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# Enhanced fuel cell hybrid electric vehicle power sharing method based on fuel cost and mass estimation

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## HIGHLIGHTS

- A method for selecting an optimal driving cycle knowing a trip road.
- A method for adaptive energy management using online vehicle mass estimation.
- A comparative study demonstrating the effectiveness of the adaptive method.

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## ABSTRACT

In this paper, we investigate an adaptive energy management and power splitting system for a fuel cell hybrid electric vehicle. The battery pack is the main power source whereas the fuel cell is considered as a range extender that cannot sustain alone the vehicle traction power. In addition, the fuel cell contributes to reduce the battery pack degradation by limiting its depth-of-discharge (DoD). This energy management system is based on a two layer architecture in which the upper layer computes the anticipated end-of-trip DoD using online mass estimation. The lower layer is designed to split the driver power demand by minimizing a cost function which includes the hydrogen/electricity cost ratio. Therefore, the best trade-off between reducing battery pack degradation and using cost effective energy is provided. Furthermore, the system allows the fuel cell to operate at its maximum efficiency. Comparative study results indicate that using online mass estimation improves the overall fuel consumption efficiency whilst contributing at the same time to DoD reduction.

## 1. Introduction

Terrestrian vehicle powertrain electrification is a key step towards the reduction of the greenhouse gas emission sources [1]. However, the use of batteries as a power source for vehicles raises several challenges that must be addressed to make it competitive: limited operating range, long charging time, limited lifespan, etc. Vehicle source hybridization has been proposed as a practical way to increase fuel usage efficiency and to extend operating range [2]. Thus, plugin hybrid vehicles (PHEV) with gasoline internal-combustion engines as range extenders have been proposed by car makers and several of such vehicles are being deployed around the word: Chevrolet Volt of General Motor, Outlander PHEV of Mitsubishi, etc. However, it is noteworthy that gasoline used in these vehicles contributes to the greenhouse gas emission [3,4].

To completely remove any fossil energy on the vehicle, a clean-energy vector such as hydrogen attracts a lot of attention in research community [5]. Indeed, hydrogen has one of the highest energy densities per weight and can be used in fuel cell to produce electricity or burned in an internal combustion engine (ICE) to directly generate propulsion torque [6]. Some of PHEVs with hydrogen as energy vector have been proposed in the literature [7–9]. Fuel cell PHEV (FC-PHEV) has received more attention than hydrogen-based ICE.

The vehicle global fuel saving is thoroughly related to the power flow control between each energy source and the powertrain [10,11]. Several energy management and power sharing control systems for hybrid electric vehicles (HEV) as well as PHEV have been reported throughout the literature: rule-based methods

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[8,12], optimization methods [13–15], stochastic approaches and adaptive approaches [16,17]. These methods belong to the blended mode energy management systems. Most of these works assumed that the power demand from the vehicle driver is known. However, the driver often provides a control signal using the vehicle acceleration pedal. One way to determine the corresponding power demand is to use the vehicle longitudinal dynamics which considers that the mass and other physical parameters (rolling resistance coefficient, road grade, air density, vehicle frontal area, and aerodynamic drag coefficient) as known beforehand. Whilst some of these parameters can be assumed to be constant values, the vehicle mass as well as the road grade can change during the trip. In addition, most of the reported work assumed that the on-board energy sources have similar power range, and the energy cost is not directly taken into account. Having similar operating power range simplifies the design of the energy management system. Indeed, the well-known charge-depleting charge-sustaining method can be easily used: after the battery pack has been depleted, the secondary energy source can sustain the power demand so that at the end of the trip, the battery pack energy remains close to a given low value. In addition, in blended mode, the power demand needs to be estimated in order to properly use the secondary energy source to supplement the battery pack.

This paper investigated the energy management and the real-time power splitting problems of a serial topology FC-PHEV in which the battery pack is the primary and the most powerful energy source and the fuel cell is considered as a range extender (fewer powerful energy source). Therefore, the charge-depleting charge-sustaining method cannot be used since the fuel cell is unable to sustain the power demand. So, to maintain battery pack energy close to a prescribed minimum value at the end of a trip, the fuel cell operating sequence must be carefully designed. In addition, we assume that when the vehicle is stopped during a trip, the mass may change (change in the number of passengers in the vehicle, garbage trucks, delivery trucks and buses, etc.). Furthermore, it can be used for small vehicles that cannot support the weight of a great fuel cell (mass-power ratio).

The mass estimation in the context of hybrid electric vehicle energy management has not been fully addressed in the literature. It becomes a key step towards a good energy planning system, and its online estimate is challenging. Several mass and grade estimation methods reported throughout the literature can be classified in two categories [18]: event-based and averaging. Each of these categories could be further divided into two sub-category: simultaneous estimation of mass and grade, single estimation of mass using grade measurements. For these estimations, different vehicle dynamic models were used [18]: suspension dynamics [19], yaw dynamics [20], drive-train dynamics and longitudinal dynamics [21–23].

