

Energy Management Strategy and Optimal Hybridization Level for a Diesel HEV

Laurent Thibault, Olivier Grondin, Carole Querel and Gilles Corde
IFP Energies Nouvelles

ABSTRACT

The design and the supervision of hybrid electric vehicles (HEV) are strongly coupled. The mutual influence between the optimal components sizing and the optimal operating points choice makes the problem complex. This was previously exposed in literature for spark ignition (SI) HEV. In this paper, we address the same issue for Diesel HEV. In this case, the energy management strategy must take nitrogen oxides (NO_x) emissions into account in addition to fuel consumption. This paper presents an optimal supervision strategy and its impact on the electric components sizing. The energy management strategy is based on the equivalent consumption minimization strategy (ECMS) using Pontryagin's minimum principle. It allows an adjustable trade-off between NO_x and fuel consumption to be minimized. It was validated experimentally with a hardware-in-the-loop test bed. By moving the engine operating points into optimal zones, this strategy allows important NO_x emissions reduction while keeping interesting fuel consumption. In comparison to a fuel consumption reduction oriented strategy, the integration of NO_x emissions deeply changes the energy management strategy choices and, as a consequence, the optimal electric components size. Indeed, to limit NO_x emissions engine high load operating points are avoided and a smaller hybridization level is sufficient. Compared to the SI engine, the Diesel has a better efficiency at part load. As a consequence, high NO_x reduction is possible without important fuel consumption increase. The interactions between electric components sizing and energy management strategy design are studied in this paper. Depending on the chosen value of the adjustable trade-off of the strategy, the optimal hybridization level changes because the engine optimal operation areas move. The driving cycle influence is also studied here to draw global conclusions.

CITATION: Thibault, L., Grondin, O., Querel, C. and Corde, G., "Energy Management Strategy and Optimal Hybridization Level for a Diesel HEV," *SAE Int. J. Alt. Power.* 1(1):2012, doi:10.4271/2012-01-1019.

INTRODUCTION

Electric hybridization is an interesting way to reduce fuel consumption and pollutant emissions of a vehicle. Most of the hybrid electric vehicles (HEV) already produced use a spark ignition engine. In this case the three-way catalytic converter can easily treat the pollutant emissions as soon as it is hot enough and the energy management strategy main objective is the minimization of the fuel consumption. For cold operations, a thermal management is integrated [2]. For a Diesel engine, nitrogen oxides (NO_x) emissions are problematical because even in warm conditions their after treatment is complex and costly. Associating the Diesel engine to an electric motor allows its operation to be optimized and thus reduces its NO_x emissions and fuel consumption. In this purpose an energy supervisor has been developed, to choose the engine operating points allowing at the same time low NO_x emissions and good fuel

consumption. This control issue was studied in the literature mainly in simulation. Early work from Johnson *et al.* [7] deals with heuristic supervision strategies for a Diesel HEV. On the other hand, model-based techniques have already been proposed by Lin *et al.* [8] (ECMS) and Musardo *et al.* [9], [10] (dynamic programming). In this paper the ECMS dedicated to gasoline engine and presented in [2] and [3] is adapted to the Diesel case. This adaptation consists in the integration of an adjustable trade-off between NO_x emissions and fuel consumption. The ECMS development was supported by the use of simulator through a methodology leading to experimental validations. The chosen vehicle is a light duty vehicle using a small Diesel engine without NO_x after treatment device but using low temperature combustion (LTC).

In an HEV, the engine operating points are not directly chosen by the driver but by the energy management strategy. The purpose of this paper is the study of the strong

interaction existing between the energy management strategy and the optimal electrical components sizing. Given the important cost and weight of these components, and especially of the battery, finding an optimal sizing is a key issue. Sunström *et al* [15] have proposed a methodology to find the optimal hybridization ratio, defined as the ratio between the engine and electric motor power. But this study was made for a gasoline hybrid vehicle and the energy management strategy does not take pollutant emissions into account. In this paper we study the interaction between the electrical components sizing and the energy management strategy for the Diesel HEV. Compared to the gasoline case, there is an additional degree of freedom with the adjustable trade-off between NO_x emissions and fuel consumption inside the energy management strategy.

The paper is organized as follows: after a description of the hybrid vehicle used in this study and of its modelling, the energy management strategy is presented. Then, the concept of optimal hybridization level is studied. The outlook and perspectives of this study are found in the end of the paper.

