns about global warming are increasing. Crude oil prices eventually will rise as supplies diminish and worldwide demand increases. These pressures will lead to programs to improve fuel economy or reduce GHG emissions. This should include government tax incentives, but it may take the form of fuel economy or CO₂ mandates (such as CAFE). Manufacturers can gain valuable experience by developing, manufacturing, and marketing hybrid vehicles now.

In addition, it is the right thing to do. Some companies believe in responsibility to society and in preservation of the global environment. Honda, for example, is committed to the mitigation of GHG emissions through technology, by developing and offering fuel-efficient products.

FIGURE 9 Push-pull of government-industry-consumer cooperation in increasing fuel economy and reducing emissions.



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