8.2.1 Introduction

During the Twentieth century, the vast availability of petroleum, the relative simplicity of the processes for refining and producing petroleum-based fuels, and the ease of their global distribution favoured the proliferation of motor vehicles equipped with internal combustion engines. The competition offered by electrical motor-power, already present in the early years of the century, was easily overcome by the internal combustion engine, which became the major player in the mobilization of the masses of the entire planet.

At the beginning of the Twenty-first century, however, issues related to environmental protection and the Earth’s limited resources are assuming increasing importance. Smog, the hole in the ozone layer and the greenhouse effect are worrying public opinion, now sensitive to the effects of an expanding energy system that is based on the consumption of non-renewable energy resources and that causes the deterioration of air, soil and water quality. Moreover, international tensions concerning the exploitation of the petroleum reserves still available have contributed to a significant rise in the price of petroleum.

The internal combustion engine is characterized by poor efficiency, uses fossil fuels (the reserves of which are going to run out), causes air pollution, and gives rise to fuel leakages into the soil and water during storage. As a consequence, the focus of attention turned to electric vehicles, which are capable of providing mobility without directly producing harmful emissions. Nevertheless, electric vehicles, which seem to guarantee a solution to the problems enumerated, even though they are now familiar to the general public, still suffer from a number of limitations, in particular an excessively high price, modest performance and limited range.

In 2005, a vehicle with an internal combustion engine consumes half the fuel and caused one hundredth of the pollution of a vehicle of the 1970s, and is capable of delivering better performance. Nevertheless, the average efficiency of a gasoline engine is less than 15%: the remaining 85% is dissipated through thermal and aerodynamic loss, and friction along the drivetrain and the rolling of the tyres. Adding an electric motor to a drive system equipped with an internal combustion engine results in a significant improvement in the overall efficiency. In this way a hybrid drive system is created, which makes it possible to use the internal combustion engine in operating conditions where it is more efficient, and to reduce its use in low load conditions.

To summarize:

- The electric motor can replace the internal combustion engine in whole or in part in stop and go conditions (in congested traffic driving conditions) and when the load is reduced.
- The electric motor can assist the internal combustion engine during acceleration, which makes it possible to use smaller thermal engines that are inherently more efficient given their lower thermal and frictional losses, with no reduction in overall performance.
- The electric motor can be used to recover a part of the vehicle’s kinetic energy during braking (regenerative braking), energy that would otherwise be dissipates through friction and that instead is converted into electrical power.
- The additional electrical power generated by the electric motor-generator can be used to replace onboard hydraulic auxiliary units, such as the power steering pump or the water pump, with high efficiency electrical components.

The advantages of hybrid technology, already recognized at the beginning of the Twentieth century,
have become feasible only recently with the
development of electronic control systems,
sophisticated electrical energy accumulators and
acceptable production costs. This makes it possible to
market vehicles on a large scale: hybrid-electric
vehicles are available on the market today and are
capable of bringing about a consistent reduction both
in fuel consumption and in the overall impact on the
environment, without an excessive increase in costs.

8.2.2 Current environmental
problems and potential solutions

Vehicle population

The car is an integral part of modern society and
has played a major role in economic and industrial
development as well as in everyday life. At the end of
2003, Europe was the geo-political area with the highest
number of vehicles in circulation, around 254 million,
followed closely by North America, with about
250 million and then Japan with about 55 million (Fig. 1).

Environmental consequences

The increase in the number of vehicles in
circulation on a global level, and more generally the
development model based on open cycles (a fluid in
evolution finally returned to the environment) and on
the production of energy for the most part from fossil
fuels, poses major problems with regard to air quality,
climate change and the ever increasing demand for
energy.

For years there has been an expansion taking place
in the developing countries that, combined with the
constantly rising standard of living demanded by
people in the more affluent countries, threatens to
cause an uncontrolled surge in air pollution and the
production of greenhouse gases (primarily CO₂). Cars
release substances into the atmosphere that are both
harmful to the environment and a danger to health.

The principal polluting emissions are: a) carbon
monoxide (CO), an odourless and colourless gas that
takes the place of oxygen in the haemoglobin of the
blood, with lethal results if absorbed in large amounts;
b) sulphur oxides (SOₓ), that cause what is referred to
as acid rain; c) nitrogen oxides (NOₓ) that, in addition
to causing acid rain and damage to the respiratory

In the decade from 1993-2002, the number of vehicles registered annually in the global market grew
almost linearly, rising from around 33 to 38 million (+15%). Of particular note is the percentage increase
of the vehicle population in circulation in the principal
developing countries (India +7.6%, China +7.5%,
Brazil +4.6%) between 2002 and 2003.

It is expected that the growth trend will increase in
the coming years, with a significantly more noticeable
increase in countries such as China, which is
experiencing very strong growth and has a population
in excess of a billion inhabitants; as a result, it is
estimated that in 2020 the worldwide fleet in
circulation will be fully 1.2 billion vehicles (Fig. 2).

Fig. 1. Vehicle population in circulation
in different geographical areas at the end of 2003
(about 695 million vehicles).

Fig. 2. Growth estimates
for the world vehicle
population.
system, generate ozone, contributing to photo-chemical smog and global warming; d) unburnt hydrocarbons (HC) that, in addition to being carcinogenic agents, contribute to the formation of smog; e) Particulate Matter (PM), also known as particulates, that cause serious pulmonary and cardiovascular diseases.

The increase in the number of vehicles must therefore be considered with respect to the inescapable requirement for improvement in air quality, especially in the more densely populated (residential and industrial) areas. The major concern is the prospect of an exponential increase in the number of cars in newly developed or developing countries, such as China, where standards on the emission of pollutants are very much less strict than in North America, Europe or Japan.

In addition to releasing pollutants, cars contribute to the increasing concentration in the atmosphere of carbon dioxide (CO₂), which accounts for 70% of the greenhouse effect (the contributions of CH₄ and N₂O are 25% and 5% respectively). Essentially, CO₂ is produced by the oxidation of fossil fuels such as coal, the derivatives of petroleum and natural gas. Another significant factor contributing to the increase in CO₂ concentrations in the atmosphere is deforestation. According to data that was correct as of the year 2000, the sector primarily responsible for the production of CO₂ by global human activity is the energy production sector (43.6%), followed by transportation (24%) and industry (18.5%). Within the transportation sector, road vehicles play a very significant role, as indicated in Fig. 3.

A report by the European Environment Agency (EEA) relating to November 2004 summarizes the CO₂ emissions by the countries of the European Union. The current variance of 2.1% from the target set by the 15 signatories to the Kyoto Protocol (which suggested the progressive reduction of greenhouse gas emissions by 8%, compared to 1990 levels, by the year 2010) is attributed above all to the increase of road transport, both passenger and freight: an increase quantified as 20% in the final decade of the Twentieth century. In the year 2000, six billion tonnes of CO₂ were released into the atmosphere as a result of human activity.

Today the concentration of CO₂ in the atmosphere is 31% higher than 250 years ago, before the industrial revolution. At the current rate of development it is anticipated that by the end of the Twenty-first century this concentration will double, reaching 700 ppm.

Hand in hand with the increase in the concentration of greenhouse gases in the atmosphere, a significant increase has been recorded in the average temperature of the earth’s surface. The 2001 report of the Intergovernmental Panel on Climate Change (IPCC), a working group set up by the World Meteorological Organisation (WMO) and the United Nations Environmental Programme (UNEP) to study climate change and its effects, confirms the cause-effect relationship between the increase in emissions of CO₂, CH₄ and N₂O and global warming.

