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# Efficiency, cost and life cycle $CO_2$ optimization of fuel cell hybrid and plug-in hybrid urban buses

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## HIGHLIGHTS

- Optimization of fuel, cost and LCA $CO_{2eq}$ emissions are conflicting objectives.
- Real driving cycles and ETC have significant impact in optimization results.
- Optimal bus exhibits up to 67% less LCA $CO_{2eq}$ and up to 58% less fuel consumption.
- Maximum relative gains of 0.620 \$/km can be achieved with $H_2$ price below 0.129 \$/MJ.
- FC-PHEV has higher TTW efficiencies, but higher cost and LCA impact than FC-HEV.

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## ABSTRACT

Fuel cell powered hybrid electric vehicles (FC-HEV) and plug-in hybrid electric vehicles (FC-PHEV) are being addressed by the automotive industry as improved and more sustainable alternative technologies relatively to conventional vehicles. Nevertheless, hybrid propulsion raises new challenges in designing the vehicle powertrain. This study highlights the significance of the driving conditions and the conflict between the optimization of investment cost, efficiency and life cycle impact (LCA) in powertrain design optimization of these kinds of vehicles. A single-objective (minimization of cost, fuel or LCA $CO_{2eq}$) and multi-objective genetic algorithms (minimization of the couples cost and fuel, cost and LCA $CO_{2eq}$, fuel and LCA $CO_{2eq}$), linked with the vehicle simulation software ADVISOR, are used to optimize the design of powertrain components. The main outcomes of the research are as follows. The optimization of LCA $CO_{2eq}$ emissions and cost are conflicting as well as cost and energy use, what can be observed in the Pareto solutions. The fuel and LCA $CO_{2eq}$ emissions optimization are coupled for pure hybrids but not for plug-in hybrid configurations, due to the electricity consumption. Fuel cell buses can reduce the energy consumption by 58%, and emit 67% less LCA $CO_{2eq}$ than the conventional diesel bus, and achieve compensatory payback of 0.620 \$/km (depending on the hydrogen price). The FC-PHEV configuration shows more potential for achieving higher operation efficiencies, but the FC-HEV shows to have lower life cycle impact and lower cost in general.

## 1. Introduction

Fossil fuels remain the dominant sources of primary energy worldwide. Since 2010 more than a third of the primary energy is derived from oil, and around 62% of the final energy consumption is associated to the transportation sector [1]. In Europe, in the European Union member countries (EU-27) in particular, the transport sector represented approximately 33% of the total energy consumption and was responsible for about 24% of $CO_2$ emissions in 2011 [2]. Environmental and sustainability issues associated to the oil extraction and use, including the growing economic and political disputes surrounding this energy source, has warned the international community to the importance of the research for new solutions to the mobility sector. Given that, governments have been introducing a large number of policies and measures across all modes in an effort to improve efficiency of energy use. European decision makers have established political goals in order to address these complex issues. Kyoto protocol, 2003/30/EC European, 20-20-20 targets [3] are some examples of a global trend to diminish emissions from the transportation sector that is under effect.

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**Nomenclature**

| | |
|---|---|
| AER | all-electric range |
| BAT | battery |
| BEV | battery electric vehicle |
| CAFE | corporate average fuel economy regulations in the United States of America |
| CD | charge depleting |
| $CO_2eq$ | $CO_2$ equivalent emissions |
| CS | charge sustaining |
| CTG | Cradle-to-Grave |
| DFCV | direct fuel cell vehicle |
| FC | fuel cell |
| FC-HEV | fuel cell hybrid electric vehicle |
| FC-PHEV | fuel cell plug-in hybrid electric vehicle |
| GA | genetic algorithm |
| GPS | Global Positioning System |
| HEV | hybrid electric vehicle |
| ICEV | Internal Combustion Engine Vehicle |
| LCA | life cycle analysis |
| MC | motor and controller |
| NSGA | non-dominated sorting genetic algorithm |
| OBD | On-Board Diagnostic vehicle interface |
| OEM | Original Equipment Manufacturer |
| PHEV | Plug-In Hybrid Electric Vehicle |
| REP | Relative to a component's replacement number |
| SOC | battery state-of-charge |
| TTW | Tank-to-Wheel |
| WTT | Well-to-Tank |
| WTW | Well-to-Wheel |

