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HYBRID VEHICLES GAIN TRACTION

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As car buyers turn to fuel-sipping gasoline-electric hybrid vehicles, a new generation of greener hybrids is just coming over the horizon

When gasoline prices climbed to $3 a gallon last summer, hybrid vehicles--which combine a conventional engine and a battery-powered electric motor to achieve improved fuel economy and performance--began racing out of showrooms. Whereas the average U.S. car goes about 23 miles on a gallon of gas, a full-fledged hybrid car such as a Toyota Prius travels about twice as far on the same amount, depending on how it is driven. Annual U.S. sales of hybrids from 2004 to 2005 doubled to 200,000 and are expected to swell to more than half a million by 2010. By 2020 most new car models ought to offer a hybrid power-train option.

By then, next-generation technology, called plug-in hybrids, will offer motorists still better fuel efficiency as well as other perks: low-cost battery recharging overnight by simply connecting a 120-volt plug to an electrical outlet at home or work, very few trips to the gas station each year, and even the chance to sell surplus power back to the electric grid. Beyond the consumer benefits, the new plug-ins would help reduce the release of greenhouse gases by displacing emissions from millions of tailpipes to utility power plants. Today these facilities burn domestically supplied coal or natural gas, and in the future they should generate cleaner electricity from energy sources such as wind, solar or even advanced fossil fuel-based systems that capture carbon dioxide for underground storage.

To see where the hybrid vehicle is going, one needs to look back to where the automobile has been. For 100 years, nearly every car has been powered by an internal-combustion engine running on gasoline or diesel fuel. Automotive engineers pursued the idea of matching an engine and a battery-powered electric motor to achieve greater horsepower and better fuel economy early in the 20th century but abandoned the concept as engines grew ever more potent and thus needed no boost. Fuel was cheap and widely available, so a gas-hungry power plant was no real problem. By the oil crises of the 1970s, common wisdom among drivers held that to get good gas mileage one had to sacrifice size, weight and performance. Although downsizing came into brief vogue, cars soon grew bigger and their appetite for gasoline expanded apace. When oil prices started their recent ascent, better fuel economy once again became a highly desirable feature.

Today's hybrids marry advanced power electronics and computer controls with conventional and electric drivetrains to achieve improved fuel economy and reduced emissions, together with superior acceleration and greater range. A hybrid vehicle can get by with a smaller internal-combustion engine than a conventional automobile because the battery and electric-motor system provides additional power when it is needed for acceleration or hill-climbing maneuvers.

Any technology that can raise fuel economy can be used instead to increase horsepower. So far hybrid drivetrains provide enough efficiency improvement and their electric motors develop such high acceleration that automakers have used the technology to raise both horsepower and fuel economy simultaneously. The Ford Escape Hybrid, for instance, gets significantly better mileage with almost the same power output. Others, such as the Toyota Highlander Hybrid 4x4 sport utility vehicle, exploit hybrid systems to achieve moderate increases in both categories.

The extra expense of the large battery and motor and the associated power electronics means that a hybrid inevitably costs more than a regular car. The premiums for current hybrids range from $3,000 to $7,000, with $4,000 being the average. The electric-motor and battery package adds a weight penalty: about 5 percent in Honda's Accord Hybrid, for example. This extra burden cuts fuel efficiency slightly.

For a vehicle traveling 15,000 miles a year burning gasoline priced at $2.50 a gallon, hybrid technology that raises mileage from 20 to 30 miles a gallon can save the consumer around $600 a year. Thus, at present hybrid prices, together with the newly enhanced federal tax credit for hybrids, payback can take several years, assuming that one assigns no value to benefits such as increased range.

As fuel prices mount, however, hybrid efficiency will cut payback times substantially. Meanwhile rising manufacturing levels and improved battery technology are expected to lower production costs. From 1997 to 2004, for example, the price tag for the nickel metal hydride batteries used in hybrids dropped by half, as did their weight. Even so, the batteries still represent more than 50 percent of the extra cost of today's hybrids. Toyota alone plans to offer hybrid versions of almost all its models and sell a million hybrid vehicles a year worldwide during the next decade, efforts that will spur production volumes and an associated fall in costs.

