

## **Plug-in hybrid**

### Why Hybrid Vehicles?

The coming decline in oil supplies, as well as concerns about global warming, demand vehicles that use much less gasoline or diesel than conventional vehicles. Plug-in hybrids can be powered either by an internal combustion engine or by batteries feeding electric motors. The batteries can be charged either by the engine, when the vehicle is moving, or by an external electrical source when it is parked. Since most trips are shorter than the electric-only range of proposed hybrids, the gasoline engine would be used relatively rarely. The technology is an interim solution, between the historically plentiful supply of fossil fuels and the future when oil will become increasingly scarce, expensive, and eventually unavailable. At that point electric power for charging vehicles will have to come from renewable sources.

Automobiles have been mass-produced for about a century, since Henry Ford's Model T appeared in 1908. At that time gasoline, steam, and electric vehicles were on the roads, but eventually the gasoline internal combustion engine displaced all of its competitors. The engines were compact and powerful, the vehicles had a long range because of the high energy density of gasoline, and the fuel became inexpensive and widely available.

The era of inexpensive fossil fuels is coming to an end, however. After over a century of ever-increasing consumption of oil, the world is pumping 85 million barrels from the ground every day, about 1000 barrels per second, a rate that cannot be sustained much longer. The world has already extracted about half of the recoverable oil that was originally in the ground, an energy source that ultimately came from decay of animals and plants over millions of years. Plentiful fossil fuels have enabled the earth's population to quadruple during the last century, something that has never happened before and will never happen again. Those people depend on vast supplies of fossil fuels because highly mechanized and productive modern farming, transportation and industry require those fuels. The earth is of finite size, though, and it has been pretty well explored for oil already. All of the major oil fields are in decline, but new ones are not being discovered fast enough to make up for the losses. The coming decline will be faster than the rise because the population, and therefore the demand, is so much larger. The amount of oil will decline every year until it is no longer practical to burn it as a vehicle fuel. Global warming demands that the world reduce its fossil fuel use in any case, to reduce the amount of the greenhouse gas carbon dioxide released into the atmosphere.

In this situation it is imperative that more efficient modes of transportation be developed. For the short term of a few years to a decade or so the transportation infrastructure will not change very much, because replacing the fleet of 230 million vehicles takes about 20 years. America is saddled with an infrastructure that demands huge amounts of transportation – sprawling low-density cities with widely dispersed centers of employment. Sustainable alternatives such as rebuilding cities to be compact and walkable, together with electric mass transit powered by renewable sources, are decades in the future. In the meantime, conserving the fossil fuel supply is the only alternative, and this is where more efficient vehicles come in. Conventional internal combustion engines are very inefficient, converting only about 20% of their fuel's energy

into motive power. Then they are used in vehicles that are usually only 20% occupied. Diesels provide better economy because of their superior thermodynamics, but they are more expensive to manufacture and the majority of the energy that goes into them is still lost as heat.

It is important to distinguish between fuel efficiency and fuel economy. Efficiency is a measure of how much of the energy value of a vehicle's fuel reaches the wheels, while economy measures how much fuel is required to move the vehicle over a given distance. The North American transportation system, based on private vehicles, ranks poorly on both measures. Efficiency is limited by the internal combustion engine. Fuel economy is reduced by the large size of American vehicles, compared to vehicles used for private transport in the rest of the world, and is further reduced in small trucks and SUVs ['sport utility vehicles'] by excessive weight and poor streamlining. Most of these vehicles are used only for the same transportation functions as standard automobiles. Hence there is a lot of room for improvements in vehicle fuel use, in smaller, sleeker vehicles using more efficient technology.

Hybrid vehicles have achieved substantially better fuel efficiency than conventional automobiles of similar size, promising to bridge the initial period of decline in oil availability. To reduce gasoline use even further, plug-in hybrids will be an interim part of the vehicle mix. The multiple sources of electric power – coal, natural gas, nuclear, and renewable – will become available to the plug-ins. As oil availability declines further in coming decades, it will be necessary to dispense with internal combustion engines altogether and move completely to electric vehicles powered by renewable sources, if indeed private automobiles survive at all. Of course driving less will also be necessary at all stages to achieve the fuel and energy reductions that will be required.