Event-based methods seek for driving conditions that provide sufficient excitation for mass or grade estimation: model predictive approach [24], use of grade estimation with GPS (Global Positioning System) to derive mass estimation [25] and supervisory control approaches [18].

Instead of seeking for events, the averaging method continuously monitors the vehicle dynamics in order to directly estimate the mass and grade online, using recursive least squares (RLS) [21,23,26,27] and Kalman's filter. Others reported methods can be seen in Refs. [22,28].

The proposed energy management system is based on a two-layer architecture in which the supervisor (high level of the architecture) is responsible for providing the global energy consumption profile when the vehicle mass is not constant and the anticipated battery depth-of-discharge (DoD). Given the global consumption profile, the lower level provides a locally optimal power sharing between the fuel cell and the battery pack by minimizing a cost function which includes the hydrogen and electricity price ratio.

The rest of the paper is organized into seven sections. The FC-PHEV description and its longitudinal model are presented in Sections 2 and 3, respectively. Based on this model, a new adaptive energy management system is described and discussed in Section 4. Section 5 is related to the design of the lower layer (power splitting method). The adaptive energy planning and the power splitting method validations are provided in Sections 6 and 7, respectively. Finally, the conclusion is presented in Section 8.

## 2. FC-PHEV description

Fig. 1 represents a serial topology of a FC-PHEV where the fuel cell is not required to follow precisely the dynamics of the driver power demand if the battery pack is well sized. In addition, with this topology, the fuel cell can be optimally set to provide power.

We consider that the sub-system comprising the uni-directional DC–DC converter and the fuel cell represents the fuel cell power source. The driver provides two different signals: the brake and acceleration commands. Given these signals, the Power Demand Module generates the corresponding mechanical power request $P_{\mathrm{u}}$ which is further sent to Energy Management System (EMS). $P_{\mathrm{u}}$ is interpreted as the desired mechanical power during a trip. In addition, the EMS receives the stored hydrogen energy $E_{\mathrm{fc}}$, the available energy in the battery pack $E_{\mathrm{b}}$, the different power source efficiency maps (not represented in Fig. 1) and the hydrogen/electricity cost ratio (the cost of 1 kW h of hydrogen divided by the cost of 1 kW h of electricity).

Taking into account all this information and considering that the vehicle mass $M$ can vary during the trip, the role of the EMS is to find the most appropriate power splitting of $P_{\mathrm{u}}$ by providing the fuel cell optimal reference power command $P_{\mathrm{fc}}^{*}$ and the Propulsion System reference power command $P_{\mathrm{m}}^{*}$. The fuel cell DC–DC converter is responsible for providing $P_{\mathrm{fc}}$ that corresponds to $P_{\mathrm{fc}}^{*}$. On the other hand, the Propulsion System controller (not represented in Fig. 1) generates the vehicle mechanical power $P_{\mathrm{m}}$ using the reference command $P_{\mathrm{m}}^{*}$. $P_{\mathrm{b}}$ represents the battery pack power: a positive value indicates that the battery pack is providing electrical power whilst a negative value indicates that the battery pack is being recharged.

In this paper, we consider the two-layer architecture proposed in Ref. [29] in which the upper layer is responsible of the globally optimal energy profile during the trip whilst the lower layer role is to split the power demand so that the vehicle energy consumption follows this globally optimal profile.

## 3. FC-PHEV longitudinal model

Assume that the wind speed relative to the ground is negligible. The FC-PHEV longitudinal dynamics is represented by Equation (1) [14] and the corresponding mechanical power is given by (2).

$$F_{\mathrm{m}}(k)=M\dot{v}(k)+\frac{1}{2}\rho_{\mathrm{a}}C_{\mathrm{d}}Av^{2}(k)+Mg\sin(\theta(k))+Mg\mu\cos(\theta(k)) \qquad (1)$$

where $k$, $F_{\mathrm{m}}$, $M$, $g$, $\rho_{\mathrm{a}}$, $\mu$, $C_{\mathrm{d}}$ and $A$ represent respectively the sampling index, the resultant mechanical force, the vehicle's total mass, the gravity constant, the air density, the rolling resistance coefficient, the air drag coefficient and the active frontal area; $\theta$, $\dot{v}$ and $v$ represent respectively the road grade, the longitudinal acceleration and the vehicle speed. $0<k\leq N$ where $N$ is the number of samples in a given driving cycle.

$$P_{\mathrm{m}}(k) \;=\; F_{\mathrm{m}}(k)v(k) \qquad (2)$$