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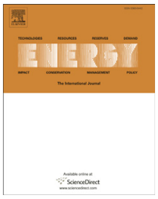

Reducing the carbon footprint of urban bus fleets using multi-objective optimization

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A B S T R A C T

The electrification of road vehicles was introduced as a way to significantly reduce oil dependence, increase efficiency, and reduce pollutant emissions, especially in urban areas. The goal of this paper is to find the best alternative vehicle to replace a conventional diesel bus operating in urban environments, aiming to reduce the carbon footprint and still being financially advantageous. The multi-objective nondominated sorting genetic algorithm is used to perform the vehicle optimization, covering pure electric and fuel cell hybrid possibilities (with and without plug-in capability). The used multi-objective genetic algorithm optimizes the powertrain components (type and size) and the energy management strategy. Although multiple optimal solutions were successfully achieved, a decision method is implemented to select one unique solution. A global criterion approach, a pseudo-weight vector approach, and a new multiple criteria score approach are considered to choose a preferred optimal vehicle. Real and synthetic driving cycles are used to compare the optimized buses concerning their powertrain components, efficiency and life cycle of fuel and vehicle materials. The conflict between objectives and the importance of the decision considerations in the final solutions are discussed. Passengers load and air conditioning system influence in the solutions and its life cycle is addressed.

1. Introduction

Governments have been introducing a large number of policies and measures aiming to improve efficiency of energy use, and push alternative fuels especially in the road transport sector. Some examples of a global trend to diminish emissions from the transportation sector are the Kyoto protocol, the 2003/30/EC European directive on biofuels for the transport sector, and the European 20-20-20 targets [1].

HEV (hybrid electric vehicles), PHEV (plug-in hybrid electric vehicles), pure BEV (battery electric vehicles), and fuel cell vehicles, have been considered as possible solutions towards the powertrain electrification in order to achieve further improvements in efficiency and mitigation of the environmental impact of road vehicles.

The BEV is a full electric vehicle with plug-in capability, which is powered by electrical energy stored in a battery pack. The main advantages of BEVs are its zero local emissions and its high efficiency (~70%); however its limited autonomy (all-electric range, AER $\leq$ 150 km), an outcome of the battery depletion, is still its major drawback. The HEV generally combines two or more power sources for propelling the vehicle. Frequently, an electrical power source and a fuel power source are used. The PHEV can be defined as a HEV with plug-in capability. BEV and hybrid vehicles may recover and store energy in the battery during deceleration events (regenerative braking), potentially increasing the overall vehicle efficiency.

In this paper, with the aim to increase the research of non-fossil fueled vehicle systems, a hydrogen fuel cell powered hybrid (FC-HEV), a hydrogen fuel cell plug-in hybrid (FC-PHEV), and a BEV, are simulated and optimized to replace a conventional urban diesel bus.

Previous works highlighted the advantages of using electric and hybrid vehicles relatively their efficiency gain and alternative fuel production pathways, by using vehicle simulation tools and the LCA (life cycle analysis) methodology [2]. Some of those studies focus on the impact of the materials used in the vehicle production and used throughout the vehicle lifetime [3]. The life cycle impact of using lightweight materials in the vehicle design has also been analyzed [4]. Other studies, besides performing a vehicle use analysis, the fuel production impact, such as hydrogen for fuel cell vehicles, has

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also been focused [5]. Complementary to the fuel production impact, the analysis of the fuel feedstock and the fuel supply infrastructures has also been regarded in these area of research [6]. In other studies, both the environmental impact and cost advantages are highlighted for alternative vehicles, such as assessing plug-in hybrids [2]. Concerning hydrogen technologies, an hydrogen network model consisting of multiple production pathways for passenger transportation, and the study of the hydrogen network interdependency and vehicle technology relatively to conventional vehicles and fuels has been addressed in Ref. [7]. Also on hydrogen technologies, other studies have been studying the life cycle impact of the vehicle powertrain composition [8].

In a more specific approach, several studies analyzed different powertrain component solutions, such as, the use of advanced batteries and ultracapacitors for hybrid, fuel cell, and electric vehicles [9]. The use of different fuel converters such as, over-expanded cycle engines, Wankel engines, and microturbines have also been analyzed [10]. Some of these solutions may include alternative fuels (e.g. gasoline and diesel blends with biofuels, hydrogen, and electricity). Moreover, the impacts on fuel consumption and vehicle emissions from different driving conditions including road type, average speed, load mass, and air conditioning, have also great significance and have been also studied for conventional and alternative buses in real conditions [11]. Additionally, the fuel economy, maintenance and operating costs per mile, and reliability of conventional, hybrid, and natural gas powered buses were also compared in a real bus fleet [12].

