Hybrid automotive power systems

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Hybrid vehicles use two or more sources of energy for propulsion. Typically, one source is a liquid or gaseous fuel and the other is energy stored in an energy storage system such as batteries or ultracapacitors. Other options for energy storage include compressed gas, pressurized liquids (hydraulics), and mechanical energy stored in a flywheel. The most common type of hybrid vehicle is the hybrid-electric vehicle (HEV), which typically uses a liquid fuel (gasoline, diesel, or a gasoline/ethanol blend) to power an internal combustion engine that works with batteries, or ultracapacitors, to power an electric motor.

Why use hybrid vehicles?

Technology in vehicles has progressed significantly since their introduction around the beginning of the twentieth century. Recent technological improvements have not been used to reduce fuel consumption, but rather to increase performance to meet consumers' demands for larger and heavier vehicles. This is seen by the widespread use of minivans and sport utility vehicles over the past three decades (**Fig. 1**). From 1981 to 2003, vehicle weight increased by 24% and accelerated from 0 to 96 km/h (0 to 60 mi/h) 29% faster, but increased fuel economy by only 1%. Meanwhile, oil demand is increasing significantly in developing countries while oil production is declining in a number of countries, leaving most of the world's significant reserves of conventional oil in only a few places. Consequently, it is useful to consider alternative means of personal and commercial transportation that use less oil. HEVs are one such alternative technology that can use less fuel while maintaining the performance levels of current vehicles. Of the alternative powertrain options, HEVs appear to be some of the best choices for providing near-term reductions in oil use, as evidenced by their increasing commercial availability from many manufacturers.

How do HEVs save oil?

To understand why HEVs save energy, one must consider how to minimize the energy losses in conventional vehicles.

Efficiently satisfy the vehicle driving forces. In physics, energy is defined by the force exerted over a distance. For vehicle energy use, four forces dominate. Newton's Second Law of Motion is shown in the equation $\mathbf{F} = m\mathbf{a}$, where $\mathbf{F}$ is the force required for a specified mass m to be accelerated at a rate of $\mathbf{a}$. As suggested here, the force (and hence the fueling rate) required to move a vehicle increases for heavier vehicles and for frequent rapid vehicle speed changes (which create large accelerations). Much of the energy used to accelerate a vehicle then is

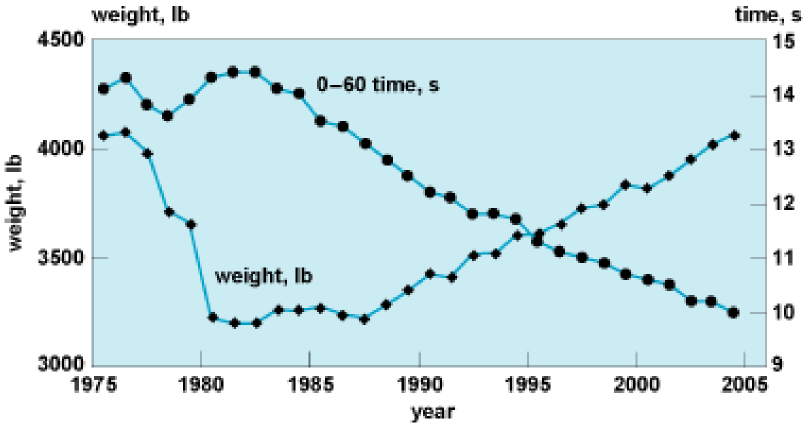

Fig. 1 **Change in vehicle weight and acceleration performance from 1975 to 2004 (*U.S. EPA Light-Duty Automotive and Fuel Economy Trends: 1975–2004, April 2004*).**

stored as kinetic or motion energy, which is equal to $^{1}/_{2}m\,v^{2}$, where v is the velocity of the vehicle. Conventional vehicles waste nearly all of that kinetic energy by dissipating it as thermal energy with friction brakes. HEVs, on the other hand, recover that kinetic energy through regenerative braking. That is, the wheels turn the shaft of an electric motor to generate electricity, which is then stored in the batteries (or other electrical energy storage device). However, the power generated by braking can be much higher than the power rating of the motor and batteries. Consider that the kinetic energy of a midsized vehicle weighing 1500 kg (3360 lb) traveling at 120 km/h (75 mi/h) is about 833 kJ. A braking event of 8 s to stop the vehicle would produce more than 100 kW of power, which is higher than the recharge rate that many systems could accept.

