



Real CO₂ emissions benefits and end user's operating costs of a plug-in Hybrid Electric Vehicle [☆]



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HIGHLIGHTS

- Real CO₂ emissions of a plug-in Hybrid Electric Vehicle analyzed.
- Impact on CO₂ emissions of the engine efficiency and of the energy source mix highlighted.
- Minimization of the overall CO₂ emissions also achieves the minimum of the energy cost.

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ABSTRACT

Although plug-in Hybrid Electric Vehicles (pHEVs) can be considered a powerful technology to promote the change from conventional mobility to e-mobility, their real benefits, in terms of CO₂ emissions, depend to a great extent on the average efficiency of their Internal Combustion Engine and on the energy source mix which is used to supply the electrical demand of pHEV.

Furthermore the operating cost of the vehicle should also be taken into account in the design process, since it represents the main driver in the customer's choice.

This article has the purpose of assessing, through numerical simulations, the effects of different technology mixes used to produce electrical energy for the battery recharging, of different Internal Combustion Engines on the pHEV performance, and highlighting the main differences with respect to the regulatory test procedure.

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1. Introduction

Increasing concern about greenhouse effects has led the United Nations Intergovernmental Panel on Climate Change (IPCC) to conclude that a reduction of at least 50% in global CO₂ emissions, compared to the 2000 levels, has to be achieved by 2050, in order to limit the long-term rise in the global average temperature [1]. Although this target has been set for all sources of CO₂ emissions, the transportation sector, which is responsible for 33% of carbon dioxide emissions [2], unlike most of the other sectors, has shown an increase in total greenhouse gas emissions, which have been predicted to grow further in the coming years [3], due to the expansion of the global vehicle fleet. In this framework electrification of the powertrain could represent a valuable solution since

Electric Vehicles (EVs) do not generate pollutants at a local level and can potentially rely on energy from a selection of renewable sources.

Nevertheless, despite continuous developments in battery technology, the costs, range capability and long recharging time are still considered barriers to the widespread adoption of such vehicles [4]. Therefore, the increasing interest in combining the desirable features of Electric Vehicles with the range capability of conventional vehicles, has led to the investigation of plug-in Hybrid Electric Vehicles (pHEVs) which can offer drivers the same range as conventional Internal Combustion Engines but can also lead to the environmental benefits of Electric Vehicles for short distances [5–7]. pHEVs shift a portion of the emission burden of automobile travel from on-road fossil fuel combustion to electricity generation at stationary power plants, and, although the European regulation exempts CO₂ production related to battery recharging in order to foster the diffusion of such vehicles, the impact of this shift on the overall CO₂ emissions depends on the average efficiency of the Internal Combustion Engine, on the amount of the electricity required from the grid and on the mix of energy sources used to satisfy the pHEV electrical demand. Therefore the real CO₂ benefits that could be achieved by pHEVs deserve a careful

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Nomenclature

C	cost
D	distance
E	energy
M	consumed mass
$\dot{m}_f$	fuel mass flow rate
ρ	density
μ	molar mass
T	time
u	control variable

Subscripts

AV	average
BATT	battery
E	electric
ELEC	electricity
F	fuel

Abbreviations

APU	Auxiliary Power Unit
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ARTEMIS	Assessment and Reliability of Transport Emission Models and Inventory Systems Driving Cycle
CIE	Carbon Intensity of the Electricity
DP	Dynamic Programming
HEV	Hybrid Electric Vehicle
ER	Extended Range
EUDC	Extra Urban Driving Cycle
EV	Electric Vehicle
FTP75	Federal Test Procedure
HEV	Hybrid Electric Vehicle
ICE	Internal Combustion Engine
NEDC	New European Driving Cycle
NVH	Noise Vibration Harshness
PHEV	plug-in Hybrid Electric Vehicle
SOC	State of Charge
UDC	Urban Driving Cycle
US06	United States Supplemental Federal Test Procedure
WLTP	Worldwide Harmonized Light Duty Test Procedure

analysis. However, such an investigation has so far only partially been carried out and reported in the scientific literature (see for instance [8]), which has been until now mostly focused on the analysis of charge sustaining HEVs.

Moreover, not only CO₂ emissions, but also the operating cost of the vehicle should be taken into account in the definition of the vehicle targets since it is one of the main drivers in the customer's choice and it depends to a greater extent on both fuel and electricity costs.

For the abovementioned reasons, this article describes the effects of different Internal Combustion Engines and different energy mixes used to produce the electricity required to recharge batteries, on the performance of a case study PHEV with the aim of minimizing its overall CO₂ emissions and of highlighting the gap between its real emissions and the value calculated through the regulatory test procedure. Furthermore, this approach is compared with an alternative methodology that is focused on the minimization of energy costs.

After a brief introduction to the methodology (Section 3), the paper presents the main features of the case study hybrid architecture (Section 4) and the reference performance achieved with a control strategy that is focused on the minimization of the overall CO₂ emissions (Section 5.1). The main findings of the sensitivity analysis, performed on both technology mixes used to produce electricity to recharge batteries (Section 5.2) and on the main powertrain components (Section 5.3) are then presented. Finally, the main differences between the CO₂ minimization and the cost minimization strategies are pointed out (Section 5.4).

2. Methodology

The main advantage of using a Hybrid Electric Vehicle is the additional degree of freedom that can be obtained due to the presence of an additional energy reservoir – the electric battery – besides the fuel tank [9]. This implies that, at each instant of time, the power needed by the vehicle can be provided by either one of these sources, or by a combination of the two. The choice from among all the available powersplit combinations depends on the actual objective of the hybridization, which can usually be defined as the minimization of a given cost function. This process represents a typical optimal control problem [10] that can usually be

addressed through several methodologies which can differ in performance, computational requirements and computational efforts [11,12]. Since the definition of an energy management system is not the scope of this article, the authors used a global optimization algorithm, the Dynamic Programming algorithm [13,14], to set the ideal performance for the case study hybrid architecture and to highlight the effects of some parameters on vehicle performance.

The Dynamic Programming (DP), generates a numerical solution for an optimal control problem and it gives sufficient conditions for the global optimality. It is based on Bellman's principle of optimality [10] and is able to manage a dynamic model of the system; since DP is commonly used to solve time-continuous control problems, the model has to be discretized in a sequence of time steps for which DP is capable of determining the optimal control laws. The optimal cost-to-go function (see Eq. (1)) is then computed for each value of the state variables (for instance the State Of Energy – SOE of the battery) in the admissible range following a backward path starting from the final time and state as depicted in Fig. 1a. Then, once the backward iterations have been completed, the law that generates the optimal cost-to-go value is defined for each time step and is used to compute the optimal control sequence through a forward iteration of the algorithm (see Fig. 1b). Even though the need for a backward procedure means that the solution can be obtained only offline, for a driving cycle known a priori, and therefore is not implementable on a real vehicle, the optimal control law can be used to gather information for the development of simpler and implementable strategies and to benchmark their performance [15,16].

All the analyses presented in this paper were carried out through numerical simulations performed on a vehicle model developed in Matlab environment. This model relies on a kinematic approach [17,18] based on a backward methodology where the input variables are the speed of the vehicle and the grade angle of the road (see Fig. 2). The powertrain speed can then be easily determined from simple kinematic relationships, starting from the wheel revolution speed and the total transmission ratio of the driveline, while the traction force that should be provided to the wheels to drive the vehicle according to the chosen speed profile can be calculated from the main vehicle characteristics (i.e. vehicle mass, aerodynamic drag and rolling resistance). Both the Internal Combustion Engine and the electric machines are represented through performance maps that were experimentally

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