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Optimum design of a fuel-cell powertrain based on multiple design criteria

Ismail Levent Sarioglu [a,b,*], Bartosch Czapnik [a], Emine Bostanci [a], Olaf P. Klein [a], Hendrik Schröder [a], Ferit Küçükay [b]

[a] Group Research Powertrain Systems, Volkswagen AG, Letterbox 011/17780, Wolfsburg 38436, Germany
[b] Institute of Automotive Engineering, Technical University of Braunschweig, Hans-Sommer-Straße 4, 38106 Braunschweig, Germany

HIGHLIGHTS

- Numerous customer-related design objectives are considered in optimization.
- Combining the simulation results with analytical methods increases the accuracy.
- Computing the entire search space provides valuable data for the trade-off analysis.
- Influences of individual design choices on a customer profile are analyzed.
- Favorable design options are presented by varying the weightings of design objectives.

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ABSTRACT

As the number of fuel-cell vehicles on the roads increase, the vehicle designs are gaining more importance. Clearly, one major topic in this field is the optimization of powertrain designs. In this design process, the aim of the car manufacturers is to meet the expectations of the potential customer best, while creating a sustainable product. However, due to several trade-offs in the design, it would be non-realistic to expect a single solution that fulfills all design objectives. Therefore, a systematical approach, which includes a trade-off analysis and evaluation methods for this multiobjective design problem, is required. In this paper, a suitable methodology is presented and applied in a case study, where an optimum powertrain design for a typical European long-range passenger car is sought. Simulation-aided powertrain models and scalable component models are used to increase the accuracy of the design process. Furthermore, various visual and quantitative evaluation techniques are applied in order to support the decision making process.

1. Introduction

Fuel cell vehicles (FCVs) represent an important concept to meet the future challenges, like the reduction of fossil fuel consumption and greenhouse gas emissions. Compared to battery electric vehicles (BEVs), an FCV offers long distance mobility and short charging times, which are comparable to today's conventional vehicles. The powertrain system of an FCV is normally designed as a hybrid topology, which combines the fuel cell (FC) with an electric storage unit, like a battery, to power the electric machine. On the one hand, this hybridization brings advantages in performance and fuel consumption by compensating the limited dynamic behavior of the FC system with the battery system and by offering possibilities to store braking energy and to optimize energy flow in the entire drive system. On the other hand, the powertrain becomes a complex structure and so does the design process. Considering the additional options in connection and sizing of the single components, which result in various hybrid topologies, the degree of freedom in the design problem is significantly increased. Furthermore, due to the numerous design criteria depending on specific customer portfolios and the OEMs' desire to introduce their powertrain concepts accordingly, the design process needs to be comprehensive and accurate. The aim is that all customer-related parameters

* Corresponding author. Group Research Powertrain Systems, Volkswagen AG, Letterbox 011/17780, Wolfsburg 38436, Germany. Tel.: +49 5361 9 43035; fax: +49 5361 9 37591.
E-mail addresses: levent.sarioglu@volkswagen.de, leventsarioglu@gmail.com (I.L. Sarioglu).

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are considered and a good customer-product match is assured. This paper presents a design methodology, which considers the above mentioned dependencies and supports the design process at an early stage so that an optimal powertrain design for a hybrid FCV can be determined.

In the following section, the state of art in powertrain design based on the results of the literature survey is presented. We compare various powertrain design methods and evaluate their suitability for this study. In the third section, the proposed methodology is explained. We discuss the modeling of the FCV powertrain and the scalable component models used in the design optimization process. In the fourth section, the results of a case study are presented and discussed. Here, an optimum powertrain design for a typical European long-range passenger vehicle is sought. Finally, the outcomes of this paper are presented in the conclusion section.

2. Literature survey

The design of a vehicle is subject to a wide range of criteria, which are continuously changing since the beginning of the automotive history. There is a long and dynamic list of criteria that a vehicle designer needs to consider. In Ref. [1], these criteria are reviewed and a catalogue of design criteria for vehicles is proposed. In this catalogue, there are seven different main groups of criteria that are classified further into subgroups of two more hierarchy levels, resulting in hundreds of design criteria. However, in this study, those ones related to the conceptualization of an FC powertrain are focused and the catalogue is reduced by excluding the non-relevant criteria for the early phase of a powertrain design. Table 1 concludes the reduced list of design criteria and the four main design objective clusters, namely economic efficiency, driving performance, comfort and environmental impact, which are explained in the following paragraphs.