To summarize: a) in the last 140 years the average temperature of the earth’s surface has increased by about 0.6°C; b) since the introduction of satellite surveys (1979), the above-mentioned temperature has grown by an average of 0.15°C each decade; c) the decade from 1990-2000 was the hottest ever, and 1998 in particular recorded the highest average temperatures; d) on average, between 1950 and 1993, minimum night-time temperatures increased by 0.2°C each decade.

Below are listed the principal consequences of global warming mentioned in the IPCC’s report: a) an extension of the seasons without frost and ice in the medium-high latitude regions, and a reduction of about 10% in the snow cover since the end of the 1960s; b) a visible reduction in the size of non-polar glaciers in the northern hemisphere; c) a reduction of 10-15% in the area of frozen seas in the northern hemisphere in the spring and summer period since 1950, and a reduction of 40% in the thickness of ice in the arctic seas in the late summer-autumn period; d) an increase of 0.5-1% in precipitation each decade in the medium-high latitude regions of the northern hemisphere, with an increased frequency of events of high intensity; e) since the mid-1970s, ever greater instances of the El Niño effect in the tropical, sub-tropical and medium latitude regions, with increases in temperature and in precipitation of exceptional intensity.

Faced with the environmental issue and climate changes, the automobile industry must contribute to a drastic reduction in the use of fossil fuels and thus also of polluting and greenhouse gas emissions.

Fig. 3. Global CO₂ emissions by sector of fossil fuel usage (2000).
From conventional to hybrid vehicles

As already stated, by the year 2020 it is anticipated that the number of vehicles in circulation on the roads of the planet will increase by about 500 million units. Compared with 30 years ago, vehicles produce 99% less pollution, but since there are twenty times as many and on average they cover ten times as many kilometres, the resulting environmental impact has not diminished; indeed it has doubled. It is therefore crucial that the major manufacturers invest significant resources into reaching as quickly as possible their final objective: the manufacture and sale within industrially compatible costs of the ultimate eco-car, the zero emissions vehicle. Research and development has not been concentrated on just one sector (during the 1980s electric vehicles were wrongly considered a goal that could be reached in a short timescale), but has involved different types of motors, both internal combustion (using gasoline, diesel and gas) and electric.

The development of gasoline and diesel engines has led to the introduction of technologies capable of increasingly higher performance and increasingly lower levels of emissions (direct injection, lean mixtures, variable inlet valve timing for gasoline engines, direct common-rail injection and filters for trapping particulates for diesel engines); but what is bringing today’s cars nearer to the zero emissions vehicle is the introduction of hybrid technology, that is, the utilization in synergy of two different propulsion systems (an internal combustion engine and an electric motor) in the same vehicle. Faced with higher production costs, it is possible to exploit fully the characteristics of the two systems, using the internal combustion engine only when necessary and converting part of the kinetic energy from the deceleration phase into electrical energy (see Section 8.2.1). The graphic in Fig. 4 shows how hybrid technology today is able to contribute significantly to the reduction of emissions of greenhouse gases. If one takes a high-level viewpoint (from oil well to automobile wheel), the New (NG, New Generation) Prius (see Section 8.2.3) emits an amount of CO₂ that is more than 40% less than a vehicle with a gasoline engine (MT, Manual Transmission) of a similar size, but less also than a diesel engine vehicle or even an FCHV (Fuel Cell Hybrid Vehicle), that is, a vehicle using fuel cells (95% of hydrogen sold today is produced using fossil fuels). Thus, while awaiting the arrival of the hydrogen era, which is not expected in less than 20 years, hybrid technology makes it possible to set even more ambitious targets: a reduction of CO₂ to one-third of that produced today by a gasoline vehicle.

The ultimate objective is the transition from open cycles (which until now have always made use of limited resources, such as fossil fuels, and have generated waste products that are harmful to the planet’s air, soil and water) to closed cycles. In this regard a hydrogen plus electricity economy is conceivable, and more specifically, assuming that hydrogen is the primary energy source, an economy that would have the following characteristics: a resource widely available on the planet, such as water, would be used; hydrogen would be obtained from the water by means of the primary source of renewable energy (solar, either directly or through the use of biomass); and at the end of the cycle, water will be produced, and not waste products, useless by-products or harmful emissions.

It is therefore foreseeable that cars of the future could have a configuration similar to that of current hybrid-electric vehicles and use a pack of fuel cells (a stack) powered by hydrogen in synergy with an electric motor in place of the present internal combustion engine. The large-scale marketing of vehicles using hybrid technology could in the meantime contribute to lowering of the production costs of more innovative components and control systems.

Fig. 4. In pursuit of the zero emissions car: comparison of CO₂ emissions from a gasoline engine and emissions from other motors (Source: Toyota Motor Corporation).
8.2.3 Hybrid-electric vehicles: historical outline and current situation

The first hybrid-electric vehicles

In 1898, Justus Entz probably became the first person to construct a hybrid electric vehicle by producing a vehicle with an internal combustion engine and an electric motor, for Pope Manufacturing (Connecticut). The prototype caught fire and the company abandoned the project.

The first production hybrid-electric vehicles were constructed in Europe at the beginning of the Twentieth century: Camille Jenatzy presented a parallel hybrid system at the Paris Motor Show of 1901 with a 4.4 kW internal combustion (thermal) engine and a 10.3 kW electric motor-generator; in 1903, Lohner-Porsche produced a series hybrid system with a 14.7 kW thermal engine which drove, on each of the rear wheels, a 20.6 kW direct current electric motor-generator; and a few years later Mercedes in conjunction with Mixte produced its own hybrid-electric vehicle.

In 1917, a famous American electric vehicle manufacturer, Baker and Woods, developed its own hybrid-electric vehicles.

At the beginning of the 1930s however, production of the last hybrid-electric vehicles came to a halt, while the internal combustion engine became the clear leader.

The advantages of the internal combustion engine (powered by fuels derived from petroleum) compared with hybrid propulsion can be summarized as follows: 40 litres of gasoline has a mass equal to about 30 kg and develops about 350 kWh of thermal energy, while a modern lead acid battery of the same mass develops 1.1 kWh of energy (almost completely convertible, however, into motive force); the engineering is simpler; the transport and distribution of the fuels is simpler.

The advantages of hybrid drive over the internal combustion engine can be summarized as follows: minimum use of the internal combustion engine under low loads; cooperation of the electric motor with the internal combustion engine during acceleration, allowing the consequent use of smaller internal combustion engines; use of a stop and go system, which eliminates fuel consumption while idling; use of the electric motor to recover part of the braking energy during deceleration; replacement of on-board mechanical and hydraulic equipment with more efficient electrical devices.

All in all, though the average efficiency of an internal combustion engine is not greater than 15%, the first attempts at hybrid technology failed for lack of electronic control systems, and because of excessive complexity, weight and costs.

Modern hybrid-electric vehicles

In the 1960s, when the environmental consequences of development based on the use of fossil fuels became clear, interest is once more renewed in hybrid-electric vehicles. The oil crises of 1973 and 1979 and the predictions of further and increasingly graver future crises prompt the first political decisions.

The United States Congress draws up the Energy Policy and Conservation Act (EPCA), which contains the first CAFE (Corporate Average Fuel Economy) standards for the consumer economy: by 1985 cars would have to halve their average fuel consumption.