Hybrid Types

HYBRID DESIGNS come in several flavors, depending on the degree of fuel economy that engineers want to achieve. A "full" hybrid takes advantage of multiple techniques to modest efficiency improvement.

A full hybrid, such as the Toyota Prius, can provide a fuel-economy improvement of 60 percent or more. The biggest fuel savings achieved by a full hybrid vehicle derives from regenerative braking, a technology that captures as electrical power much of the energy normally lost as frictional heat. Just as a motor can transform electrical energy stored in a battery into torque (the force that produces wheel rotation and hauling power), the process can run in reverse so that the torque created by slowing a moving car generates electricity that can be accumulated in a battery.

Stop-and-go city driving offers the greatest opportunity for braking energy regeneration, but the process also transpires while riding up and down hilly country. Today's hybrid vehicles collect on average about half the total braking energy. In the future, better batteries and more sophisticated systems will enable cars to collect even more of the available energy.

Like all engines, internal-combustion power plants run most efficiently in a narrow range of torque and speeds. Because a hybrid's battery and motor can provide the boost required for acceleration or hill climbing, engineers can both downsize the car's engine and optimize it to run only at high-efficiency operating points that burn much less gas. The vehicle can then electronically engage the electric motor to kick in the extra power when needed.

Some makers of full hybrids, such as Toyota and Ford, have replaced the standard Otto cycle engine used in most gasoline-powered cars with a more fuel-thrifty configuration based on the Atkinson cycle. A modern Atkinson cycle engine uses electronic controls and intake-valve timing to achieve greater expansion of the fuel/air mixture burning in the cylinder, thereby allowing the power plant to make more efficient use of the fuel. Engineers had only rarely used the Atkinson cycle before because its greater fuel economy comes at the expense of power output; however, in a hybrid, the electric motor can make up for the lost power. In highway driving, the Atkinson engine, combined with the energy savings from braking regeneration, can yield an overall hybrid system efficiency better than that of the modern diesel engine--the leading internal-combustion engine in this regard.

Hybrid vehicles call avoid yet another inefficiency of conventional car designs, which typically run the air-conditioning, power steering, water, oil pump, fan and other power-sapping systems directly off the gasoline engine. The large hybrid battery combines with new low-cost power electronics to run these fully electric, high-efficiency components. On a hot summer day, an electrically powered air-conditioning unit can consume 20 percent Jess energy than an engine-driven system.

Another major fuel-economy advantage in a full hybrid stems from its ability to use its electric motor and batteries to power the vehicle without the engine. Thus, fuel can be saved by running the car as an electric vehicle when the engine would otherwise be burning fuel while idling or traveling at low speeds.

Mild hybrid power trains, such as the integrated motor-assist system in Honda's Insight, Civic and new Accord models, provide up to a 35 percent fuel: economy gain. In addition to the start-stop function, the electric motor in a mild hybrid gives the engine a boost during acceleration and captures some braking energy.

In a micro hybrid or a start-stop hybrid, such as those being introduced by General Motors, the engine shuts down when the car comes to a halt, and an integrated starter-generator fires up the engine instantly when the driver steps on the gas pedal. This kind of vehicle, which uses electric motors to drive the accessories but not the wheels, produces a 10 percent efficiency improvement in city driving but little gain on the highway.

Plug-In Hybrids Rule

HYBRIDS OFFER one benefit that will most likely become more valuable with time; their more efficient use of gasoline results in lower emissions of carbon dioxide, the primary greenhouse gas. Future federal transportation policy may well be driven by concerns about climate change. Many industrial countries have already tightened fuel-economy standards to reduce the release of carbon dioxide. In the U.S., California passed legislation in 2002 to cut the vehicular emissions of greenhouse gases 30 percent by model year 2016, and a group of other states have followed suit (although car makers are challenging the effort in court).

