The Future of Hybrid Vehicles

This new demand from the U.S. market is being taken very seriously by key players in the field. GM and DaimlerChrysler have announced an alliance for the joint development of a hybrid vehicle scheduled to reach the market by 2007. Development projects of this type will require capital investment of several hundred million dollars over the period.
Given that it is now imperative to cut greenhouse gas emissions, the hybrid vehicle offers a credible alternative. It is already on the market, despite the constraints inherent to a configuration combining an electric motor and an internal combustion engine, and despite the added cost. The technical choices are complex and varied, depending on the objectives: potential CO_2 emissions gains range from a few percentage points to over 45%, depending on the engine/motor architecture. The gasoline hybrid vehicle is emerging as an alternative to the diesel engine, especially in Japan and the United States, but its growth will depend on the ability of the motor industry to reduce the added cost.

Introduction

The environmental impact of road transport was long considered in terms of reducing "local or" "regional" pollution. Today, the focus has shifted to the greenhouse effect and its medium- and long-term consequences on the climate. In recent years, motor fuels and combustion techniques have improved and catalytic converters have come into general use. Today's automobile pollutes up to 100 times less than twenty years ago. And this trend can be expected to continue: every four or five years, stiffer tailpipe emissions standards are implemented. As a result, it should be possible to keep reducing total private-car emissions despite the increase in traffic. However, the trend for greenhouse emissions and energy consumption in the road transport sector is very different. The growth rate for world consumption, which reached 30% for the period 1990-2001, is expected to accelerate. The International Energy Agency (IEA) forecasts that greenhouse emissions will have grown about 90% by 2030, mainly due to transport and especially road transport. This disquieting trend explains why many research projects have been undertaken to develop technologies for the vehicle of tomorrow. One is the hybrid vehicle, often cited for its promise as a medium-term solution.

Definition and History

The term "hybrid vehicle" generally applies to any vehicle that not only has a primary source of power (usually the chemical energy supplied by the motor fuel), but also a reversible system to store energy in a second form (a pressurized accumulator vessel for hydraulic energy, a flywheel for kinetic energy, a battery or super capacitor for electrical energy). In practice, nearly all of the solutions under investigation rely on the storage of electrical energy.

In motor vehicle applications, this type of vehicle presents a hybrid powertrain: an internal combustion engine (gasoline, diesel or natural gas) and an electric power source (battery or super capacitor, power electronics, electric motor). This solution is intermediate between the conventional ICE vehicle and the electric vehicle.

At first, the idea was to combine the advantages of ICE vehicles (range, flexibility) and electric vehicles (clean, no emissions). Carmakers explored various possibilities but soon came up against the difficulty of installing, in the same vehicle, a double powertrain that would ensure effective bi-modal operation.

Concern over urban air quality led to concern over CO_2 emissions (CO_2 being the principal greenhouse gas) and ICE fuel efficiency (CAFE standards in the U.S., ACEA CO_2 commitments in Europe). Researchers then considered the hybrid vehicle from another angle. Overall fuel efficiency could be improved by using more or less electrical energy to supplement the power from the ICE. Four 4 principles applied:

1. When a vehicle is stopped, the internal combustion engine can be turned off, because there is enough electric power available to ensure a smooth start.
2. When slowing and braking, part of the kinetic energy of the vehicle can be captured by the electric motor and stored, instead of being lost as heat in the brakes.
3. Generally, the ICE can be optimized in different ways: when little power is needed for vehicular propulsion, the driver

can opt to run the engine at higher power (to improve its efficiency); the energy not used will be stored in the batteries. On the other hand, for high power demands, it is preferable to give the engine a boost with stored electric energy rather than push it to the limits of its capacity, which would reduce efficiency and increase emissions. Often, internal combustion engines can be downsized.

4. A pure-electric mode of propulsion may be considered if the sizing of electrical components is application-specific. Here, the vehicle range would generally be fairly limited and dependent on battery capacity.

Seen from this new angle, the hybrid vehicle is no longer a juxtaposition of two powertrains working in alternation. All of the electrical and mechanical components must be optimized and function well together to minimize fuel consumption at all times while keeping polluting emissions at a low level — by managing the temperature of the ICE engine and its aftertreatment system and by optimizing engine starts — and delivering good performance (acceleration, driveability). As a result, the optimization of control strategies for all of these components is very complicated.

Not all modes of operation are compatible with all vehicle configurations. Different hybrid categories exist, defined by functionalities. Table 1 gives a few indications of the power ratings and CO_2 gains to be expected. The better the performance, the higher the price premium, which ranges from a few percentage points for the mini-hybrid to about 10 or 15% for more sophisticated solutions. This factor varies greatly according to mass production volume.

Models Currently on the Market

In recent years, automobile manufacturers have developed a variety of hybrid prototypes. Their diversity indicates the complexity of the technical choices involved. For the time being, no single configuration has achieved dominance.

The problems associated with electric motors, power electronics and electric energy storage are highly specialized. For motor vehicle applications, which lead to mass series production, carmakers must find solutions that optimize performance and cost. For various reasons, most of them linked to their domestic market, the Japanese automobile manufacturers were the first to undertake hybrid production.