During the same period, Toyota begins to research hybrid technology applied to vehicle propulsion, developing the following projects: a) in 1965, they begin the feasibility study of a hybrid gas turbine/electric motor system; b) in 1969, they build a bus using this system, without, however, putting it into large-scale production; c) in 1975, the same technology is applied to the Toyota Century Hybrid; d) in 1977, the hybrid gas turbine/electric motor system is applied to the Toyota Sport 800 gas turbine hybrid.

The fall in price of petroleum in the early 1980s puts a brake on investment by the major manufacturers and on the commitment of the United States administration. From 1987 onwards, the public begins to demand higher levels of luxury, comfort and accessories for new vehicles, and as a result the average levels of consumption begin to rise again. The First Gulf War (1991) once again focuses attention both on the energy issue, with the dependence of the major western countries on petroleum supplied by the middle-eastern producers, and on the question of the environment.

In 1993 the Clinton administration draws up an agreement with General Motors, Ford and Chrysler (PNGV, Partnership for a New Generation of Vehicles) for the production of a revolutionary hybrid-electric vehicle, the Supercar, capable of covering 80 miles on one US gallon of fuel (about 33 km/l). The Supercar programme fails because of the arbitrary nature of the mileage objective and, while it provides a great impetus to the research for materials and the development of hybrid systems, it does not prove to be suitable for large-scale production.

Marketing of hybrid-electric vehicles

At the beginning of the 1990s, Toyota secretly develops a programme with the more realistic objective of 55 miles per gallon or m.p.g. (about 23 km/l), producing a hybrid system with separate gasoline engine and electric motor-generator.

In 1997 Toyota, once again, launches a small bus, the Coaster HV (Hybrid Vehicle), and the Prius, equipped with the Toyota Hybrid System (THS), the
first hybrid-electric vehicle to be marketed on a large scale. The vehicle has the following features: (a) a mixed hybrid system (strong hybrid); (b) a 1.5 litre Atkinson cycle engine, with variable timing, VVT-i (Variable Valve Timing-Intelligent); (c) a 33 kW electric motor-generator; (d) 273.6 V, 2 kWh NiMH (Nickel-Metal-Hydride) accumulators with 49 kg of mass; (e) combined consumption of 51 m.p.g. (about 21 km/l); (f) an improvement in fuel consumption of about 80% compared with the urban cycle figure produced by the Environmental Protection Agency (EPA) in the United States, and of 100% compared with the Japanese figure; (g) CVT (Continuously Variable Transmission) gearbox; (h) no external recharging.

In 1999, the Honda Insight is the first hybrid-electric vehicle to be marketed in the United States; its features are as follows: (a) parallel hybrid system; (b) lean burn 1.0 litre gasoline engine, with variable timing, VTEC (Variable valve Timing with lift Electronic Control); (c) 9.6 kW DC-DC electric motor-generator; (d) 144 V, 1 kWh NiMH accumulators of 22 kg; (e) combined consumption of 61 m.p.g. (about 25 kg/l).

In the year 2000, the Prius is launched in the United States and Europe.

In 2001, THS technology is extended to a 4×4 model for Japan, the Estima Hybrid, with the following features: (a) 1.5 litre Atkinson cycles gasoline engine with VVT-i; (b) 13.2 kW electric motor-generator for the front wheels and a 17.6 kW electric motor for the rear wheels (for 4×4 operation); (c) the first application in the world of ‘brake by wire’ technology (electronically controlled braking system) on a minivan (6-8 passenger vehicle); (d) CVT gearbox.

In 2001, Toyota introduces the ‘mild-hybrid’ system (parallel drive without the all-electric mode) on the Crown luxury saloon. This saloon with the THS-M system features a parallel hybrid system, a 1.5 litre direct injection gasoline engine, and a small 3 kW electric motor-generator.

Also in 2001, Toyota again uses its THS technology on the fourth version of its experimental fuel cell vehicle, the FCHV-4. In 2002, limited marketing begins in Japan and the United States of the Toyota Sport Utility vehicle, with the following features: (a) batteries/fuel cell; (b) 90 kW of power; (c) 260 Nm of torque; (d) 300 km range.

In 2003, on request, Honda offers hybrid drive on the Civic, again offering the IMA system (Integrated Motor Assist) from the Insight. This uses a system in which 3 of the 4 valves close during deceleration and braking, and these vehicles achieve a reduction of 50% in the internal friction of the thermal engine.

In 2003, Toyota launches the second hybrid-electric MPV (Multi-Purpose Vehicle) on the Japanese market, the Alphard HV, and the new Prius, which has the following features: (a) 530 patents applied for (against 300 for the THS); (b) 50 kW electric motor-generator with the highest power density (power-weight ratio) in the world; (c) combined consumption of 23 km/l; (d) 201.6 V NiMH accumulators with 39 kg of mass; (e) power converter supplying 500 V to the electric motor-generator; (f) EV (Electric Vehicle) drive mode, or all-electric drive; (g) brake by wire braking system; (h) electrically driven A/C (Air Conditioning) compressor.

The new Prius wins the ‘Car of the Year’ award in North America in 2004 and in Europe in 2005.

In March 2005, production begins of the Lexus RX400h, the first SUV (Sport Utility Vehicle) in the world to be equipped with a hybrid drive system. In the RX400h, the Hybrid Synergy Drive system is applied to a vehicle with four driven wheels. This represents a jump in quality in the offering of hybrid-electric vehicles, demonstrating that it is possible to achieve a level of fuel economy and lower exhaust emissions without foregoing excellence, comfort and flexibility of use, as the following data for this vehicle indicate: (a) electric motor-generator for the front axle with 123 kW maximum power output and 333 Nm maximum torque; (b) electric motor-generator for the rear axle with 50 kW maximum power output and 130 Nm maximum torque, to provide all-wheel drive when necessary; (c) 3.3 litre V6 gasoline engine with 155 kW (for an overall maximum power output of 200 kW) and 288 Nm; (d) 0-100 k.p.h. acceleration of less than 8 seconds; (e) 288 V NiMH accumulators capable of delivering a maximum power output of 45 kW-0.7 seconds; (f) power converter with 650 V feed to the electric motor-generators; (g) EV drive mode; (h) brake by wire braking system; (i) electric A/C compressor.

After the 11th of September 2001 and the Second Gulf War, Ford and Nissan acquired from Toyota dozens of patents to enable them to develop their own production hybrid-electric vehicles.

8.2.4 Features of the hybrid systems in use

Types of hybrid systems

Series hybrid systems

In the series hybrid system, the thermal engine is connected to an electric generator and the current produced feeds an electric motor which provides drive to the wheels or recharges the accumulators. This type of vehicle can be viewed as an electric vehicle equipped with a generator driven by a thermal engine (Fig. 5). The principal advantage of this type of
configuration is that the thermal engine can be made to operate in its most efficient manner and can be stopped when its use is no longer required; an almost constant speed of rotation of the drive shaft helps maximize fuel economy and reduce exhaust emissions. Because the conversion of the mechanical energy delivered by the thermal engine into electrical energy for driving the electric motor is very inefficient if the thermal engine is used as the primary energy source, series hybrid systems usually make use of a small thermal engine that supplies surplus energy to a fairly large battery pack. As a whole, this configuration suffers the disadvantages of requiring large accumulators and of being very inefficient in conditions of medium to high speed. These disadvantages are due to the losses involved in both the conversion of mechanical energy into electrical energy and the recharging and discharging of the accumulators. Moreover, in a series hybrid system, there are no mechanical links between the thermal engine and the wheels, that is, the thermal engine cannot provide drive directly to the vehicle.

