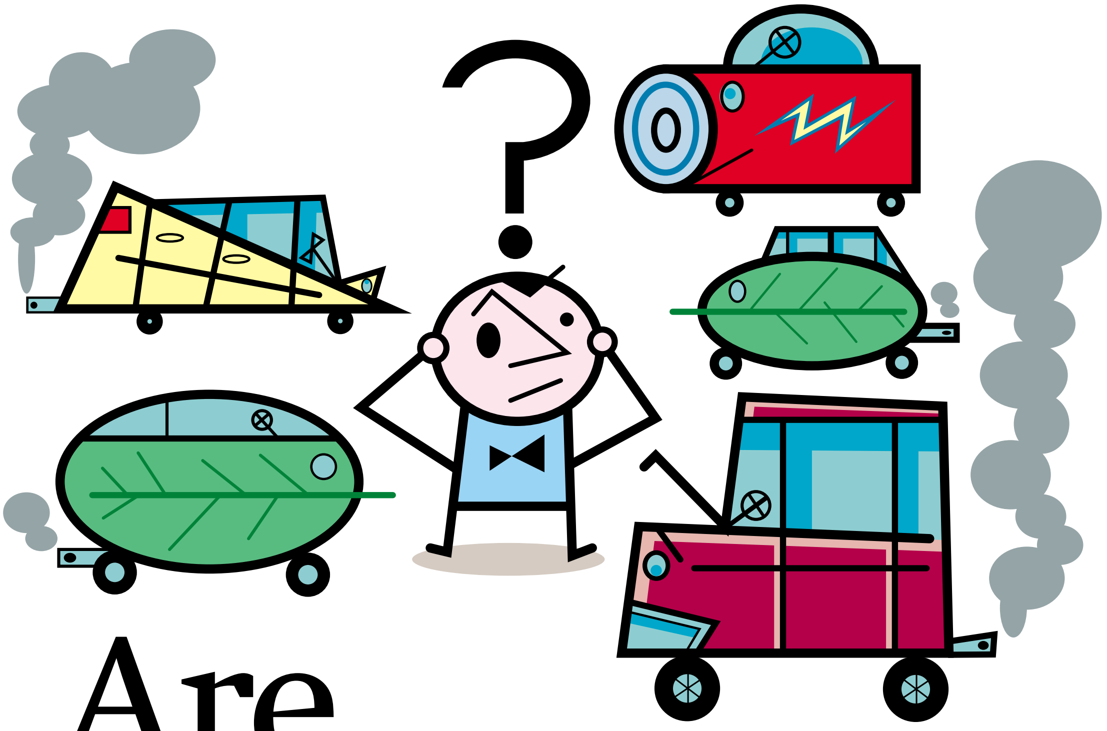

Are Hybrid Vehicles Worth It?

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To a vice president of R&D, a chief financial officer looks like Oscar Wilde's cynic—someone who knows the price of everything and the value of nothing. So it is probably a good thing that those financial officers are not in charge of determining most companies' R&D agendas. If they were, their cost analyses would condemn the majority of projects as unlikely to meet the companies' desired return on investment, and the world might be without such modern marvels as disk drives and cell phones.

Sometimes, however, the bean counters get it right, as with the battery-powered cars built by General Motors Corp., the EV1, and Toyota Corp., the RAV4 EV. Both companies have discontinued manufacturing those "pure electric" (powered by batteries only) vehicles after investing nearly half a billion dollars in R&D and millions more in promotion and subsidies. The cars simply failed to find a market.