In 1985, well before public opinion had focused on the greenhouse effect and related issues, Toyota decided that electronics and on-board electricity would determine the future of the automobile. In 1989, a research and component production center opened in Hirose, Japan and a program was launched for the industrial development of hybrid-specific technologies. Backed by a decade of research and partnerships with many industrial firms (e.g. Panasonic for batteries), the Japanese automaker brought out the first series hybrid vehicle in 1997: the *Prius*.

For Toyota, this vehicle did much more than prove that the hybrid car was technically feasible. It demonstrated that this solution could be applied to series production. Yet the Toyota Hybrid System (THS) solution is not simple from the technical standpoint. The engineers developed a semi-parallel configuration to combine the advantages of series design (close to the electric vehicle) and parallel design (close to the ICE vehicle): equipped with 2 electric motors/generators (see Figures 1 and 2), it can operate in series mode (using electric power for propulsion and the ICE as a generator), in parallel mode (the engine drives the car and the electric motor supplies additional torque) or in intermediate mode (with one electric motor in series mode, the other in parallel mode). To ensure flexibility, a new transmission (the power split device shown in Figures 1 and 2) was developed. Based on the

Table 1
Hybrid classification

Type of hybrid	Functions	Power rating	CO_2(1) gain
Mini-hybrid Stop & Start generator-starter system	**1** (Engine off at low engine speed)	2 kW	8%
Stop & Go	**1 + 2** (Regenerative energy of braking captured)	3 kW	13%
Mild-hybrid	**1 + 2 + 3** (downsized ICE, assisted acceleration)	10 kW	30%
Full hybrid series or parallel	**1 + 2 + 3 + 4** (pure electric)	30 kW	45%

(1) Estimated gains for city driving.

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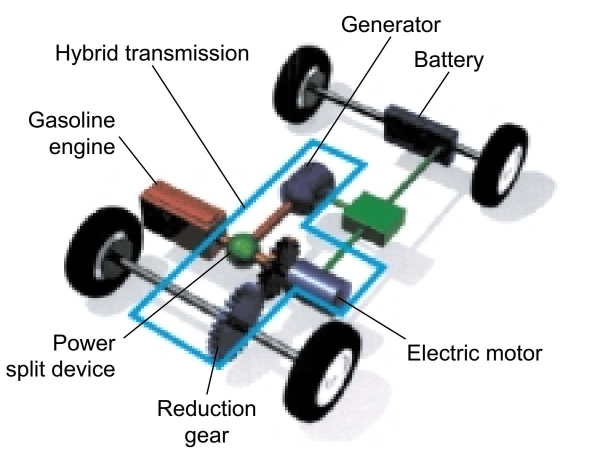
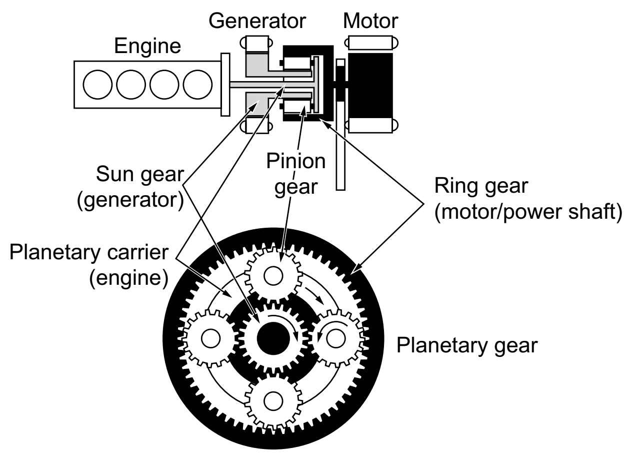
Fig. 1 General configuration of the Toyota *Prius*, 2003 version (THS 2 system)



Source: Toyota

Fig. 2 Detail drawing: Powertrain in the THS 2 system used by the *Prius*



Source: Toyota

concept of the planetary gearset, it allows all three motors to combine their torques without imposing a set ratio between their speeds. The *Prius* has been modified twice since 1997, but retains the original configuration. After extensive redesign work (THS 2), the latest version brought out in 2003 offers substantially improved fuel economy. The *Prius* obtains CO_2 emissions measured at 104 g/km on European cycle — significantly lower than other European vehicles of similar weight (Toyota says the *Prius* obtains CO_2 emissions 40% lower than an equivalent gasoline-powered vehicle) — while offering the performance and driveability expected in a modern car.

As for the other Japanese manufacturers, Nissan commercialized the *Tino* Hybrid in Japan, which resembles the *Prius* in configuration but replaces the planetary gear transmission with simpler technology (continuously variable transmission via a steel belt, or CVT) plus a pilot clutch. Honda has opted for a simpler design, also with CVT, that is 100% parallel: the ICE and electric motor share the same shaft, which allows them to combine their torques but obliges them to be at the same speed at all times. This Honda design was initially tested on the Insight, a little two-seater coupé brought out in 1999 in Japan and in the United States. Thanks to the feedback obtained, Honda incorporated its hybrid system (Integrated Motor Assist, IMA) in vehicles for larger scale production, starting with the Civic. Unlike Toyota, which developed a hybrid model that only existed as such, Honda is commercializing the hybrid function with as a range on the same footing as, say, a diesel range. Since 2004, the catalogue has listed the hybrid 1.3 l version of the Civic with the other versions, such as the sporty 1.5 l VTEC.