Plug-in hybrid electric vehicles combine the best of electric and hybrid-drive technologies. They can be fully functional in either electric or hybrid mode and make possible even larger emissions and oil savings. These vehicles run partly on electricity generated at local power plants, which can lessen the nation's reliance on oil, while offering utilities a robust market for their off-peak power and drivers a cleaner, much lower-cost transportation fuel option. And like the straight hybrid, the plug-in can burn liquid fuel to afford a long driving range with rapid refueling. What is more, these plug-in hybrids should not be much more complex, heavy or pricey than present hybrid models. First, their internal-combustion engines will shrink as their electric motors and batteries grow. Second, batteries and electronic components have been steadily dropping in price.

A conventional auto costs about 12 cents a mile to operate at current gasoline prices. A plug-in hybrid could run on electrons at three cents a mile using electricity costing about eight cents a kilowatt-hour, the current average residential rate. And given that half of American cars travel only 25 miles a day or less, a plug-in with a battery capable of providing power for a 20 mile range could cut petroleum-based fuel consumption by as much as 60 percent. Even a long-distance commuter driving a plug-in hybrid could go most of a typical day on less expensive electricity stored in an advanced battery that was topped up overnight via a conventional wall socket and partially recharged at work during the day.

The larger battery of a plug-in hybrid, coupled with a higher-powered electric motor, allows significant downsizing of the gasoline engine and other related mechanical systems. Researchers at the University of California, Davis, have built plug-in hybrid prototypes that can travel 60 miles on electricity alone with engines that are less than half the size of standard engines. Their eight sedans and full-size SUVs are now undergoing testing. In 2005 DaimlerChrysler brought out the first plug-in hybrid prototype vehicles built by a major automaker, a hybrid version of its Mercedes-Benz Sprinter Van. The modified Sprinter features a 143-horsepower combustion engine and a 120-horsepower electric motor, it can travel 20 miles in all-electric mode and has 40 percent lower gasoline consumption and better acceleration than a conventional Sprinter Van. Only a few such plug-in hybrid Sprinters have been operated to date.

As battery technology advances, engineers should be able to develop plug-in hybrids that consume far less gasoline than conventional vehicles. Urban driving range when operating; on a single tank of gasoline and a full battery charge could be from 600 to 1,000 miles. The actual size of the different power systems in each car will depend on the driving needs of the car buyer. Long-distance commuters might purchase a plug-in with a bigger battery, for instance, although we expect that a 20-mile all-electric range will satisfy most consumers.

The lower fuel bills for a plug-in hybrid would offset its higher price, assuming that steady progress in battery technology continues and costs drop. Extended-range electrochemical batteries currently run as much as $10,000 apiece. We believe nickel metal hydride or lithium ion batteries with affordable price tags of $3,000 or less will eventually provide enough energy for ranges of 20 miles or more. In time, engineers are expected to extend the operational lifetimes of these batteries to more than 15 years and 150,000 miles.

With modified internal-combustion engines, plug-in hybrids could also run on a mixture of 15 percent gasoline and 85 percent biofuel, such as cellulosic ethanol (from non-corn sources such as agricultural waste and dedicated energy crops). These kinds of vehicles could travel 500 miles on one gallon of gasoline blended with five gallons of ethanol and thus constitute a long-term strategy for dealing with the inevitable peak and subsequent decline in world oil supplies.