## Hybrid Technology

Current vehicles waste significant energy even beyond the low efficiency of their engines. They consume fuel even when no motive power is required, as in going downhill, slowing, or stopped in traffic. Energy invested in accelerating the vehicles is lost as heat in braking. The engines consume excessive fuel because they must be large enough to provide peak power that is rarely required.

Hybrid vehicles use electrical power to greatly reduce these losses without reducing performance. They are more expensive to produce than conventional vehicles; in the U. S. the expense is justified by reduced fuel cost, while in Europe, where vehicles are typically driven less, small cars with efficient diesel engines are generally preferred. In the hybrid vehicles currently available, all of the power driving the wheels comes eventually from an internal combustion engine. There are two basic designs – series hybrids and parallel hybrids. Both rely on internal combustion engines, electric motors, and batteries to smooth out the power requirements.

In the series arrangement, a gasoline or diesel engine runs a generator that in turn charges batteries and powers electric motors at the wheels. All of the motive power for the wheels comes from the electric motors. For peak loads the motors call on both the generator and the batteries, so that more power is available than could be obtained from the engine alone. This means that the engine can be smaller and more fuel-efficient than would be necessary to achieve the same peak power from a conventional transmission,

though the motors must be strong enough to handle peak loads unassisted. There are losses in converting from mechanical power at the engine to electrical power at the generator, and back to mechanical power at the wheels. Many diesel railroad locomotives use this scheme, though without the battery supplement. No series hybrid automobiles are currently manufactured.

Parallel hybrids distribute the engine's power either to batteries through a generator, to electric motors at the wheels, or directly to the wheels without going through a mechanical-electric-mechanical path. The components and controllers are more complex than in series hybrids, but the arrangement can be more efficient under many conditions, recovering more of the energy produced in the internal combustion engine. The system developed by Toyota has an internal combustion engine connected to both the vehicle's wheels and an electric motor/generator through a planetary gear arrangement that acts as a continuously variable transmission, more efficient than the fixed gear ratios of conventional transmissions because the engine can always be run at an optimum speed for current conditions. Power can be shared between the engine and the electric motor in any combination. During braking, torque (twisting power) from the wheels rotates the motor, which serves as a generator to recharge the batteries. This is called 'regenerative braking', because energy stored in the vehicle's motion is regenerated as electricity. A system developed by Honda uses regenerative braking to charge batteries, which then offer some power to assist acceleration, but there is no mechanical interaction between the gasoline engine and the electric assist system.

Plug-in hybrids are an interim technology between gasoline-powered and electrically powered vehicles. The best-known conception is the proposed Chevrolet Volt, a series hybrid with large batteries that can be charged either from an external electrical power source or from a small gasoline engine onboard. The series design makes sense because the electric motor must be powerful enough to power the Volt unassisted. Promised range on battery power is about 40 miles, the power in one gallon of gasoline; since the great majority of trips in the U. S. are less than 30 miles, most consumers would seldom engage the gasoline engine. Astronomical fuel economy figures are claimed, though they omit the plug-in electrical power that charges the batteries when the car is parked. Charging would be through an ordinary household plug, either 110 volts or 220 for a faster charge.

Appearance of this model in mass production depends on advances in battery technology, probably using improved lithium-ion batteries like those in cell phones and laptop computers, but of course on a larger scale. These batteries have a higher energy density than the lead-acid battery in conventional vehicles, but they are expensive; heat buildup and safety are issues. An alternative is to base a plug-in on an existing successful hybrid design such as the Toyota Prius, adding more batteries to increase the electric-only range. The Prius uses nickel-cadmium batteries, superior to the lead-acid alternative but offering less power per unit weight than lithium-ion. Toyota is developing a plug-in version of the Prius, based on the existing hybrid model. If the vehicle depends more on battery power the gasoline tank can be made smaller to leave room for more batteries. A plug-in hybrid will always have a smaller all-electric range than a similar-sized all-electric vehicle, though.