Despite superior fuel economy and low emissions, HEVs cost too much at present to make economic sense

In contrast, the direct-injection diesel engine has revolutionized diesel (com-

ILLUSTRATIONS: J.D. KING

Vehicle Attributes and Emissions

			Exhaust emissions[a]									
			Nonmethane organic gases (NMOG), g/km		Carbon monoxide, g/km		Nitrogen oxides, g/km		Carbon dioxide, g/km		Fuel economy, L/100 km[b]	Acceleration from 0–96.6 km/h (0–60 mi/h), seconds
Vehicle	Car class	Curb Weight, kg	Car	TE	Car	TE	Car	TE	Car	TE		
Prius	Compact	1237	0.002	0.033	0.025	0.062	0.001	0.063	112	155	4.8	12.7
Perf-Prius	Compact	1237	0.002	0.039	0.025	0.068	0.001	0.069	125	173	5.4[c]	10.3
Corolla	Compact	1143	0.025	0.068	0.808	0.864	0.124	0.205	157	217	6.8	10.3

Perf-Prius weight and emissions are assumed identical to those of the Prius. Corolla is Toyota Corolla 2001 LE (automatic transmission).

[a] "Car" values are vehicle exhaust (tailpipe) emissions. "TE" values are total emissions—car plus upstream, including fuel cycle emissions from raw material extraction through vehicle refueling. Pollutant emissions of Corolla are from test at 160 900 km; Prius at 193 080 km. All tests made using California Phase 2 reformulated gasoline.

[b] Fuel economy data are EPA label values for combined city/highway driving.

[c] Author calculation based on acceleration/fuel economy adjustment formula from "Trends in Alternate Measures of Vehicle Fuel Economy" by K.H. Hellman, J.D. Murrell, and J.P. Cheng, Society of Automotive Engineers Inc., Paper No. 861426, 1986.

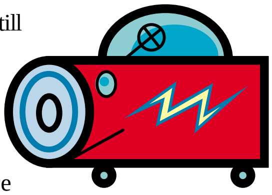
pression-ignition) engine technology, producing solid improvements in efficiency, cold weather starting, and noise reduction.

To invest, or not to invest, that is the question. R&D planning often comes down to discerning whether a new technology will create a revolution or offer only a tiny improvement at too high a cost, wasting time and resources. While this analysis has no magic answer to the general question, it evaluates the outlook for three advanced electric vehicle technologies that are the subject of great hope and large R&D expenditures. The analytic approach provides insights for evaluating a wide class of new technologies so that auto manufacturers can determine the price and performance necessary to appeal to consumers or environmental regulators.

Three approaches

To lower emissions of pollutants and greenhouse gases and to improve the fuel economy of cars, automakers have been working on improving internal combustion engines (ICEs) as well as three electric vehicle (EV) technologies: battery-powered "pure" electric vehicles, hybrid electric vehicles, and vehicles powered by fuel cells.

Manufacturers have achieved steady progress on fuel economy and remarkable progress on emissions using conventional technologies, making it difficult for electric vehicle technology to compete. Battery-powered cars have three inherent limitations, plus the additional handicap of a skimpy charging infrastructure. First, because batteries store much less energy per unit mass than gasoline tanks do, EVs wind up being heavy vehicles with low payloads. Admittedly, electric drives make possible regenerative breaking and "zero" energy use at idle. They are also capable of rapid acceleration, but the General Motors EV1 offered motorists only 65–113 km of driving between charges, compared with the 550–650 km of range of current vehicles powered by ICEs. The EV1 and RAV4 EV cars attracted no more than a few hundred U.S. customers because of their limited range and the several hours required to refuel (charge their batteries). New battery technologies increase the range by about 50 percent, which is a meaningful improvement, but still not enough to put them on a par with conventional vehicles.



This is why the lack of charging infrastructure hurts. The cars' limited range would be mitigated to a considerable extent if owners could be confident of finding a charging station whenever they needed one. However, it would still take much longer to recharge the batteries than to refill a gas tank.

A second issue is cost. The manufacturing cost of these vehicles is perhaps twice that of a conventional ICE vehicle because of lightweight materials, special features, and low production volume. Large-scale production would lower manufacturing costs but increase demand for battery materials. For example, for nickel-metal hydride batteries, the large demand increase for nickel, and especially cerium, would push up prices, perhaps offsetting the manufacturing cost savings.