Plug-in hybrids offer other unique benefits. Because they can connect to the grid, they can take advantage of off-peak power rates that are far lower than typical residential ones. Utilities have excess power capacity, especially at night, because the peak load comes from summer air-conditioning. Plug-in hybrids could charge up at night and feed voltage-regulation services or electric power back to the grid at peak power times during the day. Vehicle owners may be able to get a rebate or revenue stream from electric utilities for this service. According to researchers at the University of Delaware, the potential value of such services is significant, as much as $3,000 annually, which could subsidize the cost of purchasing a plug-in hybrid or its battery. One can speculate that a utility might lease a plug-in hybrid to a consumer or business willing to leave the vehicle connected when it was not on the road and to permit the utility to control when the vehicle's battery was charged and discharged depending on its generation or voltage-regulation needs. Such an arrangement would help utilities with load balancing, for instance.

For policymakers concerned about global warming, plug-in hybrids hold an edge over another highly touted green vehicle technology--hydrogen fuel-cell cars. Plug-ins would be better at utilizing zero-carbon electricity because the overall hydrogen fueling process is inherently costly and inefficient. Any effective hydrogen economy would require an infrastructure that could use zero-carbon power to electrolyze water into hydrogen, convey this highly diffuse gas long distances, and pump it at high pressure into the car--all for the purpose of converting the hydrogen back to electricity in a fuel cell to drive an electric motor. The entire process of electrolysis, transportation, pumping and fuel-cell conversion would leave only about 20 to 25 percent of the original zero-carbon electricity to drive the motor. In a plug-in hybrid, the process of electricity transmission, charging an onboard battery and discharging that battery would leave 75 to 80 percent of the original electricity to drive the motor. Thus, a plug-in should be able to travel three to four times farther on a kilowatt-hour of renewable electricity than a hydrogen fuel-cell vehicle could.

If current trends in fuel costs and concerns about climate change continue, we expect a broad market transition around the year 2020, when hybrids are likely to become an option for most models. Relatively soon thereafter, we believe plug-in hybrids will probably become the dominant alternative-fuel vehicle, with the speed of that progress determined primarily by oil price rises and government policy on climate change and energy security. Whenever the world's transportation system finally moves to replace oil as its main power source, the most plausible car design would be a flexible-fuel, plug-in hybrid vehicle running on a combination of zero-carbon electricity and a biofuel blend. If the performance of batteries were to improve substantially at some point, drivers might then gradually switch to all-electric cars. It makes sense for us to adopt this highly practical personal transportation technology as expeditiously as possible.

Overview/Hybrid Vehicles

• A Small but growing number of hybrid cars and trucks combine electric motors with conventional petroleum burning engines to reduce fuel consumption. The technology is now starting to evolve rapidly.

• Hybrid power trains currently add several thousand dollars to a vehicle's price tag; owners must operate the vehicle for a few gears to gain back their additional initial investment in savings from the lower fuel costs. But as battery technology improves and manufacturing production volumes rise, the premiums for hybrid vehicles are expected to drop significantly.

• Better batteries should also spur the commercialization of plug-in hybrid vehicles, which can recharge overnight via the electric grid to take advantage of lower, off-peak rates. Because power plants generate electricity overwhelmingly from domestic sources such as coal, nuclear energy and hydropower, the shift would reduce reliance on foreign oil imports for transportation.

HOW HYBRIDS GET GREEN

Engineers employ several strategies to save energy in hybrid electric vehicles, which combine a gasoline engine and an electric motor. Here is a breakdown for "full" hybrids, such as the Toyota Prius, which employ all these techniques. Full hybrids can achieve fuel-economy savings of GO percent or more, whereas mild hybrids get up to 35 percent savings and micro hybrids about 10 percent.

USE ENERGY-SAVING ELECTRICAL COMPONENTS

In conventional cars, the air-conditioning, power steering, water and oil pumps, and fans draw mechanical power directly from the engine's rotating parts via belts. Yet such electric components run best at a fixed battery voltage--whereas the mechanical systems must adapt to widely varying engine speeds. The hybrid's larger battery lets it supply these components directly, thereby saving energy.

DESIGN ENGINE TO SHUT DOWN AT STOPS

Conventional engines run inefficiently when idling at stoplights or working under light loads. Hybrids trim the losses by shutting the engine off, leaving the electric motor and battery to power the vehicle.