### *1.1. Hybrid and plug-in vehicles*

In order to comply with the established targets, to reduce the energy consumption and $CO_2$ emissions, new fuels, as well as the respective production pathways improvement, and new vehicle technologies become extremely important to study. Some solutions regard technology improvements like hybrid electric vehicles (HEV), plug-in hybrid electric vehicles (PHEV), pure battery electric vehicles (BEV) and fuel cell vehicles. Other kinds of solutions consider new energy sources like biofuels (e.g. ethanol, biodiesel, and methanol), natural gas, biogas, electricity and hydrogen. In this framework, with the growing importance of sustainability policies, the automotive industry is experiencing the gradual penetration of alternative technologies and fuels. Vehicle electrification enables the improvement of urban air quality (no local emissions), the diversification of primary energy sources (electricity can be generated from a wider range of sources, not necessarily with fossil origin), and allows the use of technologies that may improve energy-efficiency (such as regenerative braking and low consumption electric driven components). The BEV is a full electric vehicle which has a rechargeable battery providing its power and energy. A problem with the BEV is its short range (all-electric range, AER). The HEV uses energy provided by a combustion engine or by a fuel cell, with an energy storage system (usually the battery). The battery in a HEV is used to better control the energy flow and is usually useful in improving the vehiclés efficiency when compared to the majority of the conventional powertrains. However, most of the efficiency gains in hybridizing a vehicle are modest and rivals with some of today's state-of-the-art diesel technologies.

The PHEV combines HEV with a BEV configuration, since it is possible to use the battery energy in a pure electric locomotion, and when needed it uses the fuel converter to achieve higher power or to extend the vehicle range (and then working like an HEV). In the PHEV the batteries can be recharged directly from the fuel converter or from an external electric supply [4,5].

Goncalves et al. [6] monitored and simulated a fuel cell transit bus. In Wipke et al. [7] one of the most used vehicle simulators is presented, the ADVISOR, which is capable to model different types of conventional and alternative powertrains in specific driving conditions. Using this software, Ribau et al. [8] analyzed different kinds of FC-PHEVs and BEVs, namely, motorcycles, buses, and light duty vehicles. The performance of several battery types in hybrid vehicles is of great importance and was studied by Burke et al. [9]. Moreover, the environmental impact of the battery production was addressed by McManus [10]. Additionally, the different fuel converters for HEVs were also studied by Ribau et al. [5].

The implementation of new technologies for road vehicles such as HEVs and PHEVs depend not only on the public acceptance, but also on the involved logistics for energy distribution. Petrol and diesel logistics problems are solved, but not for electricity supply, required by the PHEVs and BEVs (that need an electricity socket to charge the battery) nor alternative fuels like hydrogen (for fuel cell vehicles). Therefore, a way to boost the alternative vehicle penetration in the transportation sector is to develop fleet implementation projects, since in a fleet (like a taxi fleet or a post fleet) the travelling routes and the infrastructures are better defined than in a personal vehicle. Moreover, the initial investment for alternative technologies can be directly transformed in energy savings (and pollutant emissions reduction), and more important in cost reductions in fuel for the fleet owner.

Fuel cell and plug-in hybrid public transit buses can take advantage of well-defined duty cycles and a fixed fuel and maintenance infrastructure that facilitates the working schedule and refueling of the bus. Buses also allow more space for propulsion system and fuel storage. An example of the implementation of fuel cell buses was explicit in the Project Clean Urban Transport for Europe (CUTE) [11].

Additional advantages of the PHEV powertrains were studied by Al-Alawi and Bradley [12]. They calculated the relative value that PHEVs can have in reducing an automaker's costs for CAFE compliance.

### *1.2. Optimization of alternative vehicles*

In a hybrid powertrain, component sizing and energy management strategy significantly affects vehicle performance, cost and fuel economy. The ability to integrate the optimization of the energy management control system with the sizing of key hybrid powertrain components presents a significant area of research, since optimizing the vehiclés powertrain design can greatly improve the vehicle efficiency and cost. In some cases, when companies acquire their vehicles (e.g. postal fleets, public transportation, services fleets), little efforts are made to adopt optimized vehicle powertrains resulting in the use of vehicles that are usually oversized regarding the real purpose and requirements. In order to minimize the $CO_2$ emissions produced in the vehicle operation or indirectly by the fuel supply, Stockar et al. [13] developed an optimal supervisory control for the energy management of a PHEV using the Pontryagin's minimum principle. In [14] a real-time power splitting method for a FC-PHEV was also developed addressing different driving conditions and aiming to minimize the fuel consumption and to preserve the battery life. Light-duty vehicles