The environmental impact of the vehicles depends on the source of the electricity generation; for example, a coal-fired plant has much higher emissions than a hydroelectric dam.

Electricity generation in the United States results in large emissions of pollutants and greenhouse gases. The Economic Input-Output Life Cycle Analysis model developed by Carnegie Mellon University researchers (and available at http://www.eiolca.net) calculates these emissions for the current U.S. generation mix. Generating the electricity needed to power an EV one kilometer results in emissions of 0.5–2.2 grams of NO_x, 208–624 grams of CO_2, and 0.7–2.1 grams of SO_2.

The table above shows that a current Corolla emits 0.2 grams of NO_x and 217 grams of CO_2 per kilometer (for the fuel cycle, not just the vehicle). Thus generating the electricity for running an EV produces much more NO_x, more CO_2, much more SO_2, and slightly less CO and nonmethane organic gases (NMOG) than does running an ICE Corolla on gasoline for the same distance.

Of greater importance than the environmental discharges from generating the electricity are the environmental discharges from mining and smelting the battery metals and manufacturing and recycling the batteries. These activities put large quantities of heavy metals into the environment [see To Probe Further].

In the authors' judgment, these battery-powered cars lower environmental quality. They should not be required, or even encouraged, by regulators. Thus, aside from particular niche markets, battery-powered cars will not, and should not, have substantial sales unless a major advance in electrochemistry occurs using battery materials that are less toxic than lead, cadmium, and nickel, together with a major advance in lowering pollution emissions from generating electricity.

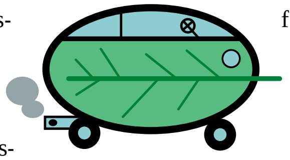
Hybrid-electric vehicles

Hybrid-electric vehicles (HEVs), such as the Toyota Prius, are a marvel of new technology that offer improvements in fuel economy and emissions—of both pollutants and greenhouse gases. Some transportation experts predict that this technology will claim a key share of U.S. light-duty vehicle sales.

To see whether the predictions make sound economic sense, the Prius is here evaluated in terms of lifetime private and social costs, comparing it with an almost identically sized conventional Toyota Corolla. Assumptions include a lifetime of 250 000 km and 14 years for both vehicles. The evaluation includes upstream fuel cycle emissions.

The costs to the vehicle owner include the price of the vehicle plus its lifetime fuel and maintenance costs. Social costs include those for pollutants—NMOGs, nitrogen oxides (NO_X), and carbon monoxide (CO)—and for carbon dioxide (CO_2) emissions. The price of the U.S. Prius is US $19 995 (not including transportation), $3495 more than the cost of a comparable 2001 Model Year Corolla LE (with automatic transmission). In the authors' judgment, the more complicated Prius is unlikely to be cheaper to maintain than the Corolla; the analysis assumes equal cost.

Toyota predicts that the Prius's battery will last the lifetime of the vehicle. The analysis, therefore, assumes that no battery replacements will be required over the 250 000-km vehicle lifetime. Note, however, that the batteries have a warranty for just 160 000 km.



Toyota tested the emissions of the U.S. Prius and a Corolla LE [see table at top of opposite page]. The table shows the characteristics of those two cars as well as a hypothetical car called the "Perf-Prius."

The reason for the hypothetical car is that the Prius is not really comparable to the Corolla LE because of its sluggish acceleration (its time to accelerate from zero to 96.6 km/h (60.0 mi/h) is 12.7 seconds). To compare the Corolla with an equivalent hybrid, fuel-economy data was calculated for an imagined high-performance version of the Prius with acceleration comparable to that of the Corolla. The Perf-Prius is assumed to have the same pollutant emissions as the Prius.

The fuel economy adjustment was derived for conventional ICE-powered cars and so might not be accurate for the Prius. However, a sensitivity analysis shows that inaccuracies in the adjustment would not change the conclusions reached in the analysis that follows.