CAPTURE WASTE ENERGY

A large part of the fuel savings comes from regenerative braking, which reclaims some of the energy that would otherwise be lost as frictional heat when the vehicle is slowing. Essentially the electric motor runs in reverse, as a generator, converting the energy of wheel rotation into electricity for the battery.

SWITCH ENGINE TYPE

Some car makers replace the conventional Otto cycle gasoline engine with the Atkinson cycle, which burns Fuel much more efficiently but has not been widely used because of its lower power production. The hybrid's electric motor makes up for the lost brawn.

REDUCE ENGINE SIZE

Engines run best at a few high-efficiency speeds and torque levels, but standard cars must operate over a wide range of power outputs in everyday driving. The ability of the electric motor to boost vehicle power during acceleration or uphill climbs allows hybrid designers to downsize engines.

IN THE FUTURE: PLUG-IN POWER

In a next-generation hybrid design, the addition of a larger battery plus an electrical cable with an outlet plug would let the vehicle recharge overnight, when utilities produce cheaper, off-peak power. More than half of a typical American's driving needs could thus be accomplished on less costly (and increasingly cleaner) centrally generated electricity alone.

[2006 Hybrid Model Lineup](#)

An array of cars, sport utility vehicles and pickups now on dealership floors offer hybrid electric systems. Some get very good fuel economy; others trade some savings for performance, and still others offer little mileage benefit at all. Estimates are based on a 45 percent highway, 55 percent city driving cycle, 15,000 annual miles, and $2.50 a gallon for regular gasoline.

Legend:
A: MAKE, MODEL AND TYPE
B: POWER TRAIN
C: COMBINED MPG
D: RANGE
E: ANNUAL FUEL COST
F: ANNUAL CO₂ EMISSIONS

A B	C	D	E	F
HONDA INSIGHT: TWO-SEATER 3-cylinder, 1.0-liter engine with automatic continuously variable transmission (CVT)	56	530 miles	$670	3.5 tons
HONDA CIVIC HYBRID: COMPACT CAR 4-cylinder, 1.3-liter engine with automatic CVT	50	550 miles	$750	3.9 tons
TOYOTA PRIUS: MIDSIZE CAR 4-cylinder, 1.3-liter engine with automatic CVT	55	590 miles	$680	3.5 tons
HONDA ACCORD HYBRID: MIDSIZE CAR 6-cylinder, 3.0 liter engine with automatic transmission	28	430 miles	$1,340	6.8 tons
FORD ESCAPE HYBRID: SPORT UTILITY VEHICLE 4-cylinder, 2.3-liter engine with CVT transmission, 4-wheel drive (4WD)	31	420 miles	$1,210	6.2 tons
SPORT UTILITY VEHICLE 6-cylinder, 3.3 liter engine with automatic	29	450 miles	$1,290	6.6 tons

CVT, 4WD				
MERCURY MARINER HYBRID: SPORT UTILITY VEHICLE 4-cylinder, 2.3-liter engine with automatic CVT, 4WD	31	420 miles	$1,210	6.2 tons
TOYOTA HIGHLANDER HYBRID: SPORT UTILITY VEHICLE 6-cylinder, 3.3-liter engine with automatic CVT; 4WD	29	500 miles	$1,290	6.6 tons
CHEVROLET SILVERADO HYBRID: PICKUP TRUCK 8-cylinder, 5.3-liter engine with automatic transmission, 4WD	19	450 miles	$1,970	9.9 tons
GMC SIERRA HYBRID: PICKUP TRUCK 8-cylinder, 5.3-liter engine with automatic transmission, 4WD	19	450 miles	$1,970	9.9 tons

These calculations are based on EPA mileage ratings. Actual Fuel-economy numbers may be somewhat lower

Hybrids in the Real World

Some car buyers have been disappointed because their hybrid vehicles have failed to achieve the lofty mileage promised by the U.S. Environmental Protection Agency ratings. Like most cars, hybrids often post mileage results significant y lower than their EPA rating. Several factors explain the shortfall. (The EPA announced revisions to its testing procedure earlier this year that should address some of these problems.)

