François Badin believes that electrification is destined to play a key role in the optimisation of future vehicles

Electrifying the propulsion systems of vehicles provides a number of functions that can help reduce energy consumption. This is achieved by optimising the operating conditions of the heat engine and by recovering a variable fraction of the available energy during braking in hybrids that we will hereinafter call 'discrete'. The simplest systems, which make it possible to eliminate idling, yield fuel savings of 5 to 7 percent in the standardised European cycle. The most complex systems, which provide more functions, lead to savings of up to 40 percent.

Electrification also allows the creation of additional functions, of benefit to the users of the vehicle or to the community, such as all-electric range and connection to the grid. Implementation of these functions will require the addition of electric motors that will be coupled to the engine in various architectures – series, parallel, series-parallel, and all-electric – and will be more or less compatible with the existing components (transmission or wheel).

The announcements of the various automakers and equipment suppliers suggest that vehicle electrification may accelerate in the future, and constitute an opportunity in today's difficult economic and environmental context. The penetration of electrification among vehicles sold will then depend on the successes achieved in mastering energy storage, costs, and industrial production.

Situation of Vehicles with Conventional Propulsion Systems

This can be illustrated through the three examples described below.

Electricity on Board

The primary function of a vehicle's propulsion system is to move it, but the following remarks may be made:

- the increasing number of functions performed on board, for comfort, safety, and communication, has led to an increase of the number of electrical actuators and in consequence of the power of the on-board network. This power passed the 1000 W mark in the 1980s, doubled by 2000, and may reach nearly 5000 W in 2010;
- the mean power needed to move a vehicle is less than 10 kW for urban trips on level ground, and so of the same order of magnitude as the power of the on-board electrical network.

This convergence of power levels indicates that, for some types of use, it may be worthwhile to use electrical energy in the vehicle's propulsion system.

The Energies Involved

If we consider the flows of energy involved when a vehicle travels on a level road, we find that they depend on three forces: aerodynamic drag, rolling resistance, and inertia. The energy associated with the first two forces is dissipative and is lost as heat. The third force is a potential that can be recovered each time the vehicle decelerates. Analysis of these flows shows that the potential for energy recovery under urban conditions is very large and that it quickly falls off when traffic conditions become more fluid.[1]

Conditions of the Use of the Internal Combustion Engine

Analysis of engine operating conditions shows that they are very sensitive to the use made of the vehicle. Engine speeds and loads are low under urban conditions, leading to rather low efficiencies, whereas under open road and motorway conditions the zones of operation are close to the peak efficiencies of the engine.

If we consider the use of the vehicle itself, it becomes apparent that many trips are too short for the engine and exhaust gas treatment system to reach their optimal temperatures.

As we shall see below, electrification of the propulsion system can significantly improve the conditions of use of internal combustion engines and thereby reduce their harmful effects.

Functions Provided by Electrification

The various functions listed below are implemented in the vehicle primarily for the purpose of reducing fuel consumption. The vehicles concerned, which can be called 'discrete hybrids', provide no other new functions.

1 *Le génie électrique automobile: La traction électrique:* Alleau T., Badin F., Beretta J., Bleijs C., Bonal J. (2005). Hermès Science, Traité EGEM – Série Génie électrique. Paris: Lavoisier.

Optimised Management of Electrical Energy on Board

Electricity is produced on board conventional vehicles by a belt-driven alternator that delivers power via a diode rectifier bridge to the on-board 12-V network. Until recently, such a system was optimised mainly in terms of cost, to the detriment of global efficiency, limited to between 50 and 60 percent. The increasing power of the on-board network and the search for minimum consumption has led equipment suppliers to improve the system, its electronics, and its control.

> "electrification of the propulsion system can significantly improve the conditions of use of internal combustion engines and thereby reduce their harmful effects"

In an optimised system, the energy delivered by the alternator is not determined solely by the consumption on the on-board network, but can be coordinated with the use of the vehicle. Recharging the battery is for example favoured during decelerations, when the engine is driven by the wheels, for the purpose of reducing fuel consumption by recovering a fraction – even if it is still a very small one – of the energy of deceleration.

While it is true that this approach has limited effects, it is very inexpensive and could come into widespread use in the short term.

Stop–Start System

The function implemented in this system, also called 'micro hybrid', is stopping the engine when it is not producing motive power for the vehicle, in other words essentially eliminating idling. The fuel savings, and the reduction of CO_2 emissions, will therefore be greater to the extent that idling accounts for a significant share of running conditions: for a mid-sized car, if the measured saving is 5 to 7 percent in the standardised European MVEG cycle, it can reach 10 to 15 percent in an urban type cycle but will be negligible in motorway type use.

The implementation of this function depends on the possibility of engine starts that are dependable, clean (in terms of regulated pollutants), rapid (a few tenths of a second), quiet, vibration-free and automatic (in response to driver action on the pedals). The engine is started by a motor that is more powerful than a starter (2 to 4 kW), can be linked by belt to the engine, and can also be used as a generator.