**Parallel hybrid systems**

In the parallel hybrid systems, both the thermal engine and the electric motor are connected directly to the transmission to provide drive to the wheels. In this system the electric motor can also function as a generator to recharge the accumulators while the vehicle is in motion (Fig. 6). The principal advantage of this configuration is its ability to use relatively small accumulators. The mild hybrid system, operating in parallel, has an electric motor that is not, however, able both to assist the thermal engine and at the same time generate electrical energy for the accumulators; in other words, it is a parallel hybrid-electric vehicle that cannot be made to operate by means of the electric motor alone. Moreover, the parallel hybrid system is more complicated than a series system and presents a set of problems associated with the integration of the two motors. A mild type of hybrid system has been used by Honda since 1999 on their Insight and Civic Hybrid models; the system is called the IMA system (Integrated Motor Assist). On the Insight, the first hybrid-electric vehicle marketed in the United States, the electric motor is located between the 3-cylinder gasoline engine (of one litre) and the 5-speed manual gearbox; the motor is a direct current brushless motor (see below) and requires 60 mm of axial space, is connected directly to the drive shaft of the thermal engine and delivers a maximum of 10 kW of power. It provides power to supplement the thermal engine when necessary; it uses kinetic energy recovered under deceleration; and, when drive is not required, functions as a generator to recharge the NiMH accumulators (120 cells of 1.2 V, rated voltage of 144 V, and an overall mass of 22 kg). The same IMA system, combined with a continuously variable transmission CVT gearbox, was then adopted for the Honda Civic Hybrid in 2003. The Insight and the Civic Hybrid are capable of achieving excellent levels of fuel economy, 61 m.p.g. (over 25 km/l) and 48 m.p.g. (over 20 km/l) respectively, in the American urban cycle.

**Toyota THS and THS-II hybrid systems**

The hybrid system developed by Toyota for the first generation Prius (marketed in Japan in 1997) is called the THS (Toyota Hybrid System) and consists of an evolved version of the basic configuration of a parallel
hybrid system. The hybrid system in the Prius (see also Section 8.2.3) uses: 

a) a 1.5 litre thermal gasoline engine using the Atkinson cycle (high thermal efficiency and low performance), with variable inlet valve timing; 
b) a device for distributing the power (specifically, an epicycloidal transmission); 
c) an electric motor-generator (MG1) for recharging the accumulators while travelling and capable of restarting the thermal engine; 
d) a motor-generator (MG2) for driving the front wheels and regenerative braking; 
e) an inverter group to feed alternating current to the motor-generators; 
f) NiMH accumulators with a capacity of 2 kWh and an overall mass of 49 kg (38 modules of 6/11001 V1.2 V cells each, with a rated voltage of 273.6 V).

Compared to other systems with a similar complexity of construction, the THS offers significant operating flexibility, has an electronically controlled, continuously variable transmission gearbox (E-CVT), and does not require a conventional clutch-gearbox arrangement (Fig. 7). The system consists of alternating current electric motor-generators (synchronous motors by permanent magnets) and high voltage accumulators (direct current), with a power transformer to bring the voltage to the desired level, and an inverter, which can either perform the continuous-alternating conversion to feed the alternating current motor-generators or convert the alternating current produced by the motor-generators into continuous current to supply the accumulators. In this way, the system’s electric motor ensures the conversion into electrical energy of a part of the kinetic energy that is dissipated under deceleration and braking. The THS is a complete hybrid system that combines the principal advantages of series and parallel hybrid systems. Under low-load and low-speed conditions, the electric motor alone can provide the drive (provided that the state of charge of the accumulators is high enough), while under loaded conditions and higher speed, the thermal engine and the electric motor can be used in combination. THS automatically selects the optimal operating combination of the two motors. In the absence of any load, the thermal engine can be started to recharge the accumulators by means of the generator (Fig. 8). In summary, the primary functions of the THS introduced in the Prius are ‘stop and go’, regenerative braking, assistance to the thermal engine and all-electric drive.

There is no provision with THS for recharging the accumulators with public utility electricity and hence the Prius and the other hybrid-electric vehicles developed by Toyota can for all intents and purposes be defined as HEV-0 (hybrid-electric vehicles having no significant range in all-electric drive mode). One of the principal advantages of this configuration is, however,
the reduced size of the NiMH accumulators, which make it possible to use the available space primarily for passengers and their luggage. The Prius has achieved excellent fuel economy, with a good 51 m.p.g. (about 21 km/l) in the American combined cycle.

The new Prius, marketed in Japan and the United States in September 2003 and in Europe at the beginning of 2004, uses the THS-II (Hybrid Synergy Drive) system, which is an evolution of the THS. It requires, among other things, push-button selection of all-electric drive (EV), both for short distances (maximum of 2 km) and under specific conditions (sufficiently charged accumulators, maximum vehicle speed of less than 50 km/h, etc.).

Compared with the THS system of the first generation Prius, THS-II introduced the following improvements, among others: a) NiMH accumulators that take up less space and have a reduced mass (only 39 kg, a 14% reduction), that are capable of greater power density, and that have improved recharge and discharge characteristics; b) an inverter group with a 500 V power transformer to feed MG1 and MG2, compared with the 273.6 V of the previous model, which makes it possible to achieve a higher power output from the motor and lower feed currents (and hence lower dissipation of energy and greater efficiency) for the same level of power; c) an electric motor (MG2) with 50% more power (50 kW against 33 kW, today the greatest power density on the market); d) an electric motor with 14% more torque (400 Nm rather than 350 Nm); e) greater recharging capacity of the electric generator (MG1); f) an EV button to activate all-electric drive mode under the previously mentioned conditions.

The simplest configuration for a hybrid system involves an electric motor in line with the thermal engine. An initial possible variation of this configuration consists of supplying drive to an axle through a conventional thermal engine and to the other pair of wheels through an electric motor (or through a pair of electric motors). This system is called a through the road parallel hybrid system and has the principal advantage that it provides temporary all wheel drive (part-time AWD). This configuration also allows greater flexibility in the positioning of the electric motor. However, AWD function is limited to the energy available in the accumulators and the system involves a significant degree of complexity of construction and high costs. The Toyota Estima Hybrid, marketed in Japan in 2001, was the first vehicle in the world with a through the road parallel hybrid system, providing a front axle equipped with a thermal engine and an electric motor-generator, and a rear axle with a second electric motor capable of providing temporary all wheel drive. The electric motor-generators of the Estima Hybrid are capable of providing 13 kW and 18 kW of power respectively and are fed at 216 V. The electronic control system can select the optimal combination of the three motors and which of the motor-generators to use to recharge the NiMH accumulators.

The launch of the Lexus RX400h saw the first application of the Hybrid Synergy Drive system to a luxury SUV, thus creating an innovative, electronically controlled 4WD. The RX400h uses the same configuration as the Toyota Estima Hybrid, with an electric motor-generator for each axle and a high performance V6 gasoline engine for the front axle. The major features are: a) all wheel drive in driving conditions where it is necessary; b) all-electric drive, when the efficiency of the thermal engine is low (provided the state of charge of the accumulators permits it); c) recharging of the accumulators when the thermal engine is operating under medium-low load; d) integrated electronic management of the vehicle’s dynamics, also known as Vehicle Dynamics Integrated Management (VDIM), providing integrated control of the brake by wire braking system (with regenerative braking on both axles), of the steering, and of the entire THS-II hybrid system.