Flawed EPA testing procedures. The driving cycle used during the government mileage tests does not reflect actual experience or road conditions, because it is based on unrealistic assumptions about typical driving practices. The test's top highway speed is 60 miles an hour, for example, whereas the average driver often exceeds that velocity.

Larger seasonal mileage drops. In hybrids such as the Toyota Prius, computer software decides when to run the engine, when to run the electric motor and when to recharge the battery.

Owners of hybrids in northern climes inevitably see a sharp fall in fuel economy compared with the EPA rating, which is measured at temperatures ranging from 68 to 86 degrees Fahrenheit.

Inherent hybrid design. Because hybrids rely on regenerative braking systems, their mileage is much more sensitive to how ' they are driven. Motorists who optimize their driving for hybrids--by coasting to stops, for instance-report fuel-economy figures close to the EPA ratings. Aggressive driving can cause the fuel efficiency of hybrid vehicles to decrease more than 30 percent, whereas such driving has a much smaller impact on conventional vehicles. In general, full hybrids get the best mileage in stop-and-go traffic and offer fewer benefits on the highway.

MORE TO EXPLORE

The Car and Fuel of the Future. Joseph Romm. Report for the National Commission on Energy Policy, 2004. Available at www.energyandclimate.org

Driving the Solution: The Plug-In Hybrid Vehicle. Lucy Sanna in EPRI Journal; Fall 2005. Available at mydocs.epri.com/docs/CorporateDocuments/EPRl_Journal/2005-Fall/1012885_PHEV.pdf

To learn more about plug-ins, visit www.calcars.org

To learn more about hybrids, visit www.hybridcars.com

Andrew A. Frank's technical articles on plug-ins can be found at www.team-fate.net

DIAGRAM: HOW HYBRIDS GET GREEN

PHOTO (COLOR): PLUG-IN HYBRID'S use of gasoline and electricity will minimize overall emissions of carbon dioxide by vehicles in the future, especially as utility power generation grows greener

PHOTO (COLOR): DIESEL-ELECTRIC HYBRIDS, such as this Ford Reflex concept car, can achieve even better mileage than gasoline-electric vehicles. The Reflex prototype is expected to deliver up to 65 miles per gallon of diesel fuel and also features solar panels in the headlights and taillights to generate auxiliary power for the battery

PHOTO (COLOR): PLUG-IN HYBRID TECHNOLOGY from a major automaker debuted in 2005 with the rollout of the Mercedes-Benz Hybrid Sprinter Van prototype.

PHOTO (COLOR): A door opens to reveal the electrical socket for connecting the battery to a power source and charging it overnight

PHOTO (BLACK & WHITE): STICKER SHOCK: New gasoline-electric hybrid vehicles can fall short of the fuel-economy levels promised by EPA test ratings. The authors explain why.

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By Joseph J. Romm and Andrew A. Frank

JOSEPH J. ROMM and ANDREW A. FRANK have advocated the adoption of hybrid vehicle technology for many years. Romm, who received his doctorate in physics from the Massachusetts Institute of Technology, is a principal with Capital E, a clean-energy consulting firm. His latest book is The Hype about Hydrogen: Fact and Fiction in the Race to Save the Climate (Island Press, 2004). As an acting assistant secretary of the U.S. Department of Energy in the late 1990s, Romm helped to manage the agency's efforts to develop and use advanced energy technology. Frank earned a Ph.D. from the University of Southern California. He was professor of electrical engineering at the University of Wisconsin-Madison for 18 years and is now professor of mechanical and aeronautical engineering at the University of California, Davis. His research interests include the engineering of advanced hybrid vehicles, including plug-ins.

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