Such systems retain energy storage using optimised 12-V lead-acid batteries and add only a few hundred Euros to a vehicle's cost. They are currently implemented in vehicles that are primarily urban, in which the potential fuel savings are largest.

Stop–Start System with Regenerative Braking

These other systems are derived from those just described but use a more powerful motor (4 to 6 kW, belt-driven) and a storage system combining a lead-acid battery and supercapacitors. This configuration recovers a fraction of the energy available during braking and can start larger gasoline and diesel engines, and so be used in more vehicles. Highly satisfactory preliminary results have been obtained.

Regenerative braking increases the fuel savings, which could then reach, in a passenger car, 10 to 12 percent in the standardised cycle. The presence of the supercapacitors makes it possible to run the motor at a higher voltage (42 Volts), but requires the use of a DC/DC converter to supply the 12-V on-board auxiliaries network.

The use of a more powerful motor and new components (supercapacitors, converter) adds to the cost of this system (of the order of 500 to 900 Euros), so it will not spread as rapidly as the previous one.

Engine Assistance

In this configuration (called 'mild hybrid'), a more powerful electric motor (10 to 20 kW) is used, making it possible, in addition to the functions already mentioned, to assist the engine by providing additional torque during driving phases ('boost' mode). The torque curve obtained by combining the heat engine and electric motor preserves good performance at low engine speeds, like a turbocharged diesel engine, while using a severely downsized gasoline engine.

The automaker Honda markets this configuration with its IMA system implemented on the Insight and the Civic. The electric motor, characterised by a very high ratio of diameter to length, is fitted on the end of the crankshaft, in place of the flywheel, between the engine and the transmission. For this power level, the storage voltage is generally 120 to 150 V, with a total energy of less than 1 kWh. In this vehicle, compared to its gasoline equivalent, the fuel savings are of the order of 30 percent under urban conditions, 15 to 25 percent in the standardised European MVEG cycle, and very low under extra-urban conditions. The added cost of this system will be higher, in the range of 1000 to 2200 Euros.

All-electric Mode

This function allows the vehicle to run using its electric propulsion system alone; in other words, the engine can be isolated from the transmission and stopped during these phases. This 'full hybrid' configuration provides many more ways to optimise the operation of the engine, since most of the low-efficiency situations can be offloaded to the all-electric mode. The electric propulsion system will be larger here, with a 20 to 50 kW motor, storage at a voltage of 200 to 300 V, and a total energy of 1 to 2 kWh.

The very high level of optimisation that will be possible in the use of the engine will lead to extremely high fuel savings, up to 40 percent in urban conditions, where conventional propulsion systems are least efficient. These relative savings fall off, to between 10 and 20 percent under open-road conditions and become nearly negligible on motorways. The complexity of this system and the dimensioning of its components induce however a large added cost, currently estimated at between 2500 and 5000 Euros. The most widely used hybrid to date, the Toyota Prius, implements all of these functions.

Optimised Management

These various operating modes must be used in a dynamic manner, changing in the course of use of the vehicle, and make allowance for the state of the various components, in particular the state of charge of the energy storage system. This complex management cannot be entrusted to the driver, so automakers, equipment suppliers, and research laboratories have developed complex software specific to the management of hybrid propulsion systems.

The objective is to ensure optimal management and control of the components in order to minimise the energy consumption of the vehicle while preserving its performance and if possible enhancing its drivability. In the near future, the management laws might make allowance for the parameters of the vehicle's environment, such as traffic conditions and relief, and for fleet operating parameters.

Complementary Functions

The functions listed below will enable a hybrid vehicle, one that might be called a 'functional hybrid', to provide one or more advantages for the driver, the passengers, or the local or global environment. Such additional functions should help justify the added cost of the vehicle by extending its uses (entering a downtown area closed to polluting vehicles) or by reducing its energy cost (use of another energy vector).

Electric Mode with Range

This complements the electric mode presented above, from which it is distinguished by the fact that the driver, or possibly an external infrastructure, will be able to stop the engine and keep it off for a specified distance (the 'all-electric range' or 'AER', of the order of 5 to 20 km in Europe, up to 60 km planned in the United States). This operation without local harmful effects makes it possible to consider special uses of the vehicles, such as night deliveries in city centres.

Connection to the Grid

Grid recharging: In a discrete hybrid, the battery's 'state of charge' (SoC, conventionally 100 percent in the fully charged state and 0 percent in the discharged state) is constantly kept close to an intermediate value (generally 50 to 60 percent; this is the 'charge sustaining' mode); in the grid recharging case the energy management system lets the SoC drift (this is the 'charge depleting' mode) down to a lower limit generally determined as a function of aging and performance (of the order of 20 percent). The battery can then be recharged from the grid ('plug-in' hybrid).

> "cooperation with local and national authorities will have to be reinforced so that progress can be made in the areas of standards, incentives, and energy infrastructure"

This function will make it possible to shift consumption from a hydrocarbon to another primary source of energy, using electricity as vector. Because of the size of the battery, the added cost of the all-electric range and grid recharging solutions will be very high; the price range estimated using current data is 5000 to 20,000 Euros.