SYSTEM DESCRIPTION AND MODELLING

The studied architecture is a parallel hybrid. The post-transmission electric machine (EM) allows for power assist, full electric drive, regenerative braking and battery recharge. A manual gearbox (GB) is used and the engine is turned off at idle using a stop and start generator (SSG). Thus the engine speed profile for a given drive cycle is directly given by the driving cycle setpoints of vehicle speed and gearbox ratio. The main degree of freedom for the energy supervisor is the choice of the engine torque setpoint.

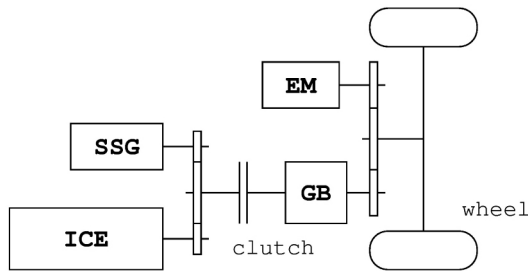


Figure 1. Hybrid Architecture

The internal combustion engine (ICE) used here is a Diesel one and is able to reach Euro 6 emission levels on a light duty vehicle. It is a supercharged, 1.6 liter, four cylinder engine fitted with low pressure exhaust gas recirculation (EGR) system. This engine uses low temperature combustion (LTC) strategies and has no dedicated after-treatment system for NO_x emissions. It should be noticed that the cold-start period is a key issue for Diesel engine emission reduction. This aspect can be included into the energy management strategy but this particular issue is not presented in this paper.

The main characteristics of the vehicle used in this study, a compact MPV, are given in [appendix](#).

HYBRID VEHICLE MODEL

The aim of this section is to introduce the mathematical model of the parallel hybrid powertrain shown in [Figure 1](#). This model is designed for the energy management strategy. It has a backward causality and it is steady-state. All the dynamics except for the vehicle longitudinal dynamics and the battery accumulator dynamics are neglected. These models equations are accepted to be relevant for optimization tasks. They are physically based, they capture the dominant phenomena and they can be implemented online. In backward modeling, the vehicle speed profile and the driver's torque demand are the main model inputs. The torque request at wheel $T_{pwt\ sp}$ depends on the driving conditions (speed and acceleration) and can be evaluated from drivers demand (throttle and brake pedal positions). Moreover,

$$T_{pwt\ sp}(t) = R_1 \cdot T_{mot}(t) + R_{GB} \cdot T_{eng}(t) \quad (1)$$

Where R_{GB} and R_1 are the gear and front axle ratios. T_{mot} is the requested electric motor torque and T_{mot} the engine torque which will be the commanded variable. The electric motor power, P_{elec} , is described by a map as a function of the motor torque and speed N_{mot} .

$$P_{elec}(t) = f_{elec}(N_{mot}, T_{mot}) \quad (2)$$

The engine fuel mass flow $\dot{m}_f(t)$ and the NO_x exhaust mass flow $\dot{m}_{NOx}(t)$ are provided by steady-state maps that depend on the engine torque and speed N_e :

$$\dot{m}_f(t) = f_{FC}(N_e, T_{eng}) \quad (3)$$

$$\dot{m}_{NOx}(t) = f_{NOx}(N_e, T_{eng}) \quad (4)$$

The injected fuel mass $\dot{m}_f(t)$ is transformed into a fuel power using the lower heating value of the fuel Q_{lhv} which is a constant for a given fuel:

$$P_{fuel}(t) = Q_{lhv} \cdot \dot{m}_f(t) \quad (5)$$

The battery pack is modeled as a basic equivalent circuit comprising a voltage source U_0 a resistance R_0 placed in series. These two variables depend on the battery state of charge ξ . The temperature dependence is neglected at first but could be easily introduced if necessary. The

electrochemical battery power can be expressed as (whole calculation is given in [2]):

$$\dot{\xi} = h(U_0(\xi), R_0(\xi), P_{elec}) \quad (6)$$

$$P_{ech} = -\dot{\xi} \cdot U_0(\xi) \cdot Q_0 \quad (7)$$

Where Q_0 is the battery capacity and η_{bat} represents its faradic efficiency.

