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Influence of the heating system on the fuel consumption of a hybrid electric vehicle

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ABSTRACT

This research work aims to study the impact of the heating system on the fuel consumption of a hybrid electric vehicle (HEV). The thermal engine is less used in an HEV than in a thermal vehicle, thus the cabin heating is partly ensured by electrical resistances. However, because the battery is partly charged by the thermal engine, this electrical heating has an impact on the fuel consumption. In the present work, a multi-domain model is proposed to analyze the impact of the heating system on the fuel consumption of a HEV. The models of the different physical subsystems are organized and unified by energetic macroscopic representation (EMR). Experimental validations, with an accuracy of 95%, are provided for each subsystem model. The validated simulation models are used to study the impact of the heating system for a specific driving cycle and climatic condition. For a simple energy management strategy (EMS), there is an over-consumption of 19% that is due to the heating system. When a more efficient EMS is used, the over-consumption is reduced to 12%. This study shows the interest in developing advanced energy management strategies that couple the traction and the heating functions of the vehicle.

1. Introduction

Global warming and the depletion of petroleum resources are actual challenges that the world face today [1,2]. The transportation sector is a large contributor to the emission of green house zazes and the consumption of petroleum resources. New kinds of vehicles have been developed such as electric vehicles (EVs) or hybrid electric vehicles (HEVs). EVs suffer from weak autonomy, long charging time and battery cost [3,4]. HEVs present a better midterm solution by combining the advantages of thermal vehicles and EVs [5,6]. However, the fuel consumption of HEVs has to be addressed to reduce their excessive cost.

The classical studies of HEVs are generally limited to the energy conversion from the tank and the battery to the wheels [5–7]. Therefore the vehicle propulsion subsystem is the most important energy consumer. The energy management strategy (EMS) deals with the power distribution between the fuel tank, battery and wheels. Many strategies have been proposed to optimize the energy consumption of different hybrid vehicles [8–14]. Some recent papers deal with the traffic condition [7] and cold-start of the ICE [15].

However the thermal comfort of the passengers is another important energy consumer. In cold conditions, the heating subsystem requires energy to heat the cabin. In hot condition, the air-conditioning subsystem requires energy to cool the cabin. In a conventional thermal vehicle, the cabin heating is generally ensured by the heat produced by the internal combustion engine (ICE). But in HEVs, the ICE is less used than in thermal vehicles, thus heat from the ICE could be not sufficient to warm the cabin. In such a case, resistors connected to the battery are also used. However, because the battery State-of-Charge (SoC) is partly managed by the ICE charging function, the electrical heating has an impact on the fuel consumption. A more global energy management strategy could be developed taking into account the thermal power flows: an increase in the operation time of the ICE could sufficiently warm the cabin and reduce the fuel consumption in cold conditions. To develop such a global EMS, a multi-physical model is required. A first thermal-based strategy was proposed for a plug-in HEV [16]. However, this approach was based on simple thermal models of components. Moreover, the plug-in HEV was a series HEV with a high battery capacity to drive in pure electric mode. In such case, by using an off-line optimization algorithm,

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the authors showed a reduction in the fuel consumption of up to 40%. In [17], another very simple global model was used to define a Model Predictive Control of a parallel HEV. In this case, the fuel consumption was reduced only up to 3%. All these previous works were based on simplified models of the thermal parts, and provided no experimental validations. More accurate models could thus be of interest.

Multi-physical simulation tools are often used for HEVs [18,19]. In this case, different multi-physical subsystems are connected from libraries in a structural way. The development of the system control and energy management strategy is then built in a heuristic way from the expertise of the designers [21] or using fuzzy logic or meta-heuristics [4]. The Energetic macroscopic representation (EMR) formalism has been introduced to organize models of complex systems [22,23]. EMR is a graphic description that interconnects subsystems in a functional way. It enables a clear understanding of the different power flows, a systematic organization of the control scheme, and an easier definition of the energy management. Similarly to Bond Graph [24], which is a popular description formalism in the automotive sector, EMR applies the action – reaction principle to describe a subsystem (effort and flow). EMR imposes respect for the integral causality whereas, Bond Graph enables the derivative causality to respect the physical organization of the system. In fact, Bond Graph leads to a structural description of the system that focuses more on the design and analysis [25]. In contrast, EMR leads to a functional description of the system that concentrate more on system control and energy management. A more complete comparison of both formalisms could be found in [26] and [27]. Many models, controls and energy management strategies of innovative vehicles, such as thermal vehicles [28], hybrid vehicles [29,30], hybrid locomotives [31] and innovative subways [32], have been developed using EMR. However, they are all focused on the vehicle propulsion subsystem and energy management.