The additional force a vehicle must overcome when it climbs a hill is $F = mg \sin(\theta)$, where g is the gravitational constant and θ is the angle between the horizonal and the road surface. Although force is required to climb a hill, the vehicle's potential energy increases with increasing elevation. When a conventional vehicle descends a steep hill, the mechanical brakes again convert the potential energy to waste heat energy to maintain the vehicle at a safe speed. However, an HEV descending the same hill benefits from the ability to convert the potential energy and store it as electricity through the regenerative braking process.

Vehicles also face an opposing force to push through the surrounding air. This is known as aerodynamic drag and is equal to $^{1}/_{2}\rho C_{d} A_{f}\, v^{2}$, where ρ is the density of air, C_{d} is the coefficient of drag for that vehicle's design (including the effects of the vehicle shape, wheel wells, underbody, etc.), and A_{f} is the frontal area of the vehicle. This equation again illustrates that vehicle design and use (for example, high-speed driving) affect the force and hence the fuel required to operate the vehicle. Design improvements to minimize aerodynamic drag can be applied to any vehicle platform, but occur with greater frequency in HEVs, because they emphasize efficiency improvements. Typical drag coefficients range 0.4–0.45 for light trucks and 0.3–0.35 for cars; the drag coefficient for the Toyota Prius HEV is at 0.26 and the Honda Insight HEV is at 0.25. In comparison, an F-16 Fighting Falcon (jet) has a C_{d} of 0.0175.

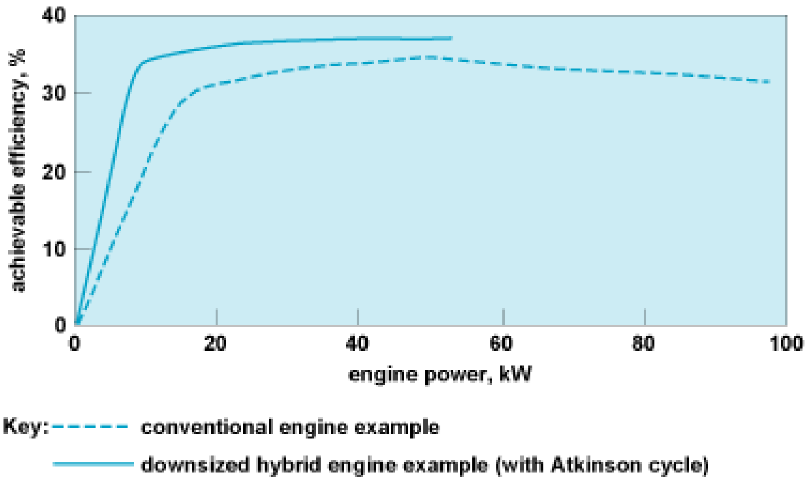

Fig. 2 **Engine efficiency curve showing peak efficiency at high power levels and low efficiency at low levels. A smaller engine lowers the inefficient operation power region. An Atkinson cycle engine can also achieve higher peak efficiency.**

The last significant force is overcoming the rolling resistance of the vehicle, which is equal to $C_{rr}\ mg$, where C_{rr} is the coefficient of rolling resistance for the tires, m is the vehicle mass, and g is the gravitational constant. As with drag reductions, efforts to reduce tire rolling resistance are not unique to HEVs, but may be included in those vehicles as part of the overall fuel-saving package. Rolling resistance for car tires on a hard paved surface ranges 0.007–0.013. Train wheels on steel have rolling resistances of less than 0.0025.

Efficiently convert fuel to motion energy. A conventional vehicle ultimately derives all of the energy to satisfy the vehicle driving requirements from its liquid fuel. The same is true of a standard HEV, except that the electric components can help the engine use the fuel more efficiently. The engine size in a conventional vehicle is typically dictated by the largest expected power requirement, such as that to satisfy a 0–97 km/h (0–60 mi/h) acceleration in 8 s. During other driving situations, the vehicle power is often quite a bit lower than this peak value (power is calculated by multiplying vehicle speed by the sum of the force equations). Engines are most efficient when operated at substantial power levels, and efficiency drops off significantly at low power levels (see the conventional engine efficiency curve in **Fig. 2**). This creates the counterintuitive phenomenon of vehicles often achieving better fuel economy while cruising at 65–75 km/h (40–47 mi/h) than at 25–35 km/h (16–22 mi/h). Even though the road load power demands increase with increasing speed, the increase in engine efficiency more than compensates for it by moving up the steep portion of the efficiency curve (Fig. 2).