A disadvantage of the plug-in hybrid is that the vehicle must carry both a heavy battery load and all of the equipment needed for a gasoline engine: the engine itself,

radiator, gasoline tank and pump, muffler, catalytic converter, etc. The vehicle's body must also be able to handle the heat and vibration of the gasoline engine. This adds weight to the vehicle, a problem in electric vehicles because batteries have a much lower power density than gasoline or diesel fuel; a larger weight and volume of batteries is required to achieve the range of a smaller amount of fuel.

Improvements on the Chevrolet Volt design are possible. The gasoline engine might be scaled down considerably, allowing more batteries to increase the electric range somewhat. An engine designed only to charge batteries in a series hybrid could be optimized to run efficiently at one speed, because it would not need to handle other speeds. The car would normally operate in an all-electric mode, where the gasoline engine engages only when the batteries are nearly exhausted. For short trips this would never occur, as the batteries would cover the entire trip. Alternatively, to achieve a 300-mile range to which drivers are accustomed, drivers could select a long-range mode where the engine starts running as soon as a trip starts, with battery power supplementing the electricity generated by the engine. The engine need not be large enough to provide all the power needed to drive the vehicle and keep the batteries charged; they would gradually discharge over the 300-mile range of the trip, so that battery power assisted by the engine runs out at the end of that range. The engine would continue to run during a refueling stop at that point, adding further range.

### Fossil Fuel and Electricity

Practicality of plug-in hybrids depends on the relative availability of fossil fuel (gasoline or diesel) and electrical power in the future. The hybrids already on the market offer improved fuel economy without compromises in range or performance. As fuel inevitably becomes scarcer, plug-in hybrids will continue to offer long range at some compromise in vehicle weight, while all-electric designs will be the only viable alternative when fossil fuels become unavailable decades in the future.

As fossil fuel becomes unavailable or prohibitively expensive, an advantageous design for plug-ins would be to assemble the gasoline engine and all its accessories, including the gasoline tank, in a module that can be removed to make room for more batteries in an all-electric mode. This would probably require government intervention, as vehicles are normally designed to meet immediate needs rather than future contingencies.

### Economic and Ecological Impact

Though plug-in hybrid vehicles offer both the range of gasoline vehicles and the economy of electric drive, they will be more expensive to manufacture than conventional vehicles of comparable size. They will be viable, though, if fuel costs rise enough to make the investment in the hybrid worthwhile. This assumes that electricity remains inexpensive relative to the cost of power from gasoline. Tax policies may have to be revised so that governments can recover enough income to maintain roads and other automobile-related infrastructure, because drivers of electric vehicles do not pay fuel taxes. Higher taxes on gasoline would drive vehicle use further toward all-electric applications.

A compelling advantage of the plug-in hybrid, though, is that it allows drivers to optimize their energy use (and cost) by using the all-electric mode more or less, depending on relative energy costs and availability. This will make fossil fuel more elastic as a commodity – increasing price will tend to decrease consumption more than at present, where there is no alternative to fossil fuels for propulsion.

The ecological impact of hybrids, and especially plug-ins, depends upon the sources for the electricity that charges the batteries. Analyses of conventional hybrids conclude that the hybrid can actually use less fossil fuel per mile traveled and generate less greenhouse gas than an all-electric mode if the plug-in uses electricity generated from coal or oil. This is because the losses add up from power generation, transmission, charging batteries, holding the power, and releasing it to the electric motor. As a greater proportion of electricity originates from renewable sources, however, this balance changes in favor of the plug-in hybrid or the all-electric vehicle. Plugging in a vehicle at night for recharge uses the power grid and electrical generating plants when they are being used below their capacity, minimizing the infrastructure cost of the added electrical demand. And the vehicle can take advantage of intermittent sources such as wind by charging only when that power source is available. In the American West, about half of the electricity in the power grid already comes from non-fossil fuel sources, mostly hydroelectric and nuclear.

In summary, the plug-in hybrid promises a vehicle with range and handling similar to current vehicles, with improved operating economy and energy flexibility.

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