COMPONENTS SIZE ADAPTATION

To study the interaction between the optimal hybridization level and the energy management strategy, it is necessary to define a scaleable model of the electrical components. In this paper, the battery capacity will be adapted proportionally to the electric motor power. This assumption is based on the fact that in this parallel architecture, the whole power given (or provided) by the battery comes to (or from) the electric motor. The electric motor efficiency map, minimal and maximal torque are calculated from a reference machine whose characteristics are scaled depending on the chosen maximal power $P_{mot \max}$. Indeed its maximal torque is calculated by:

$$T_{mot \max} = T_{mot \max ref} \times \frac{P_{mot \max}}{P_{mot \max ref}} \quad (8)$$

Where $T_{mot \max ref}$ and $P_{mot \max ref}$ are the maximal torque and power of a reference electric machine. Then the electric power is given by:

$$P_{elec}(N_{mot}, T_{mot}) = \frac{P_{mot \max}}{P_{mot \max ref}} \times f_1(N_{mot}, T_{mot} \times \frac{T_{mot \max ref}}{T_{mot \max}}) \quad (9)$$

The relation $P_{elec} = f_1(N_{mot}, T_{mot})$ has been characterized for a reference electric machine. The adaptation of the battery capacity is made by changing the number of cells which constitute it:

$$Nb_{cells} = K_1 \cdot P_{mot \max} \quad (10)$$

Since only the number of cells is changed and all the characteristics of one cell do not change, all the battery parameters like its capacity and maximal power are varying with the electric motor maximal power. The HEV weight m_{HEV} is calculated by adding an additional value depending on the hybridization level to the mass m_0 of the reference vehicle. This additional mass m_{elec} corresponds to the cumulated weight of the battery, the electric motor and their respective power electronics.

$$m_{HEV} = m_0 + m_{elec} \quad (11)$$

$$m_{elec} = K_2 \times P_{mot \max} \quad (12)$$

These sizing laws are illustrated in Figure 2 ($K_1 = 2,3$ cells/kW and $K_2 = 8,2$ kg/kW).

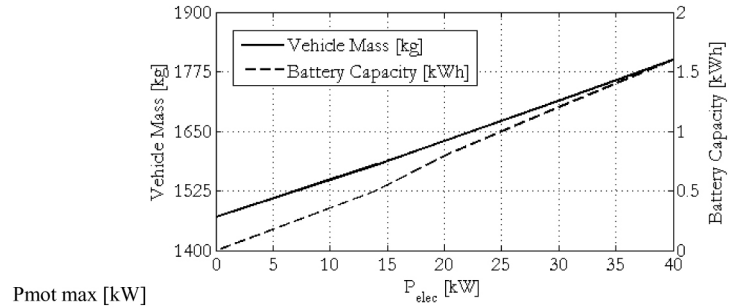


Figure 2. Vehicle Mass and Battery Capacity Modelling

ENERGY MANAGEMENT STRATEGY

In a conventional vehicle, the engine torque is directly linked to the wheel torque demand. Hybridization offers a degree of freedom in the choice of engine operating points which is used to minimize fuel consumption and NO_x emissions. This optimization is made in the energy management strategy and its realisation is detailed below.

OPTIMIZATION PROBLEM

The proposed strategy is based on the ECMS (Energy Consumption Minimization Strategy) previously developed ([1], [13] and [14]) and already implemented on a gasoline hybrid electric ([2] and [3]). In previous studies considering SI engines, the global optimization criterion was the overall fuel consumption. For a Diesel HEV this objective is modified to minimize a trade-off between fuel consumption and NO_x emissions. Then, the integral cost of the fuel is defined to be the integral of the weighted sum of the fuel consumption and the NO_x emissions over the driving cycle. Thus, the cost function is expressed as:

$$J(u) = \int_{t_0}^{t_f} [(1 - K_{NOx/FC}) \cdot \dot{m}_f + K_{NOx/FC} \cdot \dot{m}_{NOx}] dt \quad (13)$$

Where the parameter $K_{NOx/FC}$ allows the trade-off between fuel consumption and NO_x emissions to be adjusted from pure fuel minimization ($K_{NOx/FC} = 0\%$) to pure NO_x reduction ($K_{NOx/FC} = 100\%$). The optimization problem has a state constraint which imposes that the final value of the state of charge $\xi(t_f)$ must match the initial one $\xi(t_0)$. The system

input is the engine torque request that belongs to an admissible space such that $U = [T_{eng, min} \ T_{eng, max}]$, the bounds of this interval being given by the minimum and maximum values of the two motors. The optimal control problem is then:

$$\begin{cases} \min_{u \in U} \int_{t_0}^{t_f} J(u) dt \\ \xi(t) = f(\xi(t), u(t), t) \text{ with } \xi(t_f) = \xi(t_0) \end{cases} \quad (14)$$