In a comparable HEV, the engine can be smaller because the electric motor assists the engine during the momentary peak power events. Compared with a larger engine, the lower efficiency region of operation for a downsized engine shifts to lower power levels (Fig. 2). This means that the smaller engine will use less fuel to satisfy the significant amount of vehicle operation that requires relatively low engine power output. Also, for very low power levels, an HEV engine may turn off altogether and allow the electric motor to propel the vehicle. At slightly higher but still fairly inefficient power levels, the engine may be used to power the vehicle's wheels and to turn the shaft of the electric motor, generating electricity to store in the batteries. The added load of the motor on the engine requires additional fuel, but helps the engine operate at a higher efficiency and stores electrical energy that the motor can use later to help propel the vehicle. This process is known as "load leveling" the engine. Finally, the added control capability provided by the electric drive components can enable an HEV to use engine technologies with higher peak efficiencies but a narrower operating range than those typically employed in conventional vehicles. This is the case with the Atkinson cycle engines used in the Toyota Prius and Ford Escape Hybrid.

Efficiently power the vehicle's ancillary loads. A conventional vehicle engine continues to burn fuel even when the vehicle is idling and requires no power for propulsion. This keeps the engine operating so that it can provide power as soon as the driver accelerates, and keeps powering the vehicle's ancillary loads, which run off belts attached to the engine crankshaft. Ancillary power is required for low-voltage electronics such as the lighting and entertainment systems, for power steering and power braking assistance, and for climate control (up to 6 kW during cabin cool-down). In an HEV, these ancillary loads can be electrified, which alleviates their drag on the engine and allows them to operate more efficiently (rather than being tied to the speed of the engine). HEVs can therefore turn off rather than idle their engines when stopped and rely on their batteries to power the required ancillary loads. Because an electric motor, unlike an engine, can provide near-full torque before it begins to spin, the electric motor can then launch the vehicle and restart the engine after the vehicle is in motion.

Summary of efficiency improvements. Hybrid vehicle designs will include some or all of the following: use regenerative braking to recapture kinetic and potential energy; downsize the engine by using electric motors to assist with acceleration; provide electric launch and low-speed electric-only operation; load level the engine for efficient operation and battery charging; use advanced engine technologies; turn off the engine at idle; and use efficient electric accessories.

In addition to these hybrid functions, HEVs can benefit from efficiency improvements that could be applied to any vehicle. These include reducing vehicle mass (such as through use of lightweight materials), aerodynamic drag, and rolling resistance. Design changes to reduce ancillary loads can improve the efficiency of any vehicle, but are particularly important for HEVs, as high loads can increase the fuel consumption of an energy-efficient vehicle by as much as 50%. Similarly, less aggressive driving (avoiding rapid speed changes and excessive speeds) can improve the efficiency of any vehicle and make a particularly large impact on an HEV. Other areas of research into broadly applicable vehicle component improvements include work on advanced combustion and variable compression ratio engines, and six-speed as well as continuously variable transmissions.

Hybrid electric vehicle components

HEVs add three major components to conventional vehicle designs: energy storage, electric motors, and power electronics.

Energy storage system/batteries. Typically, nickel-metal hydride batteries are used in HEVs, although lithium-ion batteries are being considered for future use. The challenge is to develop low-cost batteries with high energy density (for extended use), high power density (for short bursts of high power to accelerate and accept high rates of regenerative energy), and long life that are safe for consumer use. A key issue is the state-of-charge window; that is, how much of the available energy can be used without significantly degrading the life of the battery. Ambient low and high temperatures affect battery life and performance. In addition, charging and discharging the battery generate heat that must be managed.

Electric motors and generators. Electric motors can convert electrical energy from the batteries into mechanical energy to help drive the wheels of the vehicle. An electric motor can typically also operate in reverse as a generator: taking mechanical energy to drive its shaft and create electrical energy, such as during regenerative braking. Typically, three-phase alternating-current (ac) motors are used because of their cost and reliability.

Power electronics. The electronics required for HEV operation include an inverter to switch between ac power for the motor and direct-current (dc) power for the energy storage systems, as well as converters to change the voltage of the battery system to a lower voltage for ancillary devices or to a higher voltage for more efficient motor operation. A 100-kW inverter operating at 90% efficiency generates 10 kW of heat that must be managed to ensure long component life.