Although great improvements are claimed for the electrification of powertrains in relation to conventional ones, the use of optimization methods applied to the vehicle components and the EMS (energy management strategy) system may potentiate further improvements in the vehicle design. Several different optimization techniques are used in the research community. Dynamic programing techniques are frequently used to compute state variables of the battery use strategy in hybrid vehicles, aiming to minimize the vehicle use cost and emissions [13]. Some studies use metaheuristics, such as genetic algorithms to perform parametric optimization on the size of the components and on the control strategy [14] aiming to increase the vehicle overall efficiency. Other studies perform a mixed optimization process, by using two combined optimization loops: one for sizing the energy sources, using a genetic algorithm, and another one for computing the optimal energy management strategy using dynamic programming [15]. Adaptive intelligent techniques have also been applied to optimize the control strategy of hybrid vehicles where some control parameters tuning mare adjusted throughout the vehicle operation [16].

Besides vehicle performance and powertrain efficiency, the consideration for the economical aspect in the optimization objective has demonstrated to be essential in the powertrain design using metaheuristics [17]. Additionally to the cost of the components of the vehicle the subsequent minimization of the vehicle energy consumption also demonstrated to be beneficial in the design stage of the vehicle [18]. In order to address both economic and environmental optimization objectives, Multiobjective algorithms have also been addressed to achieve useful optimal trade-off solutions [8].

When improving the transport sector by considering the best vehicle technology, optimizing a vehicle powertrain or by selecting the best energy pathway, decision-making and multi-criteria analysis methods become useful for selecting preferable solutions relatively to specific criteria. Some of these methods have been applied in ranking alternative vehicle technologies and fuels [19], as well as in scoring methods used to evaluate various alternative fuel modes for the transport sector, taking into account economic, technical, social and political criteria.

The objective of the research presented in this paper is to present a methodology to optimize alternative powertrains (components power and EMS parameters) and support decision-making aiming to select the best theoretical candidate to replace a conventional diesel bus, in urban environments. The alternative bus must achieve both less carbon footprint and maximum financial gain.

In this paper a multi-objective optimization algorithm is used to find the *Pareto* front solutions, and subsequently, three decision-making techniques are considered to select the preferred solutions, which are: global criterion, pseudo-weight vector and multiple criteria score [20]. Unlike previous studies, this paper addresses different powertrain configurations and powertrain components, as well as their sizing, aiming to select the best type of component and their correct sizing for specific driving conditions. Besides comparing the resultant powertrains for different driving conditions, the impact of consumables, embodied materials used in the bus, component replacements, fuel production, and the financial gain (considering vehicle cost and fuel consumption) for each optimized possibility is also evaluated. Moreover, the influence of passengers and the air conditioning system in the solutions and its life cycle is addressed.

The proposed methodology also provides an innovative approach to deliver a ranking of optimized vehicle solutions sorted by the best achievements in the desired criteria, which can be applied to fleets or personal transportation. The conflict between the objectives and the importance of the decision considerations in the final solution are highlighted.

Fig. 1 shows the scheme of the developed methodology.

The paper is organized as follows. Section 2 describes the vehicle modeling as well as the environmental and financial assessment procedures. The life cycle impact and the manufacturing and operational costs associated with the vehicle are included in this section. Sections 3 and 4 describe respectively the optimization method and decision approaches used in this study. The results are presented in Section 5, followed by the discussion of the main results. Finally the conclusions are presented in Section 6.

2. Modeling and assessment of vehicles

2.1. Vehicle modeling

A vehicle simulator, ADVISOR, is used to model the vehicles. The ADVISOR (ADvanced VehIcle SimulatOR) [21] software, created by the U.S. Department of Energy's National Renewable Energy Laboratory's, was developed using the object-oriented programming language of Simulink/MATLAB from the MathWorks, Inc. ADVISOR is driven by the input driving profiles which can be the classic speed vs. time, or a speed and grade vs. time driving profile (represented in discrete steps). With a given driving profile goal, ADVISOR then works its way backwards from the required vehicle and wheel speeds to the required torques and speeds of each component between the wheels and the energy source (fuel converter or battery).

The official driving cycle, ETC (European Transient Cycle) for heavy duty vehicles was used to simulate the bus driving conditions [22]. The ETC driving cycle is characterized by a distance of 29.5 km and an average speed of 59 km/h. A real driving cycle, *LisDC*, was also used in order to simulate real driving conditions, for which data was measured in Lisbon downtown concerning a real bus route. The *LisDC* is characterized by a distance of 23.04 km, an average speed of 15.8 km/h, 72 stops, 42 s of idling, and a variable road grade. Although the occupancy rate of the *LisDC* was also measured, the main results are concerned to the bus operation without passengers in order to be fairly compared with ETC, since