Basic economic efficiency of a vehicle is found out in conceptualization considering its initial and driving costs. Ref. [2] shows that alone the material and manufacturing costs of a vehicle play a significant role in the suggested retail price of that vehicle. This makes an early cost analysis essential in a powertrain conceptualization. Driving costs depend on the consumption of a vehicle and the price of the energy sources used in that vehicle. These costs may vary with driving style, driving environ (e.g. road, weather and vehicle conditions) and the driven vehicle parameters, as the consumption may vary.

One of the important design criteria for conceptualization of an FC powertrain is driving performance. As listed in Table 1, basic vehicle performance includes maximum driving speed, acceleration performance and climbing ability. A vehicle's maximum speed can differ according to its continuous and peak performance. So called "boosting effect" can help a vehicle drive faster than its continuous maximum speed for a certain duration. The duration of the peak performance in an FCV is mostly limited by the energy capacity of the hybrid storage system or by the overheating of certain components, like the electric machine. On the other hand, acceleration performance of a vehicle is represented typically by the time that is required to accelerate the vehicle from standing state to 100 km h^{-1}. Different speed intervals, such as 60–100 km h^{-1} or 80–120 km h^{-1} can be used to evaluate the vehicle elasticity, as well. Finally, climbing ability is a term to define the maximum grade that the vehicle can drive at a given constant speed.

Maximum allowed payload, available volume and driving range are important criteria for the comfort of a vehicle. An early volumetric analysis of a powertrain reveals if it basically fits into the intended volume and the unused space can be assumed as the available volume for transport comfort. Similarly, a simple weight analysis finds out if there is free weight capacity that can be used for payload. Finally, the consumption estimation is required to determine the driving range, which also depends on the amount of the energy source that is stored in the vehicle.

Environmental impact of FCVs, which do not emit harmful gases locally, is represented by using global CO_2 emissions due to the fuel production. Commonly used hydrogen generation methods are shown and compared with each other according to their well-to-tank CO_2 emissions in Fig. 1 [3]. Although hydrogen can be produced by using renewable methods without any CO_2 emissions, today the production methods are mostly based on fossil fuels. Therefore the second pathway (450 g kWh^{-1}) is used for well-to-tank analyses in this study.

Considering the above mentioned powertrain design criteria and the increasing complexity of vehicles, the number of corresponding design methods grew significantly over the years. The methods to find out optimum power split between two drivelines concerning fuel economy of a vehicle have been subject to many research topics. The proposed methods vary from non-simulative analytical approaches like the one presented in Ref. [4] to more complex approaches based on advanced vehicle modeling as in Ref. [5]. Among the works about optimization of hybrid vehicles (HVs), especially [6] proposes an effective and accurate approach. The optimization algorithm is run to minimize a total cost function from a financial perspective. However, other relevant vehicle specifications (e.g. driving performance) are not included.

Although HVs with ICE and battery have managed to improve fuel economy in most of the cases, the increasing demand for technologies that use alternative energy sources forces researchers to seek for completely different designs and, hence, design methods. For example, in Ref. [7] components that are based on different technologies are optimized and evaluated as an alternative energy storage system for HVs. Especially the methodology that is developed in Ref. [8] introduces an approach to identify technologies that might have a potential to replace ICE in the next decades for mobility purposes. However, this work focuses on general comparison of today's and tomorrow's mobility concepts, rather than a certain powertrain technology optimization.

In literature, there are numerous new methods to find out optimum FC powertrain concerning the fuel economy. Most of these aim to optimize the energy management strategy. For example, Refs. [9,10] propose universal energy management strategies to reduce fuel consumption, while [11] presents a comparison of the most common energy management strategies for FCHVs with battery. On the other hand, Refs. [12,13] focus on the same research topic for FCHVs with supercapacitors. However, these works focus

Table 1
List of design criteria and design objectives for conceptualization of FCV powertrains.

Design criteria	Objective
Economic efficiency	
Driving cost	Minimize
Vehicle cost	Minimize
Driving performance	
Maximum driving speed	Maximize
Acceleration time	Minimize
Climbing ability	Maximize
Peak performance duration	Maximize
Comfort	
Allowed payload	Maximize
Available volume	Maximize
Driving range	Maximize
Environmental impact	
Greenhouse gas emissions	Minimize