Compared with the preceding Lexus RX300 and other 4WD SUVs, the RX400h has a simplified drivetrain, without a central differential or propeller shaft (Fig. 9). Compared with the new Prius, the RX400h also includes: a) 650 V alternating current feed to the two motor-generators of the front axle and the one of the rear axle; b) NiMH accumulators capable of storing and delivering direct current electrical energy at 288 V (30 modules made up of eight 1.2 V
The electric motor-generator of the rear axle of the RX400h is used, together with the front axle motor-generator, when the vehicle starts from a standstill under conditions of low load, reverse gear, acceleration under full load, deceleration or regenerative braking. Under normal, medium-load driving conditions, the RX400h’s hybrid system interrupts the drive to the rear wheels in order to achieve greater fuel economy. However, as soon as the vehicle is driven over surfaces offering poor grip, or when it is subjected to sudden acceleration, the control system intervenes and restores the drive link between the front and rear axles in order to optimize the traction.

**Other types of hybrid systems**

One possibility to consider, as far as the operation of hybrid systems is concerned, is the external recharging of the accumulators by connection to the electricity grid. This system is called the *grid connected hybrid* and can be adopted by both series and parallel configurations. The advantage of this type of system is that it allows a greater driving range in all-electric mode, without the need to start the thermal engine. The disadvantage lies in the use of accumulators of significant dimensions, which are heavy and expensive, and require long recharging times.

**Components of hybrid systems**

**Electric motor**

Whatever hybrid system is adopted, an electric motor is used, mainly for the drive and regenerative braking, so its efficiency and torque characteristics are very important. Furthermore, if the electric motor is positioned between the thermal engine and the transmission, the compactness of its structure and its resistance to high temperature assume major importance. There are two types of electric motors: induction motors fed by alternating current; and permanent magnet motors fed by direct current, with windings arranged appropriately on the stator.

The alternating current motors are simpler and more economical, even though brushless permanent magnet electric motors fed by direct current, also known as Brushless Direct Current (BLDC), are more compact and lighter, and they also dissipate the heat more rapidly, all contributing to efficiency; but the cost of the magnets (the most efficient being made of neodymium) makes direct current motors more expensive.

Another factor of considerable importance is the feed voltage of the electric motor, on which depends the choice of accumulators and the power electronics. A higher voltage feed makes it possible to reduce the amperage of the current, to use smaller section cables, and to have more efficient motors and inverters. If the electric motor is placed between the fly-wheel and the clutch, it becomes important to have an electric motor that is as compact as possible to reduce the overall motor-transmission length; and this is particularly important in applications with front-wheel drive and transversally mounted motors, where the distance between the wheels is limited. For example, the Honda Civic Hybrid uses a BLDC electric motor with very compact windings to economize on space.

The Prius, since its first appearance on the market, has used two permanent magnet electric motor-generators fed by alternating current, one for driving the front-wheels and for recovering electrical energy under deceleration and when braking (MG2), and the other for starting-up the thermal engine as necessary and for recharging the accumulators (MG1). The MG2 motor features a maximum power output of 50 kW between 1,200 and 1,540 rpm and a maximum torque of 400 Nm between 0 and 1,200 rpm.

In the new Prius, the geometry of each permanent magnet inside the rotors of the MG2 motor has been optimized with a V configuration; this made possible a considerable improvement in the power and torque characteristics. The strength of the MG1’s rotor has been increased, which served to widen the operating field of the MG1 motor from 6,500 rpm to 10,000 rpm, improving its capacity to recharge the batteries. To manage the MG2 motor, a system has been developed to control the average speed conditions of the motor, with an increase in torque of up to 30% under these conditions. The feed to the MG1 and MG2 electric motor-generators is ensured by the use of high tension cables and high intensity current to connect the NiMH accumulators to the inverter group and this to the MG1 and MG2. Safety labels are provided that indicate the presence of high voltage circuits and the associated dangers of improper operation.

** Accumulators**

The accumulators are the primary source of electrical energy for hybrid-electric vehicles. The only reasonable alternative would be ultracapacitors, that is, a higher power and energy-specific version of electrolytic capacitors that store energy in an electrostatic form.
Unless there were a demand for a significant range in all-electric mode (HEV-20, HEV-40, or HEV-60 vehicles, that is, hybrid-electric vehicles with a range of 20, 40 or 60 miles without using the thermal engine), accumulators with relatively modest specifications and limited dimensions could be used. In its application to HEV-0 vehicles (such as the Prius), the accumulator supplies accumulated energy to assist the thermal engine during acceleration and in driving in conditions of low load and reduced speed, and it is also used in the regenerative braking phase. However, to obtain a substantial reduction in the dimensions of the thermal engine, the electric motor must be able to supply at least 50% of the torque in low speed conditions and at least 15% of the power of the thermal engine. Consequently the accumulators for hybrid-electric vehicles must be able to make available high levels of power during acceleration and absorb significant quantities of energy under deceleration and braking.

The accumulators developed until the 1990s for electric vehicles are not suitable for hybrid-electric vehicles. New accumulators have been designed to deliver a greater power density (power supplied per unit of mass of the battery pack), rather than the energy density (energy stored for every kg of the battery pack). Obviously the greater the quantity of energy that has to be stored inside the accumulators, the higher will be their cost and mass. Ultracapacitors have a very high power density, an excellent power release speed and they guarantee significant reliability and good cooling characteristics; however, since their energy density is very low, they are not able to accumulate the energy needed to assist the thermal engine in conditions of high load (for example, while being driven up-hill). This is why the manufacturers consider ultracapacitors only for providing momentary assistance to vehicles with fuel cells.

Below is an examination of the main types of accumulators used in hybrid vehicles.

**Lead-acid accumulators.** Compared with other types, lead-acid accumulators have a lower cost, a shorter life-cycle (a substitution interval of about 4 years, with a consequent increase in the effective costs of the system) and a relatively low energy density. Lead accumulators have until now been developed primarily for high power applications, with Valve Regulated Lead Acid (VRLA type technology, in which the pressure of the electrolyte, slightly above atmospheric, is regulated by means of valves), and there is some prospect that they could be used on some low-powered hybrid-electric vehicles because of their low cost.

**Nickel-metal-hydride accumulators (NiMH).** Research into NiMH accumulators had its start in the 1970s for the purpose of storing hydrogen for nickel-hydrogen accumulators. Today, nickel-hydrogen accumulators are used only for satellite applications, since the system is complex and very expensive. Initially the metallic hydride alloys appeared to be unstable and incapable of guaranteeing the desired performance, but since the late 1980s major progress has been made. The success of NiMH accumulators lies in their high energy density and in the use of environmentally compatible metals. NiMH accumulators are used in all the hybrid-electric vehicles already on the market (Toyota Prius, Honda Insight and Civic Hybrid, Lexus RX400h) and have been chosen by Ford and General Motors for their first hybrid technology models. The main advantages of NiMH accumulators are: *a) energy density 40% higher than that of nickel-cadmium accumulators, with the possibility of improving their performance still further; b) superior life cycle compared with lead acid accumulators; c) simplicity of storage and transportation; d) environmental compatibility, since they contain toxic substances only in small quantities.*

The disadvantages of NiMH accumulators are: *a) higher cost; b) limited duration if subjected to complete cycles (charge levels from 0 to 100%); c) limited discharge current, since elevated chargings reduce the duration of the accumulators—the best results are obtained by using the accumulators themselves at between 20 and 50% of their capacity; d) greater development of heat during the charging phase, with the impossibility of absorbing over-chargings; e) high static current (dissipation when at rest in the absence of external chargings), which can be reduced with special chemical additives at the cost of the energy density; f) reduced performance at high temperatures and at particularly low temperatures; g) the necessity of being used at least once every three months to avoid the formation of crystals.*

On the new Prius, as on the previous model, there is no provision for external charging of the battery pack; this is made up of 28 modules of 6 cells of 1.2 V each, for a rated direct current voltage of 201.6 V and an overall mass of barely 39 kg. The previous Prius instead had 38 modules of 1.2 V, for a rated voltage of 273.6 V. A more compact battery pack configuration has thus been obtained. Furthermore, on the new Prius the cells are connected at two points (instead of only one), and that has made possible a reduction in the internal resistance of the accumulators and therefore of the static current. Control of the temperature of the battery pack and the intensity of the currents that flow inside them is assured by a special Electronic Control Unit (ECU) that controls the operation of the cooling fan.

