Automatisierte Auslegung von Brennstoffzellenantriebssystemen

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Zusammenfassung

Brennstoffzellenfahrzeuge werden als eine mögliche Lösung für die wirtschaftlichen und ökologischen Herausforderungen des Automobilsektors diskutiert. Ähnlich wie batterieelektrische Fahrzeuge bieten sie emissionsfreie Mobilität. Das Antriebssystem von Brennstoffzellenfahrzeugen besteht aus mehreren Komponenten, wie z. B. einem Brennstoffzellensystem, einem Elektromotor, einer Leistungselektronik, einem Wasserstoffspeichersystem und einem wiederaufladbaren Energiespeichersystem, in der Regel einer Batterie. Das Leistungsverhältnis zwischen dem Brennstoffzellensystem und dem wiederaufladbaren Energiespeichersystem wird als Hybridisierungsgrad bezeichnet. In diesem Manuskript werden verschiedene Definitionen vorgestellt.

Um Entwickler bei der Identifizierung optimaler Antriebssystemkonfigurationen und Energiemanagementstrategien durch multikriterielle Optimierung zu unterstützen, werden in diesem Beitrag automatisierte Auslegungsmethoden für Brennstoffzellenantriebssysteme vorgestellt. Die Autoren konzentrieren sich auf die Integration der Optimierung von Energiemanagementstrategien in den Auslegungsprozess von Antriebssystemen und schlagen verschiedene Ansätze vor, die anschließend hinsichtlich ihrer Optimierungsleistung und -ergebnisse bewertet werden.

Abstract

Fuel cell electric vehicles are being discussed as a potential solution to address the economic and environmental challenges facing the automotive sector. Similar to battery electric vehicles, they offer emission-free mobility. The drive system of fuel cell electric vehicles comprises several components, such as a fuel cell system, electric motor, power electronics, hydrogen storage system, and a rechargeable energy storage system, typically a battery. The power ratio between the fuel cell system and the rechargeable energy storage system is known as the degree of hybridization. Different definitions are presented in this manuscript.

To assist developers in identifying optimal drive system configurations and energy management strategies through multi-objective optimization, this paper presents automated design methods for fuel cell drive systems. The authors concentrate on integrating energy management strategy optimization into the drive system design process and propose various approaches, which are subsequently evaluated in terms of their optimization performance and results.

Introduction

The decarbonization of the transport sector relies heavily on the electrification of drive systems, leading vehicle manufacturers to introduce a range of battery electric vehicle (BEV) models in recent years. Although fuel cell electric vehicles (FCEV) have the potential to contribute to carbon-neutral transport and have been subject of research [1, 2], they have not been widely adopted, with only a few models currently available and low production numbers [3 – 6]. This can be attributed to the high costs of fuel cell and hydrogen storage systems [7], as well as a lack of hydrogen infrastructure [8]. There is ongoing debate regarding the most beneficial applications of fuel cell drive systems and whether they include passenger cars, and uncertainty about the optimal fuel cell drive system configuration [9 – 11]. While most FCEVs have a battery integrated into the drive system, the sizing of the fuel cell and battery also varies depending on the vehicle application and drive system concept, with several approaches to drive system optimization having been published [12, 13].

In this manuscript, different definitions of the degree of hybridization (DoH) of FCEVs are presented. The DoH can be used to support marketing and comprehensibility of different drive system designs due to its recognition value and can also be used as an optimization criterion for drive system optimization and component sizing tasks. Furthermore, a brief overview over existing drive system design methods is given before presenting a new approach for the integrated design and optimization of fuel cell drive systems and energy management strategies.

Fuel Cell Electric Vehicles

Fuel cell electric vehicles (FCEVs) are typically hybridized due to the lack of dynamic behavior in fuel cell systems caused by the inertia of the air path [14]. Hybridization involves the installation of at least one rechargeable energy storage system (REESS) alongside the fuel cell system, as outlined in [15]. The components of a fuel cell drive system include the fuel cell system itself, the REESS, the hydrogen storage system, power electronics, and at least one electric traction motor. Usually, the REESS in a fuel cell drive system is a battery, although there has been research into the use of supercapacitors [16 - 18]. The integration of the REESS provides numerous benefits, such as improved dynamic behavior of the drive system and the ability to perform functions like regenerative braking and load point shifting of the fuel cell system to enhance efficiency [16, 19, 20]. Additionally, the REESS can assist the fuel cell system during cold start, and might enable a reduction of the size of the fuel cell system to lower costs [21 - 23]. A fuel cell drive system and its components is shown in Fig. 1.

