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The electrification of vehicles

IFP's work

The transport sector today is facing a number of limitations and obstacles: fluctuating fuel prices, increasingly stringent pollution control standards, the pressing issue of controlling CO_2 emissions and reducing reliance on oil. It is not a question of seeking one single technology to provide all the answers to these challenges. But among the solutions being considered, the electrification of vehicles seems highly promising in terms of reducing fuel consumption, mitigating the environmental footprint and diversifying energy sources. The low-carbon vehicle plan launched by the French government paves the way for the emergence of a range of rechargeable electric and hybrid vehicles by 2012.

IFP is building on its expertise in the key areas of engine technologies, modeling and simulation to step up the development and marketing of hybrid vehicles, working in close partnership with manufacturers.

A solution to optimize onboard vehicle energy management

Hybrid vehicles which combine an internal combustion engine, an electric motor and their respective energy storage systems (fuel tank and battery) offer considerable potential in terms of reducing CO_2 emissions. The combination makes it possible to choose the optimum propulsion mode (internal combustion, electric or combined) as a function of the driving cycle and, in particular, to reserve the use of the IC engine when it is most efficient (mainly areas outside towns and cities). Hybrid vehicles, therefore, are likely to develop on an unprecedented scale over the coming decades and by 2018 they could well account for between 6 and 7% of global market sales.

Increasing electrification

The electrical energy available onboard vehicles for powertrain requirements is set to be gradually increased and many more potential solutions will be made available. The first technology to be developed will be the micro hybridization – at low additional cost - *stop&start* system. This technology consists in cutting out the conventional engine when the vehicle is at a standstill. The fuel savings (and hence corresponding reduction in CO_2 emissions) amount to between 5 and 7% over the mixed cycle and between 10 and 15% in the urban cycle. A second, more ambitious configuration, known as *mild hybrid*, consists in assisting the conventional engine while the vehicle is moving. The associated fuel savings are around 30% in urban conditions. Lastly, the *full hybrid* configuration – as is the case with the Toyota Prius, the hybrid model par excellence – allows the vehicle to operate in all-electric mode over very short distances. *"This hybrid mode provides the most options when it comes to optimizing the performance of the IC engine since most of the unfavorable situations encountered (low load-low speed range of the conventional engine) can be performed in all-electric mode",* specifies François Badin, Expert Director hybrid vehicles and powertrains in IFP's Energy Applications Techniques Division. Fuel savings amount to 40% in urban conditions and between 10 and 20% on main roads. However, fuel savings on motorways are virtually nil. In the medium term, 2nd generation hybrids – rechargeable hybrid vehicles capable of covering longer distances in all-electric mode (10 to 60 km) that can be recharged from the mains grid ('plug-in') -, are likely to appear.

Furthermore, in the long term, 100% electric powertrain solutions with a range of between 100 and 200 km can be considered, particularly for the urban and peri-urban driving. An appropriate recharging infrastructure will be required before this technology can be rolled out however.

Depending on the intended market segment and usage, the choice will be made on the basis of the best compromise between the gains and savings (energy performance and CO_2 emission reductions) and the additional cost associated with the onboard system and infrastructures. However, in order to make these technologies competitive, some major challenges remain relative to the cost of the equipment as well as their performance and durability (particularly concerning the battery).

IFP and hybrid technology: a global approach

To meet these challenges, IFP is conducting R&D work in the field of hybrid technology, from the development of engine simulators to the production of demonstrators. Research covers 1^{st} generation vehicles as well as 2^{nd} generation rechargeable hybrid vehicles and urban electric vehicles. Irrespective of the degree of electrification, the aims are ambitious: to minimize vehicle energy consumption, adapt to future pollutant emissions standards and maintain drivability.

Designing internal combustion engines dedicated to the hybrid

IFP is conducting research on internal combustion engines dedicated to the hybrid in order to make full use of the advantages offered by hybridization.
"First and foremost, we need to take advantage of the good complementarity that exists between electric and internal combustion engines when used in combination", points out Pierre Leduc, 'Hybrid Powertrains' project manager in IFP's Energy Applications Techniques Division. Using the electric engine, particularly in driving configurations where there is a reduced demand for power, makes it possible to reserve the use of the conventional engine when performance can be optimized (increased compression ratio for petrol engines, reduced turbocharging limitations for diesel engines).

Furthermore, with frequent stopping and starting – an average of once per minute in towns and cities – the internal combustion engine in a hybrid vehicle requires appropriate management in order to maintain drivability (modification of apparent compression ratio via variable distribution, for example).

Lastly, pollution control issues must be tackled specifically, particularly taking into account problems brought about when the vehicle is entering the stop phase and the increased stress on the internal combustion engine when it is operating. In the case of the diesel engine, the tuning trade-offs must be re-optimized to compensate for the increased risk of NOx emissions.