This current study aims to analyze the fuel consumption of an HEV considering the heating of the vehicle in cold conditions. In particular, it focuses on the hybrid vehicle DS5 of Groupe PSA (Peugeot Citroën) based on the HY4 topology [29]. This vehicle is composed of a Diesel engine and 2 electric machines. Previous modeling works has been achieved:

– model and control of the propulsion subsystem, validated by experimental results [29,33];
– model of the ICE including the thermal aspects, validated by experimental results [28];
– model of a simplified cooling system used in simulation [34].

However, all subsystems have been studied separately. Moreover, the thermal model of the cabin has not been developed. In the present work, the cabin model is developed and all subsystem models are interconnected by using EMR. The objective of this study is thus to propose a multi-domain model of a HEV including the thermal power flows to analyze the fuel consumption in cold conditions. This analysis should lead to the development of a more efficient energy management strategy as a function of the ambient temperature.

A multi-domain energetic model is firstly developed using EMR in Section 2. The different models of subsystems are validated in Section 3. The impacts of the climatic conditions and of the energy management strategy are finally studied.

2. Unified representation of the vehicle

The studied vehicle is a double parallel topology composed of a 120 kW Diesel internal combustion engine (ICE), a 27 kW rear electrical drive and a 7 kW front electrical drive. Different physical power flows are thus exchanged by the subsystems (Fig. 1) [33].

For the vehicle propulsion, 4 energy sources are considered: the tank, the battery, the mechanical brake and the road (Fig. 2). The fuel in the tank is converted into mechanical power to the mechanical transmission (MT). The energy in the battery is converted by the electric drives (ED, electrical machines and power electronics). The mechanical transmission interacts with the road (positive power in traction and negative power in deceleration). The braking energy can be recovered in the battery by the electric drives during deceleration; a mechanical brake ensures the deceleration in some conditions. The battery is also charged by the ICE because the vehicle is not a plug-in HEV.

For the vehicle heating, 3 energy sources are considered: the tank, the battery and the ambient air (Fig. 3). The heat of the ICE is extracted by the cooling system (CS) to heat the cabin or to dissipate the heat in the ambient air. A supplementary heating subsystem is provided by the battery through the heating resistor (HR).

Thus, all power flows are interdependent. The battery and the fuel tank contribute to the vehicle propulsion and the cabin heating. To decompose this complex system, 4 subsystems are considered first: the ICE, the cooling subsystem, the propulsion subsystem and the cabin heating subsystem. Several decompositions can be taken into account. The chosen decomposition is proposed in function of the previous works and also of the possible separated experimental validations.

To interconnect all the elements in a unified way, EMR formalism is used [23]. EMR is a graphic description composed of 4 energy functions (the energy source, energy storage, energy conversion and energy distribution, see Appendix). The elements are interconnected according to the interaction principle (the product of the action and reaction variables is the exchanged power) [24,35]. Moreover, only the physical causality (i.e. the integral causality) is considered [36,37]. This last property enables a systematic deduction of control schemes and a better understanding of the physical power flows. Variables and subscripts nomenclatures are given in Tables 1 and 2.

2.1. Internal Combustion Engine (ICE)

The thermal power distribution in the ICE is generally described by using dynamical models [38,39]. The main dynamics are the inertia of the rotating parts, the thermal dynamics of the engine block and the thermal dynamics of the in-cylinder gases. An EMR of the studied ICE has been proposed and experimentally validated [28]. For a global simulation, this dynamic model has been reduced to a quasi-static model. The dynamics of the gases has been neglected and equivalent static maps have been built. This

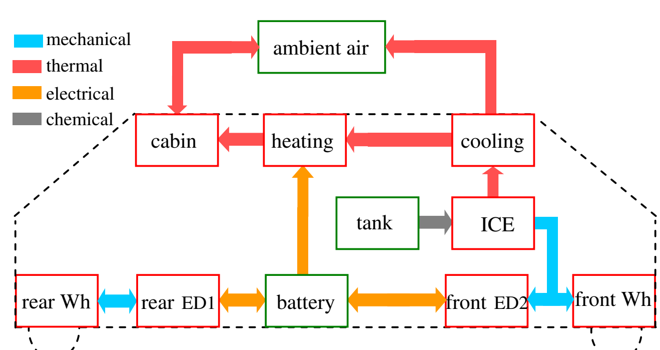

Fig. 1. Power flows of the studied double-parallel HEV.