Applied Energy 202 (2017) 662–672

Contents lists available at ScienceDirect

Applied Energy

journal homepage: www.elsevier.com/locate/apenergy

Design-space exploration of series plug-in hybrid electric vehicles for medium-duty truck applications in a total cost-of-ownership framework

Ashish P. Vora[a], Xing Jin[a], Vaidehi Hoshing[a], Tridib Saha[a], Gregory Shaver[a,*], Subbarao Varigonda[b], Oleg Wasynczuk[a], Wallace E. Tyner[a]

[a] Purdue University, West Lafayette, IN, USA
[b] Cummins Inc., Columbus, IN, USA

HIGHLIGHTS

- A model-based framework for parametric design of hybrid electric vehicles is shown.
- Powertrain efficiency and Li-ion battery degradation are both simulated.
- The framework enables design from a total cost-of-ownership perspective.
- Results are shown for the series architecture over medium-duty truck applications.
- Significant impact of payback period and battery replacement limitations.

ARTICLE INFO

Article history:
Received 20 May 2016
Received in revised form 8 May 2017
Accepted 9 May 2017

Keywords:
Economic analysis
Plug-in hybrid electric vehicles
Energy storage system
Component sizing
Battery life
Payback period

ABSTRACT

The light-duty vehicle market has seen some adoption of hybrid electric vehicles that is not reflected in the heavy-duty market. The major challenges associated with the heavy-duty segment are: (i) greater emphasis on economic viability, (ii) reluctance to take on risk associated with new technologies, and (iii) numerous diverse applications that preclude a one-size-fits-all approach to hybrid-electric powertrain design. To overcome these challenges, a model-based framework is required that enables the exploration and optimal design of powertrain architectures for diverse applications while capturing the impact of hybridization on the economics of ownership under different economic scenarios. This paper demonstrates such a framework that incorporates powertrain simulation and battery degradation models to predict fuel consumption, electrical energy consumption, and battery replacements. These results are combined with economic assumptions to enable the exploration of a large design space (which spans powertrain design & control variables, noise variables, and economic scenarios) from a total cost-of-ownership perspective to provide better insights to vehicle integrators, component manufacturers, and buyers of heavy-duty hybrid electric vehicles. The methodology is applied to series plug-in hybrid electric and extended-range electric powertrain architectures for medium duty truck applications. The results show that under the assumptions made, economically favorable solutions for series plug-in hybrid electric medium-duty trucks exist in the 2020 time-frame for the NY Composite Truck drive cycle, while for the HTUF Refuse Truck and HTUF Class 6 P&D Truck drive cycles, feasible solutions are not obtained until 2025 and 2030 time-frames respectively.

1. Introduction

Optimizing the powertrain design and control for hybrid electric vehicles (HEV) has been an area of great interest and work in the past decade. The proliferation of HEVs in the light-duty automotive segment has not been mirrored in the heavy-duty segment for several reasons. The commercial nature of the heavy-duty vehicle market means that economic profitability of vehicle operation is the major consideration for fleet owners and operators who purchase such vehicles, unlike the light-duty sector where several other considerations such as comfort, utility, styling, and brand image affect buying decisions. This especially reduces the appetite for promising but unproven new technologies that come with a significant up-front cost premium. Additionally, the diversity of applications in the heavy-duty space makes it difficult to design

---

* Corresponding author.
E-mail address: gshaver@purdue.edu (G. Shaver).

http://dx.doi.org/10.1016/j.apenergy.2017.05.090
0306-2619/

a single system that performs well under different driving and load demand profiles. These reasons motivate the need for a model-based approach that allows a powertrain manufacturer or vehicle configurator to accurately assess the market viability of various hybrid electric powertrain architectures and determine the optimal design and control solutions for a particular application. Early design optimization studies for HEVs, such as [1,2] for light-duty vehicles and [3,4] for medium/heavy-duty vehicles, either focused on optimizing only component sizing parameters or both sizing and control parameters, but in a sequential approach. Further, these studies did not consider the degradation of the battery. Battery degradation can have a significant impact on the economics of ownership of hybrid electric vehicles as battery life is extremely sensitive to how it is utilized. Therefore, accounting for battery degradation is critical to a total cost-of-ownership (TCO) analysis.

Ref. [5] motivated the opportunity for battery-life-extending control by demonstrating varying degradation rates with varying duty cycles using semi-empirical battery degradation models. Refs. [6–8] suggest different approaches for maximizing battery life for specific applications; however, they do not consider the problem from a cost-of-ownership over life-cycle perspective, as this involves the need to make several assumptions for various economic parameters such as the cost of technology, cost of fuel, and the utilization of the vehicle. Furthermore, these studies all look at HEVs and not plug-in hybrid electric vehicles (PHEVs), which have different operating modes during Charge Depleting (CD) and Charge Sustaining (CS) operation.