Exchange of energy with the grid: This is derived from the one just described, but in this case the system will be capable of providing energy compatible with that of the distribution grid:

- to a home network
- to the distribution grid, for the purpose of facilitating regulation by the operators, in particular with respect to supply at consumption peaks
- to the vehicle itself, from 110 or 220 V AC outlets serving to supply auxiliaries for comfort or for work.

The first two will require the use of two-way power grids capable of managing safety functions, operation, and metering in all of these cases, which may require large investments ('smart grid' concept).

Distributed Propulsion

The use of electric motors for propulsion makes it possible to consider innovative architectures, for example propulsion of the rear wheels in a FWD hybrid. The quasi-instantaneous activation of the rear electric motor makes it possible to have a vehicle that is 4WD only when necessary, in other words to enhance safety and drivability while helping to reduce energy consumption through the optimisation of regenerative braking on all four wheels.

Propulsion Architectures

The implementation of the functions described will require the introduction of electric drive motors that can be coupled to the propulsion system in several different ways:

- series coupling, similar to electric propulsion, with a heat engine that is not connected to the driving wheels but powers a generator. The advantages of this solution are that the engine is completely isolated from variations of the power and torque demand of the vehicle, full performance is available in the electric mode, and the solution is simple to control. On the other hand, this coupling requires two electric drive motors, and the efficiency of transmission from the engine to the wheels is low.
- parallel coupling, close to a conventional propulsion system in which an electric motor is mechanically coupled to the transmission. This configuration provides a large number of possible variants as regards the position of the motor (on the drive shaft or not) and its coupling to the transmission (before or after the gearbox, on

the engine and so on). Parallel coupling requires only one electric motor, the power of which can vary according to the functions provided, and allows efficient use of the engine. On the other hand, its performance in the electric mode is more limited, and controlling it is more complex.

- series-parallel coupling or power split, developed for the purpose of maximising savings by combining the advantages of the two possible configurations.
- All-electric architecture, the ultimate step in electrification of the propulsion system, with an all-electric vehicle comprising one or more electric drive motors and an on-board electrical energy storage system. There have already been attempts to manufacture electric vehicles industrially in the past, notably in France and the United States, which were not followed up. However, advances not only in electrochemistry and battery management, but also in the electrical engineering of the motors and in communication (locations of charging stations, and so on) and services (battery exchange), have encouraged manufacturers to propose new products. These latest-generation electric vehicles have ranges of 100 to 200 km and could replace conventional vehicles in a non-negligible share of uses, in particular semi-urban and urban uses. Several automakers, among them Renault-Nissan and Mitsubishi, along with Chinese automakers, have for example announced the marketing of electric vehicles between 2010 and 2012. The prices of these vehicles, equipped with 20 to 30 kWh of lithium batteries, are still very high, with added costs of the order of 10,000 to 20,000 Euros, but progress is expected with the arrival of mass production.

Problems and Prospects

Electrification is destined to play a key role in the optimisation of future vehicles, facilitated by the possibility of implementing it at more or less high levels, making its introduction gradual and thereby facilitating the adaptation of industrial infrastructures. This will make it possible to reduce the fuel consumption of vehicles, to levels that will depend on the degree of complexity chosen and the use of the vehicle, and also to implement such new functions as all-electric range or grid recharging. For these last cases, using electricity as vector will serve to reduce greenhouse gas emissions, dependency on oil and gas, and local harmful effects.

The automakers have already developed, and some of them have brought to market, various hybrid or electric propulsion system concepts. However, it would seem that massive penetration, which is necessary for a real impact on the greenhouse effect, depends on the handling of a number of factors, among them:

- energy storage, in particular the management and safety of lithium battery packs large enough for vehicles, their packaging, aging conditions, costs, new materials.
- the electric propulsion system and auxiliaries, in particular reduction of the volume and cost, improvement of performance in use and of reliability, and better integration;
- recharging infrastructure, in particular accessibility, safety, communication, metering, cost;
- life cycle analysis methodologies. These are necessary in order to determine the true footprint of the vehicle and of its components, from manufacture to recycling, and any problems concerning the availability of materials.
- the sensitivity of the fuel savings to the conditions of use of the vehicle and to the propulsion system technologies (gasoline, diesel), which will require judicious choices for the various types of application.

There are many research programmes under way aimed at progress on these various points. Concurrently, many automakers are planning to put models on the market as early as 2010–2012, after validation in test fleets. For hybrid vehicles, all technologies combined, world market forecasts suggest sales ranging from 3.5 to 8 million units by 2015, or more than 10 percent of all sales on the high assumption.

In a difficult economic context, such a change calls for setting up many collaborative ventures between partners, which already exist between automakers and storage system suppliers and between automakers and suppliers of electric power. At the same time, cooperation with local and national authorities will have to be reinforced so that progress can be made in the areas of standards, incentives, and energy infrastructure.

The determination of the various participants and the developments that have already taken place allow one to think that the electrification of vehicles could be an asset for manufacturers in the sector in the difficult economic and environmental context we are experiencing. The level of electrification of the vehicles sold will depend on success in mastering energy storage, costs, and industrial production.