Virtual models with real test benches: IFP's systematic approach

The complexity of hybrid vehicles - which combine two powertrain and storage systems with a broad variety of architectures - requires consideration of the integration and optimized management of all the components from an early stage. To reduce development costs and time, IFP has adopted an innovative method which combines virtual models via modeling and physical testing. The method is applied to the components (battery, electric motor) as well as vehicle energy management. The method initially hinges around the design of reliable mathematical models, validated on experimental test benches where predictions are compared with actual measurements. These models make it possible to optimize the sizing and characteristics of the various components, indeed the complex architecture of the vehicle. The models are then translated into control algorithms – in other words software – that are integrated into onboard controllers with a view to predicting and managing the component's function in real time.

Such use of real time algorithms is one of the keys to the large-scale development of hybrid vehicles: it makes it possible to control the battery charge at all times and throughout its lifespan as well as the distribution of power between the internal combustion engine and the electric motor. The vehicle's complex architecture can also be controlled in the same way. *"We're developing the complete engineering chain, from simulation to the experimental phases, combining simulation tools and real test benches for internal combustion engines, but also for batteries and electric motors",* sums up Gilles Corde, Head of the Control, Signal Processing and Real-Time Computing Department in IFP's Technology, Computer Science and Applied Mathematics Division. Changes in component parameters can be made directly in the software on the engine bench (electric motor power, vehicle mass, etc) and their impact on CO_2 emissions and drivability analyzed*. "Thanks to our mathematical tools",* he adds, *"we can use simulation at each of the stages and quantify performance, in other words, compare various architectures and make informed choice in terms of components".*

Developing reliable and accurate battery models

In hybrid vehicles, the battery is responsible for intermittent and reversible energy storage. In order to optimize the management of this complex equipment, knowledge – precise and at any given time – of the battery's energy reserve or 'state of charge' is crucial so that the information can be used to maximize the battery's 'health', in other words its lifespan. *"Current research is aimed at gaining a better understanding of the battery's state of charge in order to increase its working range and hence minimize fuel consumption and CO_2 emissions and limit battery weight",* explains Valérie Sauvant-Moynot, battery project manager in IFP's Applied Chemistry and Physical Chemistry Division. *"Ultimately, with a reliable estimate of a battery's state of charge and state of health, we are confident that we can increase its lifespan for the same vehicle autonomy, and hence reduce the cost".*

With this in mind, in 2007, IFP's researchers began developing models capable of describing the electrochemical and thermal phenomena at play in Ni-MH (nickel metal hydride) and Li-ion (lithium ion) batteries while operating. To test the models, IFP has sophisticated tools at its disposal: a 'power bench' to test the characteristics and function of commercially-available batteries (500V -500A) and 4 test benches to test cells (50 V - 200A). *"Our model predicts the battery voltage in the Prius to within 2% in standard use conditions with onboard controller, something that is unprecedented!",* asserts Valérie Sauvant-Moynot.

Estimating the state of charge of batteries in real time

IFP's mathematicians then transformed these electrochemical models into control algorithms to estimate the battery's state of charge in real time, and consequently the power available at any given time. These estimators have been incorporated into the battery controller – the BMS or *Battery Management System -,* to be placed onboard the vehicle*.* These algorithms will first be validated using simulation tools and then in reality on a unique testing platform developed at IFP which combines IFP's battery power bench and a BMS controller. *"It is one of the most outstanding real-time comparison tools currently being used",* states an enthusiastic Valérie Sauvant-Moynot.

Developing control strategies to optimize energy management in real time

In addition to the state of charge of the battery, it is necessary to optimize the overall energy management on board the vehicle. In other words, technologies need to be developed to allow choices to be made, in real time and as a function of vehicle usage, regarding the distribution of power between the internal combustion engine and the electric motor.

"To this end, in 2007, IFP began developing real-time energy management software based on 'optimal control laws'. The same software was later used in HyHIL", explains Antonio Sciarretta, Hybrid Vehicle Energy Management Expert in the Technology, Computer Science and Applied Mathematics Division. *"The software enables us first of all to use simulation to estimate the contribution of each component in the architecture, in terms of reducing fuel consumption, in a specific set of driving conditions. Then by implementing our models in the hybrid vehicle's onboard controller, we compare our predictions with actual* CO_2 *emission measurements taken in real time in driving conditions that, this time, we do not know in advance".*

Optimizing the sizing of the electric motor

Like the internal combustion engine, the electric motor drives the vehicle's wheels. It also generates current for the battery. As such, its optimization lies in characterization and modeling. IFP has a generic characterization bench that will make it possible to test commercially-available and prototype electric motors. *"Our test bench will be adapted to all types of electric motor, including the very smallest that operate at 20,000 rpm (the main electric motor in a Prius operates at 6,000 rpm)",* specifies Benoist Thirouard, Head of the Engine Systems Analysis Department in IFP's Energy Applications Techniques Division. The data (performance, thermal behavior, maximum available power while overtaking or going uphill, etc.) will be used to validate a model, currently being developed with the Electromechanics Laboratory at Compiègne University of Technology (LEC), before establishing real-time control algorithms.