Ref. [9] considered the Net Present Value (NPV) over the life-cycle as an objective for a sequential design and control strategy optimization of light-duty PHEVs; however, again without accounting for battery degradation. Ref. [10] define a comprehensive total cost-of-ownership (TCO) for light-duty plug-in hybrid vehicles. They also presented a brief review and comparison of various TCO models developed in literature. However, to the best of the authors knowledge, none of the TCO models in the literature tackle the design optimization problem and hence do not use vehicle simulation models to predict fuel consumption as a function of powertrain parameters, instead focusing on the analysis of current production vehicles. Furthermore, most of these TCO models are focused on passenger cars and light trucks, and none of them include the impact of battery degradation and battery replacements.

A comprehensive model-based methodology for exploring the design space for a hybrid electric powertrain in a total cost-of-ownership framework is set forth in this paper. This is achieved by executing dynamic powertrain simulation models and a battery degradation model to determine fuel consumption and battery degradation as a function of the design variables. These results are then input into an economic model (which can be configured to represent different economic scenarios) to evaluate the life-cycle TCO. The economic model includes a utility-factor-based weighting approach to combine the Charge Depleting (CD) and Charge Sustaining (CS) mode results, where the utility factor is calculated based on the annual vehicle miles traveled and the vehicle range during CD mode. Furthermore, the design space considered not only includes sizing and control design parameters but also "noise" variables - including vehicle mass, coefficients of drag and rolling resistance - to understand the sensitivity of PHEV ownership economics to variability in these parameters. The result is a framework that powertrain designers can use to determine design solutions that optimize total cost-of-ownership for particular applications, as well as assess the robustness of design solutions to different vehicle configurations and loading conditions. Additionally, the results provide insight into the economic conditions required for market viability of different hybrid-electric powertrain architectures and thus can help manufacturers with future product planning.

The paper is organized as follows: Section 2 describes the dynamic simulation models used to predict fuel consumption and battery degradation over a drive cycle, which includes the powertrain model, the power management strategy and the battery aging model. Section 3 describes the simulation framework, including the definition of the design space, the economic assumptions, life-cycle cost-of-ownership model, and the utility-factor weighting method. Section 4 presents the results and some discussion of these results for a case study of the Series PHEV architecture for the North American Class 6 medium duty (MD) truck application, across four economic scenarios. Finally, Section 5 concludes the paper with key takeaways and some promising directions for future studies using this framework.

2. Simulation models

2.1. Powertrain model

The Autonomie simulation tool developed by Argonne National Labs [11] is used as the hybrid electric vehicle (HEV) powertrain simulation environment primarily due to the ease of customization of MATLAB/Simulink based models and scripts, and the large database of component models and architectures packaged with the software.

For this study, only the Series PHEV architecture was considered and it is depicted in Fig. 1.

An HEV capable of charging off the grid can operate in two modes:

(a) Charge depleting (CD) mode, in which the vehicle will emphasize depletion of the battery starting from a full (100%) state-of-charge (SOC) to the final SOC (30%).
(b) Charge sustaining (CS) mode, in which the vehicle has already reached the final target SOC (30%) and the ICE is operated to regulate the battery SOC at this level.

For the purpose of this paper, a distinction has been made between plug-in hybrid electric vehicles (PHEVs) and extended-range electric vehicles (EREVs). For the EREV, the vehicle cannot turn on the internal combustion engine (ICE) during the CD mode, i.e. the CD mode is a purely electric mode of operation. For PHEVs, there is no such constraint imposed. Therefore, to completely assess the performance of each vehicle configuration for both PHEV and EREV applications, each design configuration has to be simulated over the drive cycles of interest in three different operating modes: two different CD modes corresponding to EREV and PHEV type operation respectively and one CS mode.

Based on industry inputs, the NY Composite Truck, Hybrid Truck Users Forum (HTUF) Refuse Truck, and HTUF Class 6 P&D Truck drive cycles are selected to represent vocations in which medium-duty trucks are utilized. These drive cycles are selected to span a reasonable range of peak/average speeds and propulsion power requirements.

The default Autonomie component models have been used for the automatic transmission, clutch and final drive while the mechanical and electrical accessories have been modeled as constant power draws. The IC engine (ICE), traction motor-generator (MG), and generator have been modeled as static maps with first-order dynamics. The battery pack (Energy Storage System or ESS) consists of two modules of cells in parallel, the number of cells in series in each module varies depending on the battery kW h variable defined in the design of experiments (DOE). This study assumes that the battery cells are perfectly balanced, and degrade in the same manner. As such, only one cell requires modeling. The battery cell is represented with an equivalent-circuit model with