Since the cars are assumed to last 14 years, an interest rate is needed in order to make costs incurred in year 14 comparable to those incurred in year zero. A 6 percent per year interest rate is used to bring future fuel costs and the social value of tailpipe emissions back to when the car was new. For greenhouse gas emissions, a zero discount rate is used since the effects of global warming are in the future and the gases stay in the atmosphere for centuries.

At a gasoline price of $0.40/liter, the Perf-Prius would use $932 less fuel than the Corolla, a savings that is much smaller than the vehicle's $3495 price premium.

The cost of pollution

The social value of abating emissions of air pollutants has been estimated by regulatory commissions in California, Massachusetts, Nevada, and New York [see table below]. The table shows the median and highest social valuations from these state evaluations as well as published research studies. According to the table data, the reduction in pollutant emissions of the Prius is worth $328 at the median valuation and $639 at the highest valuation. Adding these emissions benefits to the fuel savings still results in savings much lower than the difference in the purchase prices.

How much would gasoline have to cost to justify the difference in price between the Prius and the Corolla? Alternatively, by what factor would the value

Valuation of Difference in Emissions Between Perf-Prius and Corolla

	Median valuation, in US dollars			Highest valuation		
Pollutant	per metric ton	per vehicle lifetime, 0%[a]	per vehicle lifetime, 6%[b]	per metric ton	per vehicle lifetime, 0%[a]	per vehicle lifetime, 6%[b]
NMOG[c]	1400	10	7	4400	32	22
CO[d]	1050	209	142	1050	209	142
NO_X[e]	1060	36	25	9500	323	221
Partial total	–	255	174	–	564	385
CO_2[f]	14	154	154	23	254	254
Total	**-**	**409**	**328**	**-**	**818**	**639**

Source: "Applications of Environmental Valuation for Determining Externality Costs," by H.S. Mathews and L.B. Lave, *Environmental Science and Technology,* 2000, Vol. 34, pp. 1390–95.

[a] Social cost difference corresponding to lifetime vehicle and upstream emissions savings with no discount rate. [b] Social cost difference corresponding to lifetime vehicle and upstream emissions savings applying a discount rate of 6% per year [see text]. [c] NMOG = non-methane organic gases (assumed same as for hydrocarbons because of the similarity of the compounds involved). [d] CO = carbon monoxide [e] NO_x = nitrogen oxides [f] CO_2 = carbon dioxide (not discounted, see text)

Achieving Cost Equivalence with a Corolla

Hybrid Vehicle	Perf-Prius	Prius	Comments
Gasoline price per liter	\$1.35	\$0.94	–
Emissions multiplier	14	11	This number is the factor by which the median social cost valuations of NMOG, NO_x, and CO emissions would have to be multiplied to equate the HEV and Corolla lifetime costs.
Value of CO_2 abatement per metric ton	\$217	\$129	This is the required valuation of CO_2 abatement to equate the HEV and Corolla lifetime costs.
Incremental value of HEV	\$1260	\$1704	This is the price premium of the HEV over the Corolla justified by the higher fuel economy and lower emissions of the HEV, assuming that the owner pays \$0.40 per liter for gasoline and the median value for emissions.

Table entries are the gasoline price, the emissions multiplier, or the valuation of CO_2 abatement required to equate the lifetime (250 000 km) cost of the cited hybrid EVs with that of a Corolla, given that the HEV costs \$3495 more than the Corolla. It is assumed that the owner must pay the median price in the preceding table for the pollutant and CO_2 emissions. A discount rate of 6% per year is also assumed. Lifetime maintenance costs for all vehicles are assumed to be the same.

of emissions abatement have to be increased to achieve the same end? The table above has the answers. Values in the table hold all other parameters constant—for example, the gasoline prices reported in the first row correspond to the price required to equate lifetime vehicle costs if the pollutant and CO_2 social valuations are held constant at their median levels. Alternatively, the median social valuation of pollutant emissions would have to be increased by the factors shown in the second row if the price of gasoline is fixed at today's level.