In Europe, automakers have adopted a more progressive approach. At first, they will only offer mini-hybrid vehicles equipped with a generator-starter system. One example is the Citroen C3, equipped with the Stop & Start system by Valeo. This approach is less risky from the industrial and commercial standpoint, because the manufacturer does not have to develop a specific vehicle. It merely makes slight adaptations to the internal combustion engine and develops simple control strategies. In addition, when it presents consumers with various versions including a hybrid, it can test market reception. On the other hand, a basic hybrid offers limited functionalities: the ICE turns off at low engine speed and, in some cases, braking energy is captured and stored but in an amount limited by low battery capacity. The next step — produce more complex hybrid vehicles offering better fuel economy — is not planned before 2006-2010.

In the United States, carmakers have focused their efforts on the “gas-guzzlers” in their ranges: the big 4 × 4s and vans. Different companies have opted for different solutions. GM chose to install a generator-starter system in its first hybrid vehicles, i.e. the GMC *Sierra* pick-up (planned for year-end 2004) and the GMC *Saturn* van (2006). In a more remote future, they may transfer the lessons learned from the manufacture of heavy vehicles like urban transit buses to private cars. The GMC *Yukon* (2007) may be heavily hybridized, based on a design concept from the company that makes Allison bus transmissions. Ford is already marketing a sporty hybrid 4 × 4 (the *Escape*), whose design and certain components recall the Toyota *Prius* (NiMH battery, electric motor, CVT, etc.). This vehicle is the result of the Ford-Toyota license agreement announced in March 2004.

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Market Outlook

Existing hybrid models prove that commercialization is justified by the technical advances made. But substantial progress is still needed in certain areas (*e.g.* batteries) and price remains a problem. Like any other emerging technology, the hybrid vehicle must find its market before it can benefit from real economies of scale.

Despite the globalization of the economy, the prospects of hybrid growth vary according to geographic area and local market characteristics (penetration rate of competing technologies such as the diesel engine, the price of motor fuel at the pump).

- In Japan, the birthplace of today's hybrid vehicles, the automobile market is characterized by a total absence of diesel vehicles and a large proportion of micro-cars reserved for city driving. This segment is the perfect niche for hybrid vehicles: they reduce urban pollution while improving fuel economy. The Japanese are fascinated by technological innovations, which may also explain their interest in these new solutions.
- In the U.S., large vehicles (SUVs, vans) dominate the market. Polluting emissions standards are particularly strict, especially in California, and fuel efficiency standards have also been implemented (CAFE). Carmakers are looking for solutions that will improve fuel efficiency while giving consumers what they want: multi-purpose vehicles that are increasingly powerful and heavy. They see the hybrid vehicle as a technical solution that will reduce consumption while delivering performance. The hybrid vehicle generally has to compete with diesel alternatives, but its public image is better. The depollution cost should also be lower for the hybrid vehicle than for the diesel vehicle (NOx, particulate matter). For many years, the typical American car will continue to consume much more than its European counterpart. This being said, the *Prius* was a surprise hit in California. Even Toyota had not anticipated its success and the wait time for prospective buyers is several months. This new demand from across the Atlantic is taken very seriously by the key players in the field. GM and DaimlerChrysler have announced an alliance for the joint development of a hybrid vehicle expected to reach the market in 2007. These undertakings will require several hundred million dollars of investment over the period.
- In Europe, France started out as an exception: diesel vehicles accounted for a large proportion of its automobile fleet. In the last few years, this trend has spread to the rest of Europe, especially Germany. In the last decade, a substantial portion of R&D funds were allocated to diesel technology research, yielding real gains in terms of performance, driveability, fuel economy and depollution (especially with the development of the particulate filter). The European automobile fleet saw average consumption decrease as average per-vehicle weight was increasing. The main reasons were the continuous improvement of diesel engines and a steady rise in diesel market share. Manufacturers and consumers instinctively compare any hybrid with its diesel counterpart. To penetrate the European market, prospective buyers need to be convinced that purchasing a hybrid is justified by advantages in terms of efficiency (fuel consumption, reduced pollution), functionalities and driving performance.

Conclusion

On the strength of recent technological advances, the status of the hybrid vehicle has been raised from research concept demonstration vehicle to series vehicle. This will not revolutionize the industry, however. Market penetration will be gradual and depend heavily on how carmakers solve the problem of the price premium. In the U.S., recent forecasts said that market share would reach 4-7% by 2008 and 10-15% by 2012. On the technical front, the electronics component in vehicles will be increasing in the years to come. In addition, external factors (oil price, motor fuel taxation, environmental policy) will influence how fast and to what extent the new technology penetrates.

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Final text received on December 7, 2004