Hybrid powertrain designs

Different HEV design approaches are possible with different component arrangements. The two classic HEV designs are known as “series” and “parallel” configurations (**Fig. 3**). A series configuration has no direct mechanical connection between the engine and the vehicle wheels. The engine is used simply to power a generator, which provides electricity that is used by an electric motor to drive the wheels or stored in the vehicle’s batteries for later use. This configuration enables precise control of the engine near its point of highest efficiency. However, the electric drive components for a series vehicle must be very large to satisfy the peak driving demands. Two examples of series-configured vehicles are the Chevy Volt and Ford HySeries plug-in hybrid concepts (plug-in hybrid vehicles are discussed in the final section).

One disadvantage of a series configuration is the inefficiency associated with taking the mechanical energy from the engine crankshaft, converting it into electrical energy with the generator, and then converting it back to mechanical energy with the electric motor to turn the driveshaft. In a parallel configuration, the engine can directly power the wheels and the electric motor works in parallel to provide or absorb supplemental power. Mechanically connecting the engine directly to the wheels avoids the double-conversion loss of the series configuration, but makes it more difficult to operate the engine at peak efficiency. Several commercial HEVs use more complicated variations of the classical design configurations to take better advantage of the benefits of each, including the power-split approach used in the Toyota and Ford HEVs and the two-mode configuration used in the Chevy Tahoe hybrid.

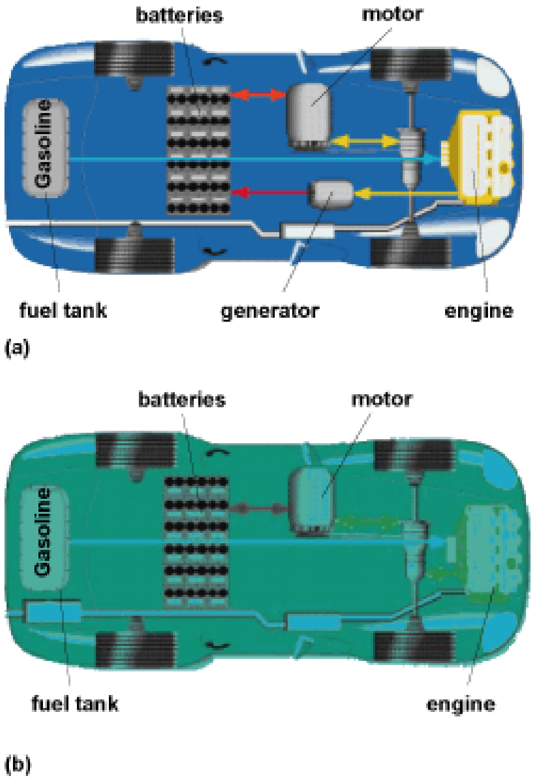

Fig. 3 **Classic HEV designs. (*a*) Series HEV configuration, where the engine only provides power to an electric generator that either charges the batteries or powers an electric motor to turn the wheels. (*b*) Parallel HEV configuration, where either the engine or the electric motor can power the wheels. The engine can also charge the batteries.**

HEVs are often discussed with respect to their approximate placement on a continuum (low to high) from “micro” and “mild” to “full” hybrid. In general, hybrids moving up the spectrum use larger batteries and higher power motors (relative to the size of the vehicle’s engine), and take advantage of more of the hybrid functions discussed previously. Hybrids on the lower end of the spectrum may also have their electric motors directly coupled to the engine, whereas those on the upper end can generally operate the drivetrain with the electric motor alone. For instance, three of GM’s HEVs that could be placed into categories of micro, mild, and full hybrid are the Chevy Silverado, the Saturn Vue, and the Chevy Tahoe, respectively. These vehicles follow the trend of increasing relative electric component size and increasing number of hybrid functions, beginning with engine start/stop capability, then adding electric assist and sizable regenerative energy recapture, and finally adding full electrical operation and extensive engine load leveling capability.

Do HEVs save fuel?

Toyota alone sold more than 1 million HEVs globally by mid-2007. More than two dozen hybrid models will be available to consumers soon. The average fuel consumption reduction of HEVs over the new EPA combined cycle