**Lithium ion accumulators.** Compared with other types of accumulators, in particular NiMH, the use of lithium ion accumulators shows promise because they
have higher energy and power densities; they also have better performances at low temperatures and less static current. However, lithium ion accumulators require considerable further improvement in terms of reliability and costs to become competitive in hybrid-electric vehicle applications.

**Power electronics**

Direct current electric motors use appropriate windings and need electronic commutation modules to control the flow of current on each of the windings during the rotation of the motor. These modules must be capable of commutating currents of high intensity very quickly while at the same time controlling the direction and the phase of the current itself; this makes it necessary to disperse large amounts of heat.

The dimensions and the cost of the power electronics used on a modern hybrid-electric vehicle are crucial because of the high power density required and the cooling demands. The power electronics also include a converter to provide a 12 V feed to the on-board electrical installation.

The new Prius has introduced significant changes for the whole inverter:

- The addition of a boost converter to transform the 201.6 V of the battery pack into the 500 V used for feeding the MG1 and MG2 motors. This converter consists of an Integrated Power Module (IPM), integrated with an Insulated Gate Bipolar Transistor (IGBT) that controls the commutation, and of a reactor that stores energy. Using these components, the converter amplifies the voltage for supply to the MG1 and MG2 motors. When the motors act as generators, the inverter transforms the alternating current into direct current, which the converter then transforms to 201.6 V to recharge the battery pack.
- The addition of an inverter dedicated to feeding the electric compressor for the A/C.
- Integration of the bridge circuits for feeding the MG1 and MG2 motors (each with six power transistors) in a drive power module.

**Cooling system**

Both the battery pack and the power electronics have to be cooled because the charging and discharging of the accumulators both develop heat, and high temperatures degrade the performances and the life cycle of the accumulators themselves. Thanks to the smaller amount of heat developed by the latest generation of power electronics, on hybrid-electric vehicles such as the Toyota Prius it has been possible to integrate the accumulators and the control circuits into a single unit, cooled by air with a dedicated fan. That has made possible substantial reductions in the dimensions and the mass of these components. On the new Prius, a water cooling circuit has been introduced especially for the converter group; it has a flow rate of over 10 l/min and a capacity of 2.7 l.

**Comparison of hybrid vehicles with vehicles with internal combustion engines**

**Reduction of the dimensions of internal combustion engines**

Since the highest torque and power are called for during the acceleration phase and up-hill sections, and a minimum of power is required to drive the vehicle at a constant speed on a level road, the use of an electric motor makes it possible to adopt a smaller thermal engine. Thermal engines with a smaller cylinder capacity are more efficient at a given load because they experience less internal friction, have a higher yield per unit of volume (lower pumping loss) and lower heat loss. In the case of the Toyota Prius, the first commercialized hybrid vehicle in the world, the thermal engine adopted (1.5 litres cylinder capacity, Atkinson cycle) has limited power and torque (57 kW and 115 Nm). In the new Prius, the presence of a high performance electric motor capable of producing up to 50 kW of power and 400 Nm of torque at low revolutions makes it possible to use the same thermal engine.

**Regenerative braking**

In conventional vehicles, a considerable amount of energy is lost during the deceleration and braking phase. This energy is consumed principally by the braking system and the internal friction of the engine (mechanical friction and pumping losses). In a hybrid-electric vehicle, instead, the electric motor is used as a generator to recover the above-mentioned energy and store it in the accumulators (use of the electric engine normally for drive vehicles, as a generator to recharge accumulators). In practice, a considerable part of the braking power is obtained through the electric brake of the motor-generator, and this has the effect of reducing the wear of the braking system’s friction pads (the brake pads).

In the new Prius, the front axle, on which the drive wheels are located, is connected mechanically to the MG2 motor-generator; during deceleration or braking, the drive wheels cause the MG2 motor to rotate, making it function as a generator. Regenerative braking, managed by a control system, does not rely only on the traditional hydraulic system to provide the braking power called for by the driver; consequently this control minimizes the loss of kinetic energy associated with traditional braking, recovering part of it and converting it into electrical energy. The sharing of the braking power between traditional braking and
regenerative braking varies according to the speed of the vehicle and the time. The braking power called for by the driver, after an initial transitory period, is supplied for the main part through regenerative braking power and only to a minor extent through traditional braking power. On the new Prius, the electronically controlled brake by wire system has effectively extended the usage intervals of regenerative braking.

**Switching off the thermal engine when idling**

Hybrid systems allow the thermal engine to be switched off when not under load, in particular when the vehicle is standing still (the stop and go function), which eliminates fuel consumption and emission of pollutants. The electric motor has sufficient power to restart the thermal engine, if necessary, in barely two-tenths of a second without any inconvenience to the driver. This function (which is also called idle off, and is equivalent to the stop and go function) alone results in a 5-10% reduction in fuel consumption.

**Thermal efficiency of the thermal engine**

Integrating an electric motor with a thermal engine improves the efficiency of the thermal engine substantially under various driving conditions. For example, the high torque of the electric motor allows the thermal engine to work at reduced levels, and therefore more efficiently, when driving at a constant speed on high speed roads, and at the same time it provides effective acceleration when needed. The assured thrust of the electric motor also permits the use of alternative variations of the thermal engine. For example, on the Prius the thermal engine uses the Atkinson cycle instead of the conventional Otto cycle (Fig. 10). A characteristic of the Atkinson cycle is a high expansion phase and reduced compression phase, achieved through a particular crank mechanism that allows the four strokes of the engine to be completed with just one revolution of the crankshaft; this cycle makes it possible to extract a greater amount of energy from the combustion cycle as a result also of the lower pumpage losses and of the exhaust. This is at the expense of the torque and the power developed by the thermal engine, but this is acceptable on a hybrid-electric vehicle that can count on the help of the electric motor during acceleration.

**Electric auxiliaries**

In a hybrid-electric vehicle the availability of additional electric power makes it possible to improve the efficiency of the thermal engine’s auxiliary systems (the A/C compressor, power steering pump, water pump, etc.). These are usually driven from the thermal engine’s drive shaft by means of belts, gearings or chains with very low mechanical efficiency, and their speed is dependent on the speed at which the thermal engine is running. The use of electric auxiliaries provides a much more efficient solution because they can be actuated only when needed and run at their optimal speed, independently of the speed of the thermal engine.

**Projects**

As already seen, bigger electric motors and accumulators provide an improvement in acceleration, a reduction in the size of the thermal engines, optimal braking regeneration, and the most efficient use of the auxiliaries. On the other hand, large accumulators are very expensive and the greater weight of the electric motors and accumulators affects the performance of the vehicle.