Optimizing the global architecture of the hybrid vehicle: from the HyHIL virtual hybrid vehicle to the real prototype

"Control algorithms for electric motors, just like those for batteries and energy management, complement our real time simulation models as they are fine-tuned. They enable us to optimize the complete vehicle architecture and to envisage the design of hybrid prototypes", concludes François Badin.

- The HyHIL semi-virtual test platform

This platform makes it possible to reproduce and assess the complete architecture of hybrid vehicles. In other words, it is used to simulate and assess electrical component choices and study their impact on consumption, pollutant emissions and drivability, prior to any experimentation on a vehicle. HyHIL combines an internal combustion engine test bench integrating an onboard energy manager with real time simulations.

HyHIL was set up as part of a collaborative program launched in April 2008. It has been given the Predit label and is supported by the French Interministerial Fund (FUI) and the Mov'eo competitiveness cluster. Coordinated by D2T, the project is being conducted in partnership with Renault, the Grenoble electrical engineering laboratory and LMS. "Three hybrid architectures have been tested and validated over several standard driving cycles: pure thermal mode, stop&start mode and full hybrid mode", specifies Gilles Corde. Research is now continuing on a more complex architecture, using more specific real-time models representing a 4-wheel drive Renault hybrid. HyHIL is expected to significantly reduce the time required for the design and development stage of a new hybrid architecture.

- Developing demonstrator vehicles

On the basis of existing models and often in partnership with industrial players, IFP develops demonstrator vehicles so that its hybrid technologies can be tested on a vehicle in real driving conditions.

For example, in 2006, IFP worked with Gaz de France to develop a natural gas hybrid prototype on a Toyota Prius base, the most optimized *full hybrid* vehicle on the market, with pollutant emissions in line with the Euro 4 standard and extremely low CO_2 emissions of below 75 g/km. In April 2008, as part of a Predit project partly financed by Ademe, IFP's researchers developed a natural gas Smart hybrid, in partnership with Gaz de France, Inrets and Valeo. This *mild hybrid* vehicle, called Vehgan, meets the pollutant requirements contained in Euro 5 and emits 80 g/km of CO_2, i.e. 32% less than the gasoline model.

IFP playing a central role in collaborative research

"The theme of hybrid and electric vehicles – and batteries in particular – has really taken off. IFP is involved in numerous projects alongside industrial and academic partners and we hope to see the results transferred to industry via the car manufacturers very soon", points out Valérie Sauvant-Moynot.

In particular, IFP is involved in two projects through Ademe's Research Demonstrator Fund:
- ELLISup, led by Irisbus, is aimed at developing two types of demonstrators with their recharging points: a hybrid bus fitted with batteries that are adapted for recharging at the end of each route, and an all-electric bus with associated running costs similar to that of a diesel vehicle.
- Vel'roue, with Michelin and Renault, aimed at studying the feasibility of a two-mode commercial vehicle fitted with rear-end wheel motors.

In addition, since 2007, IFP has been involved in the ANR's (French Research Agency) Simstock project, coordinated by LMS and being conducted with 15 partners including Batscap, PSA Peugeot Citroën, Renault, Saft and Valeo. The objective is to study battery ageing and provide manufacturers with the models they need to predict battery lifespan in real operating conditions. Since 2008, IFP has been coordinating another ANR project, ALIDISSI, which is labeled by the Axelera competitiveness cluster. Conducted in partnership with the CEA, CNRS and Material Mates, the aim of the project is to develop state of charge and state of health diagnosis tools for lithium-ion batteries while operating, using electric impedance measurements. When fitted on board vehicles, these measuring instruments act as genuine charge sensors.

Mov'eo-DEGE: R&D platform for the development of hybrid and electric vehicles in Versailles Satory

The objective of the Mov'eo-DEGE project is to build a technological integration platform making it possible to speed up the development and validation of hybrid and electric systems. Supported by the Mov'eo competitiveness cluster and industrialists (PSA Peugeot Citroën, Renault, Valeo, D2T), the project brings together the major public players in the field (IFP, CETIM, INRETS and the University of Versailles Saint-Quentin en Yvelines). This platform will be equipped with testing and modeling facilities making it possible to characterize the various components of these vehicles in terms of performance, robustness, lifespan and failure modes, replicating operating conditions as closely as possible. *"From simulation through to experimentation, we will have all the means at our disposal to test and optimize hybrid architectures and components",* points out François Badin.