Fuel reduction of hybrid vehicles using 2007 EPA labels										
		City label, mpg		Highway label, mpg		Combined label, mpg		HEV fuel reduction, %		
Hybrid electric vehicle	**Standard vehicle**	**HEV**	**Std.**	**HEV**	**Std.**	**HEV**	**Std.**	**City label**	**HW label**	**Combined**
Honda Insight	Civic 1.8L auto	48	25	45	36	46	29	48	20	37
Toyota Prius	Corolla 1.8L auto	48	26	45	35	46	29	46	22	37
Honda Civic	Civic 1.8L auto	40	25	45	36	42	29	38	20	31
Chevy Silverado	Silverado 2WD 5.3L	16	14	19	19	17	16	13	0	6
Ford Escape 2WD	Escape 2WD V6	31	18	29	23	30	20	42	21	33
Honda Accord	Accord 3L auto	24	18	32	26	27	21	25	19	22
Lexus RX400h 2WD	RX 350 2WD	28	18	25	23	26	20	36	8	23
Toyota Highlander 2WD	Highlander 2WD 3.3L	28	17	25	23	26	19	39	8	27
Mercury Mariner 4WD	Mariner 4WD V6	28	17	27	21	27	19	39	22	30
Lexus GS 450h	GS430	22	16	25	23	23	19	27	8	17
Toyota Camry	Camry V6 3.5L auto	33	19	34	28	34	23	42	18	32
Nissan Altima	Altima V6 auto	35	20	33	26	34	22	43	21	35
Saturn Vue	Vue 2WD 6 cyl. auto	23	18	29	25	26	20	22	14	23

label is 27% for vehicles sold in 2007 (see table). Fuel consumption is reduced by more than 40% for some vehicles in city driving, where significant kinetic energy is recaptured, the engine shuts off during idling, and the electric motor assists with acceleration. Fewer benefits are realized at relatively constant highway speeds.

What are the barriers?

The most significant barrier to wider acceptance of HEVs is the additional cost for the batteries, power electronics, and electric motors. These components also add packaging and assembly challenges.

Plug-in HEVs, fuel-cell vehicles, and electric vehicles

Hybrid vehicle technology is not an entirely new concept. Hybrid and electric vehicles (EVs) were available in the late 1800s and early 1900s. The abundance of oil supplies at that time eventually contributed to conventional combustion-engine vehicles winning out as the dominant vehicle technology during the twentieth century. More recently, growing concern about the continued availability of petroleum reserves and greenhouse gases emitted from burning oil has led to renewed interest in hybrid and other alternative powertrain technologies.

Plug-in hybrid electric vehicles (PHEVs) are HEVs that include a charging plug and sufficient energy storage to be charged from an electrical outlet. PHEVs have all the benefits of HEVs and can operate from domestically produced electricity, which provides increased fuel reliability from greater fuel diversification. Two major designs are being considered today. One provides true all-electric driving that can operate solely by the electric powertrain. This requires that the battery pack, electric motors, and power electronics be sized for all vehicle operation. The other design, called a blended control strategy, uses the electric powertrain for most of the driving, but depends on an engine for rapid (high-power) acceleration. By foregoing equivalent all-electric driving, the design can use smaller battery packs, motors, and electronics. In either case, the battery pack energy may be sized to displace fuel use for 16–64 km (10–40 mi) of conventional HEV operation. This would have a substantial impact on oil consumption because the average trip length is about 7 km (4.4 mi), and about 50% of our daily driving (generally, multiple smaller trips) is less than 53 km (33 mi). PHEVs can substantially reduce our dependence on oil, provide more reliable personal transportation, use renewable energy to provide battery charging, and shift air pollution from urban centers during rush hour to more remote locations during nighttime vehicle charging. A battery pack that provides 64 km (40 mi) or less of driving range can be recharged overnight from a conventional 110- to 120-V outlet. A key benefit of PHEVs relative to an all-electric vehicle is that the vehicle need not carry a large battery pack, which is only fully used for longer but less-frequent trips.

Fuel cell vehicles (FCVs) are already being demonstrated, but must overcome several barriers before mass introduction. The required improvements include lowering the cost of the fuel cell stack, improving the effectiveness of on-board hydrogen storage, and developing an efficient hydrogen production and distribution infrastructure. FCVs will also be HEVs (or even PHEVs) to reduce the size and cost of the fuel cell stack and to take advantage of regenerative braking.

The simple design of EVs has many benefits. Many EVs have been built and demonstrated. Current challenges include the high cost of the energy storage system, the need for higher voltage charging stations, the development of safe battery packs with higher energy densities, and the time to efficiently charge the batteries.

Advances in HEV technology (energy storage, electric motors, power electronics, control strategies, etc.) will benefit PHEVs, FCVs, and EVs as those technologies become nearer term.

See also: ALTERNATING CURRENT; ALTERNATING-CURRENT MOTOR; AUTOMOTIVE ENGINE; BATTERY; DIRECT CURRENT; DYNAMIC BRAKING; ELECTRIC VEHICLE; FLYWHEEL; FUEL CELL.

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Additional Readings

How Hybrid Cars Work

Hybrid Cars

U.S. Department of Energy: Fuel Economy