Each manufacturer has its own way of balancing the various factors, and the market will decide which
are the best choices. The various hybrid-electric vehicle projects are listed below.

System with integrated starter-generator. The simplest hybrid is the one with the starter motor and generator integrated, which entails a high-powered electric motor capable of stopping and restarting the thermal engine when necessary; the electric motor also ensures additional electric power for the auxiliaries. Hybrid-electric vehicles of this type are relatively cheap, but result in only a rather limited reduction in fuel consumption, between 5 and 10%.

Permanent hybrid system. A complete hybrid system involves the use of an electric motor capable of supplying the electric drive and actuating regenerative braking, and also a high voltage battery pack. This approach is decidedly more expensive, but makes it possible to reduce the size of the thermal engine and to integrate the functions of the thermal engine and the electric motor. A hybrid-electric vehicle of this type enables reductions in fuel consumption of from 20 to 50%; if instead the main objective is performance, the use of a complete hybrid system and a conventional size thermal engine makes it possible to obtain levels of power and torque never before achieved.

All-electric operation. In the all-electric mode of operating, running of the thermal engine under conditions when its efficiency is at its lowest (speeds below 25-30 km/h) is eliminated to the extent possible. Extending the operating period in all-electric mode calls for the use of bigger accumulators, thus foregoing the main advantages of HEV-0 type hybrid-electric vehicles (which have zero range in all-electric mode) such as the Prius, and thus also the reduced dimensions of the accumulators and the correspondingly greater space on board for passengers and baggage.

Hybrid system with external recharging. With accumulators that are designed to be recharged from the electricity grid, the costs are high, as is also the space taken up by the accumulators themselves. These factors, along with the length of time required for the recharging, seem to preclude the marketing of this type of hybrid-electric vehicle in the short term.

8.2.5 Strengths and weaknesses of hybrid-electric vehicles

Strengths
A study by the Electric Power Research Institute (EPRI) in 2002 compares HEV-0 type hybrid-electric vehicles (zero range in all-electric mode and no capability to recharge the NiMH accumulators from the electricity grid) against conventional vehicles with internal combustion engines. This study highlights the advantages of the HEV-0 type of vehicle: a) more economical fuel consumption; b) lower maintenance cost; c) greater range; d) a substantial reduction in the emission of pollutants responsible for the formation of smog (NOx and HC), from 10% for a compact saloon to 19% for an SUV; e) a substantial reduction in CO emissions, from 20% for a compact saloon to 30% for an SUV; f) a substantial reduction in CO2 emissions, at least 30%.

Weaknesses and obstacles to overcome
The main obstacle to the spread of hybrid-electric vehicles is the production cost of the accumulators, that is to say, the cost of on-board energy that can fuel electric propulsion in driving conditions of zero emissions. In the year 2000, a group of experts in the accumulators sector, the Battery Technical Advisory Panel (BTAP) calculated a limit of 600-1,200 operating cycles for an NiMH battery pack that is subjected to complete cycles (0-100%) of charge and discharge. The California Air Resources Board (ARB) estimated for the same accumulators a maximum lifespan of as little as six years or 75,000 miles, up to a maximum of ten years or 100,000 miles, before it was necessary to replace the entire battery pack.

These forecasts were reviewed, however, in a more recent study conducted by the Electric Power Research Institute in 2003; and this EPRI study, one of the first to analyse the cost of NiMH accumulator-equipped hybrid-electric vehicles over their entire life cycle, shows that these accumulators have made significant steps forward and are already capable of delivering excellent performance over a much longer lifecycle than previously anticipated. For example, the original NiMH accumulators in the Full Electric model of the Rav4 EV, after five years of actual usage, had travelled more than 100,000 miles without giving evidence of any problems, and vehicles of this type are designed to last for 130,000-150,000 miles; moreover, these results were obtained with first generation NiMH accumulators. Furthermore, laboratory tests have shown NiMH accumulators to have a lifespan of about 2,900 cycles at charge levels of between 80 and 20%. These estimates have also been confirmed by the research of the Ford Motor Corporation: using NiMH accumulators over a more restricted range of charge levels significantly prolongs their lifespan.

In summary, the results of the EPRI survey of the capabilities of NiMH accumulators were:
• Longer lifespan (in terms of operational cycles); just one battery pack per vehicle can last the whole life of the vehicle (a prospect of 130,000-150,000 miles).
• Hybrid-electric vehicles (both with zero range, like the HEV-0, and with limited range, like the HEV-20) are capable of equalling conventional
vehicles in terms of cost over their entire life cycle (purchase cost, fuel cost, maintenance cost).

- Current marketing of HEV-0 type hybrid-electric vehicles, with a forecasted production of over a million units by the year 2010, will bring about a reduction of the production costs of the high technology components, such as high power density electric motors, various parts of the power electronics (in particular the inverters) and hardware.

- While in the past (the late 1990s) a target of 150 $/kWh was set for the cost of accumulators for hybrid-electric vehicles, the latest survey by EPRI concludes that this limit could be between $380 and 471, thanks to the reduction in cost of the other hybrid components (electric motor-generators, power electronics etc.) due to the proliferation of HEV-0 vehicles.

- Compared with conventional vehicles, for an equal overall life cycle cost, hybrid-electric vehicles can reduce emissions of pollutants and greenhouse gases and the consumption of fossil fuels.

8.2.6 Possible developments in components for hybrid-electric vehicles

Electric motor

Because the permanent magnet constitutes one of the prime costs of the electric motors used in hybrid-electric vehicles, and the related technology is already advanced, large reductions of cost in this sector are not anticipated. In the first hybrid-electric vehicles, there have been additional costs for the integration of these motors into newly introduced systems; this cost will come down with the spread of hybrid technology and increases in production volumes. Furthermore, there may be additional decreases in costs over the long term with the introduction of electric motors with reluctance commutation which, compared with brushless direct current motors, offer good efficiency within acceptable space and cost.

Accumulators

In hybrid-electric vehicles with internal combustion engines capable of recharging the accumulators while travelling, the battery pack is not so big that it must occupy the space used for the back seats and the boot or trunk. In the future, if a limited number of cells is sufficient, it is possible to foresee the use of high-tech accumulators of nickel-metal-hydride, lithium ion, and perhaps metallic lithium polymers. In the short term, NiMH accumulators seem to be the leading choice because of their higher power density, their longer life cycle and their better response to short demands for high power; all of this despite their relatively high cost and the degree of cooling required. Lithium ion accumulators require considerable improvement, as far as their life cycle and cost are concerned, before being applied to widely marketed hybrid-electric vehicles.

This type of accumulator could find limited use in applications that require high performance at low temperature.

The efforts made by European and North American groups show that even lead acid accumulators can prove competitive in terms of price and performance. What is more, hybrid-electric vehicles use only a part of the interval between the maximum state of charge (100%) and the minimum (0%), and that gives lead acid accumulators a chance to achieve acceptable performance at reasonable cost. To compete with the other types, lead acid accumulators will have to extend their lifespan to at least ten years, given that today Honda and Toyota already offer eight years and 80,000/100,000 miles of guarantee on the Civic Hybrid and the Prius respectively. The Advanced Lead Acid Battery Consortium (ALABC) are running (as of 2005) a research programme for the development of lead acid accumulators intended for operation in partial charge conditions and in hybrid-electric vehicle applications. A similar European consortium, the European Advanced Lead Acid Battery Consortium (EALABC), including Hawker Batteries, Provector, Sheffield University and Warwick University, is trying to replace the accumulators of the Honda Insight (the first mild hybrid in the world to be marketed on a large scale) with a lead acid battery pack. The 144 V system requires the use of 72 cells, for a total accumulator capacity of 936 Wh. This experimentation should lead to an improvement in the characteristics of lead acid accumulators, and has the objective of reducing production costs below the amounts required by other types of accumulator (nickel-metal-hydride and lithium ion), based on the assumption of a production level of more than 100,000 units per year (with a cost of 300$/kWh).