The second column of the table, which pertains to the Perf-Prius, shows that a gasoline price of \$1.35 per liter (\$5.10 per gallon) would be required to offset the \$3495 initial price difference between the Perf-Prius and the Corolla LE.

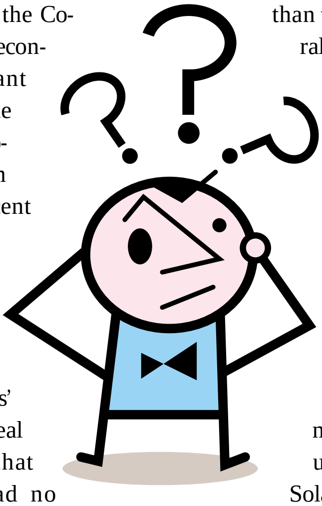
Data on the current Prius is shown in the third column. If buyers place no additional value on the higher performance of the Corolla, the taxes on gasoline in Europe and Japan are high enough to lead buyers to prefer the Prius over the Corolla—assuming that they actually pay \$328 for the Corolla's emissions.

The last row of the table above shows the maximum price premium society would be willing to pay for an HEV, given a price of \$1.50 per gallon for gasoline and the median values for air pollutant and CO_2emissions. Compared with a Corolla, the value of a Prius is \$1704 greater while the hypothetical Perf-Prius is \$1260 greater. Thus neither hybrid is worth even half the price premium over a Corolla.

In effect, the current Prius is more costly than the fuel savings and lower emissions of air pollutants and CO_2 would justify in the United States. Any HEV will have a difficult time competing with the Corolla because of the Corolla's already high fuel economy and low pollutant emissions. The private and social costs of a Corolla over a 250 000-km lifetime using a 6 percent discount rate amount to \$4573 for fuel, \$208 for pollutant emissions, and \$760 for CO_2 emissions.

Based on the authors' current analyses, an ideal hypothetical vehicle that used no fuel and had no emissions could justify a price premium over the Corolla of no more than \$5540. In practice, of course, a real HEV can improve fuel economy and emissions by only a fraction of this amount.

HEVs are unlikely to sell themselves in terms of fuel economy and lower emissions alone. Rather, they will have to attract buyers by offering features that are not available on conventional vehicles—applications requiring a large electricity supply, for example. Subsidizing HEVs or mandating their sales would not be in the public interest unless regulators value petroleum and emissions abatement much more highly than they do at present.



Fuel cell vehicles

A hydrogen fuel cell vehicle fueled with gasoline or methanol would look like a hybrid with the ICE replaced by a fuel reformer. Even after progressing down the learning curve and accounting for economies of large-scale production, this advanced electric vehicle seems unlikely to be able to compete with a Corolla.

While a hydrogen-powered fuel cell vehicle needs no reformer, it has several big obstacles to overcome. One is storage of hydrogen aboard the vehicle. Sufficient hydrogen needs to be stored to give a 400–500-km range. While this volume of storage space is available in a city bus, passenger cars have limited room.

Another problem is extracting the hydrogen. Hydrogen is an energy carrier, not an energy source. It is most cheaply obtained from natural gas, which could be burned directly in an ICE. It seems doubtful that a hydrogen-powered fuel cell would have system efficiency greater than that of an ICE burning natural gas.

Alternatively, the hydrogen could be generated by electrolysis of water using electricity generated by coal, natural gas, or solar energy. If coal were used, the associated environmental problems would be large. It makes no sense to use natural gas to generate electricity to make hydrogen rather than using the natural gas directly. Solar electricity would have to compete with the option of producing ethanol from biomass for use in ICEs.

No one can state with confidence what propulsion technology and fuel will be used in personal transportation vehicles 25 years from now. But significant technological breakthroughs will be needed before advanced electric vehicles can reasonably be expected to dominate. ●

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Michael J. Riezenman, *Editor*