It can be solved using the Pontryagin's Minimum Principle (PMP) where the optimal command writes:

$$u^{opt} = \arg \min H(\xi(t), \lambda(t), u(t), t) \quad (15)$$

Where the Hamiltonian function is defined as

$$H(\xi(t), \lambda(t), u(t), t) = [(1 - K_{NOx/FC}) \cdot \dot{m}_f + K_{NOx/FC} \cdot \dot{m}_{NOx}] + \lambda(t) \cdot \dot{\xi}(u(t), t) \quad (16)$$

An equivalent fuel power can be defined by

$$P_{fuel}^* = Q_{lHV} [(1 - K_{NOx/FC}) \cdot \dot{m}_f + K_{NOx/FC} \cdot \dot{m}_{NOx}] \quad (17)$$

The equations (6) and (7), the Hamiltonian function can be reformulated in more comparable terms:

$$H'(\xi(t), s(t), u(t), t) = P_{fuel}^*(u(t), t) + s(t) \cdot P_{ech}(u(t), t, \xi(t)) \quad (18)$$

The equivalence factor $s(t)$ weighs the electrochemical power before summing it to the fuel power. Its value modifies the balance between the use of the electrochemical and fuel energy. It is proportional to the costate as shown by (16) and (18) and its value is chosen such that the constraint on the final state of charge is fulfilled. In this paper, we assume the drive cycle is known and, under this assumption, the equivalence factor is a constant determined off-line using simulation. The sensitivity of this parameter and the online adaptation rule was studied in [3].

Figure 3 shows the evolution of the battery state of charge during a FTP driving cycle for different values of the equivalence factor. It clearly illustrates that the cost of the electric energy is modified by the equivalence factor value. The higher the equivalence factor is, the cheaper the electric energy for the energy supervisor and the higher the battery state of charge will be at the end of the cycle. A method to determine the equivalence factor off-line optimal value is proposed in [1].

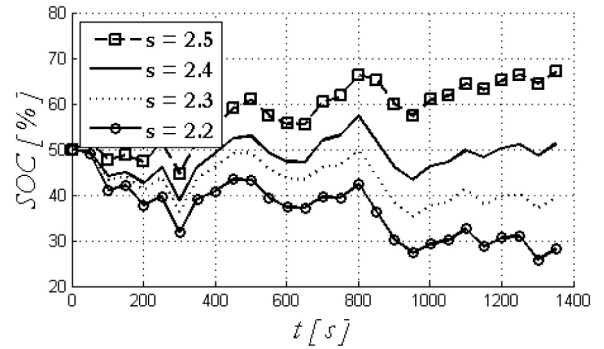


Figure 3. Cycle FTP - Equivalence Factor influence on SoC

IMPACT OF THE TRADE-OFF

By determining the optimization criterion of the strategy, the adjustable trade-off $K_{NOx/FC}$ directly fixes the optimal engine operating points. As a consequence, when fuel consumption reduction is prioritized, the engine is operated at high load. This trend is illustrated on Figure 4 which represents the engine $K_{NOx/FC}$ operating points chosen by the energy supervisor for the conventional vehicle and for the HEV with different strategies. These tests were made for an Artemis Urban and the engine field has been divided in three zones of the same range. Torque demand corresponding to engine speed below 1500 rpm are excluded to avoid being limited by the maximal torque curve and to exclude idle for the conventional case.

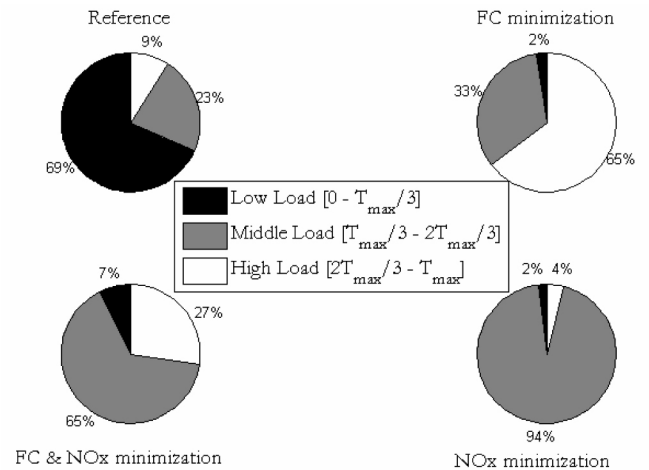


Figure 4. Engine Torque repartition for different $K_{NOx/FC}$

The trend previously presented is confirmed: hybridization cuts low load operating points whereas fuel consumption minimization leads to high load operation. The impact of the strategy setting parameter $K_{NOx/FC}$ on the cumulative scores is illustrated in Figure 5 on a FTP driving cycle for a 20kW HEV. Fuel consumption (FC) and NOx