One possibility that could be put into practice in the long term would be to combine a small size battery pack with an ultracapacitor capable of providing very high power density (but with reduced energy density). This solution would make it possible to exploit the thrust and the regenerative capacity of the ultracapacitor while at the same time using a much smaller battery pack (at a lower cost). For now, however, it remains to be seen whether those savings would compensate for the greater cost of developing and producing the ultracapacitor.

General Motors has announced the use of lead acid accumulators in its next line of hybrid-electric vehicles,
starting with the Saturn SUV (2005), indicating a cost 25% less than that of nickel-metal-hydride accumulators.

**Power electronics**
As in all other applications, the electronic components adopted in the design of hybrid-electric vehicles are intended to improve performance and reduce production costs. In particular, it is hoped that components will be introduced that require less cooling, offer higher performance and make possible solutions that are more integrated and less bulky. In this regard, it should be noted that hybrid systems will increasingly have to support the introduction of electrical auxiliary components to replace the conventional mechanical and hydraulic components. This will help to reduce costs and to supply customers with an ever greater range of accessories.

### 8.2.7 The future of the market for hybrid-electric vehicles

**Factors for success**
The success of hybrid-electric vehicles depends on a range of factors, among them the price, the performance, the cost of ownership and the manufacturers’ guarantees for the hybrid components.

As far as the price is concerned, hybrid technology should be able to ensure more economical fuel consumption and lower exhaust emissions. It remains to be seen whether the consumers will be willing to pay a slightly higher price to contribute towards the development and spread of a means of transport with a lower environmental impact.

The competitiveness of the hybrid solution has yet to be determined, especially in terms of its price/performance ratio. To reach reduced levels of consumption and emissions, hybrid technology does not in any way sacrifice pick-up and acceleration. The synergy between the internal combustion engine and the electric motor results in extraordinary low speed torque (for example, 478 Nm) and an equally impressive level of power (83 KW) under conditions of high load and speed. In the North American market, in particular, it seems to be important to extend hybrid technology to the SUV sector, in which about 40% of sales take place. Hybrid-electric SUVs could lead to a significant reduction in the overall consumption of petroleum and in the release of pollutants.

As far as cost of ownership is concerned, the Prius is already demonstrating that hybrid technology does not carry additional costs for the user in terms of ordinary or extraordinary periodic maintenance. For example, only 4.2 hours of periodic maintenance are needed in the first 100,000 km of life, with periodic maintenance intervals and operations similar in all respects to those of a compact car. Furthermore, the manufacturer does not anticipate a limited operational lifespan for the principal components of a hybrid system, such as the NiMH accumulators.

The guarantee is a key element for the success of hybrid-electric vehicles. The new Prius, for example, is sold on the European market with an eight year or 160,000 km guarantee on all the hybrid components (accumulators included), compared with a total guarantee of three years or 100,000 km for the rest of the vehicle.

**New vehicles and market prospects**
In 2002, hybrid-electric vehicles being sold in the United States market reached about 1% of the total number of vehicles sold by the hybrid manufacturing companies, exceeding 35,000 units. The increase for that type of vehicle, compared with 2001, was 77%. According to some analysts, the new hybrid-electric vehicles should appeal to families with children, and therefore have the characteristics of an SUV. For this reason the main American manufacturers have announced the launch into the market of a series of SUVs: the Dodge Ram pickup from DaimlerChrysler (2005); the Escape SUV from Ford (2004); and from General Motors the Chevy Silverado pickup (2004), the GMC Sierra pickup (2004), the Saturn Vue SUV (2005) and the Chevrolet Tahoe SUV (2007).

The Ford Escape Hybrid, in particular, is the result of an acquisition by Ford of a set of important Toyota patents and a collaboration of Ford with Aisin (a Japanese firm part-owned by Toyota that developed certain hybrid components for the Escape). The Escape applies the fundamental principles of the Hybrid Synergy Drive (used in the new Prius) to a small size SUV.

In addition, as indicated in the following examples, hybrid-electric vehicles are now entering the luxury car sector.

The Lexus RX400h, for which over 10,000 orders were placed prior to its launch in the United States, was the first luxury SUV fitted with hybrid technology and intelligent integrated drive.

For 2005, Toyota planned to use hybrid technology from the RX400h on the Highlander hybrid, an SUV with seven seats capable of covering 27.6 miles on one gallon of petrol (about 11.5 km/l) in the combined cycle, giving a range of nearly 1,000 km with one filling.

For the Mercedes Grand Sports Tourer, expected in 2005 on the United States market, a V8 diesel engine of 184 kW is anticipated, combined with a 50 kW electric motor (combined power 234 kW; maximum torque 860Nm).
Porsche has examined the possibility of using the Toyota hybrid system for the Cayenne.

All in all, the path opened up by the Japanese companies Toyota and Honda is, and always will be, the one most followed by the majority of the other major car manufacturers; and the American market is where the launch of new hybrid-electric vehicles is most keenly awaited.

As far as future prospects are concerned, according to a study carried out in 2002-03 by Autobytel (a firm operating in the automobile market):

- 90% of potential clients interviewed on-line would have considered buying a hybrid-electric vehicle if one had been offered in the same model that they possessed.
- Only 16% of potential clients said they would have given up something in terms of power and acceleration.
- Only 36% said they believed in the possibility of hybrid-electric vehicles having the same performance as conventional gasoline-driven vehicles.
- 44% of the women said they were not very well informed on hybrid technology, confessing that it was only during the interview that they understood for the first time the meaning of the word “hybrid” as applied to a car.
- 31% of the men admitted to having very little knowledge of hybrid technology.
- Only a minority of those interviewed (9% of the women and 13% of the men) considered the financial incentive ($1,500) to be a decisive factor in choosing to buy a hybrid-electric vehicle.
- 43% of the women and 34% of the men said they were prepared to spend $1,000-2,000 more to acquire a hybrid-electric vehicle capable of consuming less fuel.

Since the European Union is dedicated above all to reducing the release of CO₂, rather than to lowering emissions of NOₓ, European manufacturers (such as Renault and Fiat), unlike those in America and Japan, pay more attention to the mild type of hybrid-electric vehicles. According to Frost and Sullivan, a consultancy firm specializing on global growth, hybrid-electric vehicles are destined to gain 10% of the European market by 2015, tripling their penetration in the period 2010-15 alone. Everyone agrees on the fact that the costs of hybrid systems ought to decrease as the market increases; as a consequence, the lower costs will attract new clients, and it is foreseeable, according to other studies, that hybrid-electric vehicles will reach 1% of the market in 2005, 3% in 2009 and 5% in 2013. However, it is not clear whether the percentage of hybrid-electric vehicles will remain at 5-10% of the market, or whether the costs will fall still further, giving them access to a mass market. The industry can give the market a push by producing hybrid-electric vehicles that match the demands of the potential clients, but customers cannot be forced to buy products that they do not want. Government programmes dedicated to stimulating the demand for hybrid-electric vehicles, by providing incentives and educating customers so as to raise their environmental awareness, could have a considerable influence on the hybrid-electric vehicle market.

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