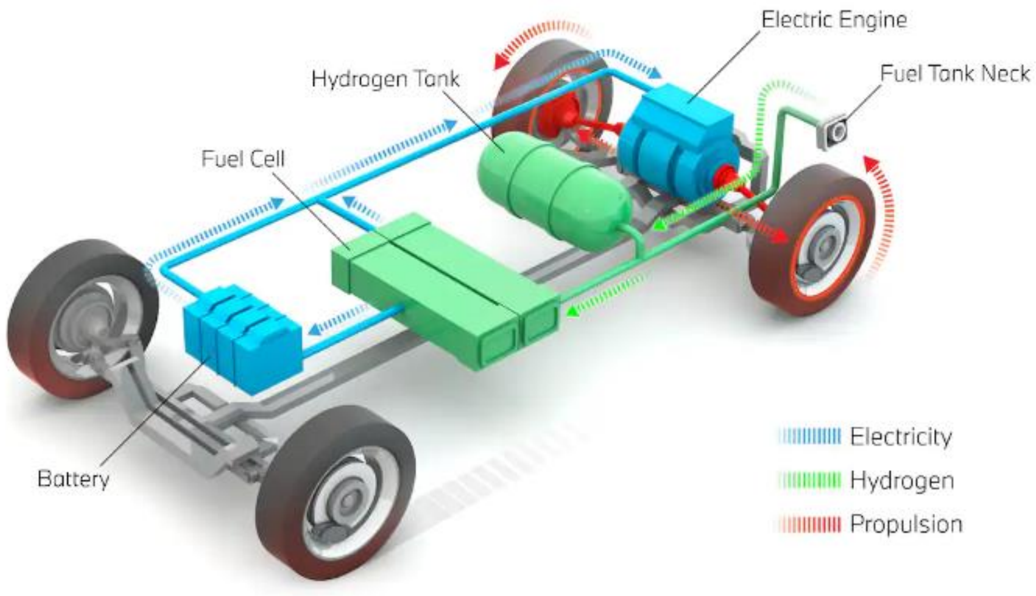

Fig. 1: Fuel cell drive system consisting of fuel cell system, battery, electric engine and hydrogen tank [25]

Degree of Hybridization in Fuel Cell Electric Vehicles

The hybridization of FCEVs is distinct from that of hybrid electric vehicles in several ways. While both types of hybrid drive systems include two energy storage units and two energy converters, the topologies of the drive systems differ. In fuel cell drive systems, only the electric traction motor can provide mechanical power for propulsion. In contrast, with the exception of serial hybrids, both energy converters (internal combustion engine and electric traction motor) in hybrid-electric drive systems can provide mechanical power. This difference also poses some challenges in comparing the DoH (Degree of Hybridization) as certain functions enabled by the hybridization of conventional vehicles, like regenerative braking or electric driving, are inherently possible in FCEVs. Also, while the definitions of the

DoH for hybrid electric vehicles, like the categories micro hybrid, mild hybrid, full hybrid, plug-in hybrid and range extender, have been established and are commonly used, multiple different definitions have been proposed for the DoH of FCEVs. While these definitions typically only consider the power ratio between fuel cell system and REESS or fuel cell system and vehicle, an expansion of this definition has been proposed in [24]. The DoH definition proposed in [23], see equation (1), is expanded with a second value considering the ratio between the energy capacity of the hydrogen storage system and the total energy capacity of hydrogen storage system and REESS, see equation (2). Thus, the DoH becomes two-dimensional, consisting of a value in the power domain, DoH_P, and in the energy domain, DoH_E. [24]

$$DoH_P = \frac{P_{FuelCell_{Max}}}{P_{Vehicle_{Max}}} \tag{1}$$

$$DoH_E = \frac{E_{H2-Storage}}{C_{REESS}+E_{H2-Storage}} \tag{2}$$

with the maximum power output of the installed fuel cell system(s) $P_{FuelCell_{Max}}$, the maximum power output of the electric traction motors in the vehicle $P_{Vehicle_{Max}}$, the energy capacity of the REESS C_{REESS} and the energy of the maximum amount of hydrogen that can be stored in the hydrogen storage system $E_{H2-Storage}$.

With this expanded definition, it is possible to identify clusters of passenger cars and vans with fuel cell drive systems based on their DoH. In [24], the DoH of nine passenger cars and two vans has been evaluated. The results are shown in Fig. 2.

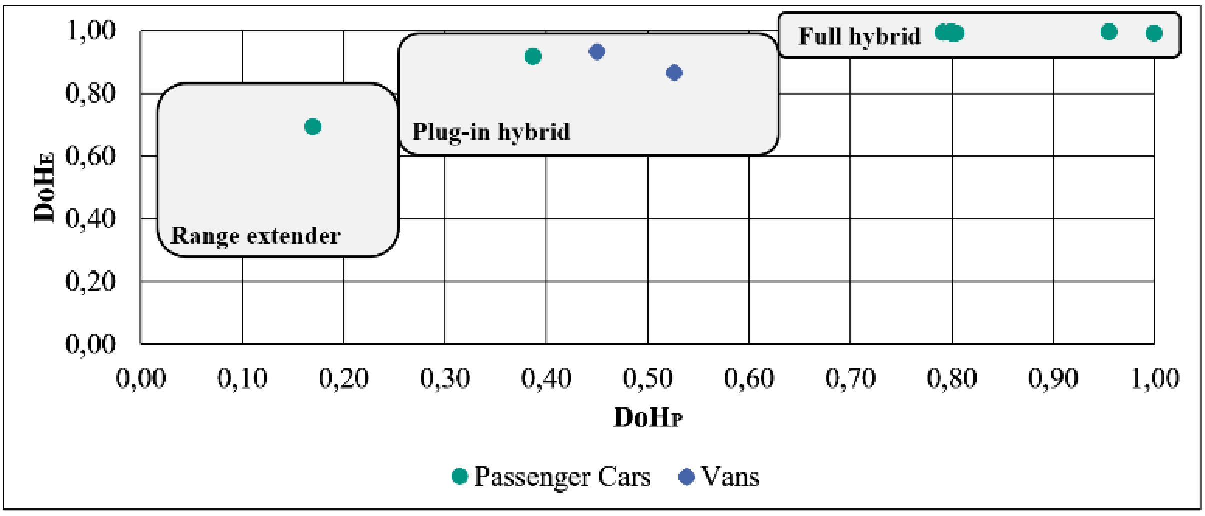

Fig. 2: Graphical representation of the two-dimensional degree of hybridization for passenger cars and vans with clusters of the investigated vehicles [24]

Furthermore, seven fuel cell buses were investigated in regard to their DoH. The typical value ranges of buses differ from passenger cars and vans, thus they could not be put into the same clusters. Therefore, different clusters have been proposed for buses and are shown in Fig. 3. To reduce uncertainty in regards to the clustering of buses, a more extensive dataset including a wider range of vehicles is required. [24]

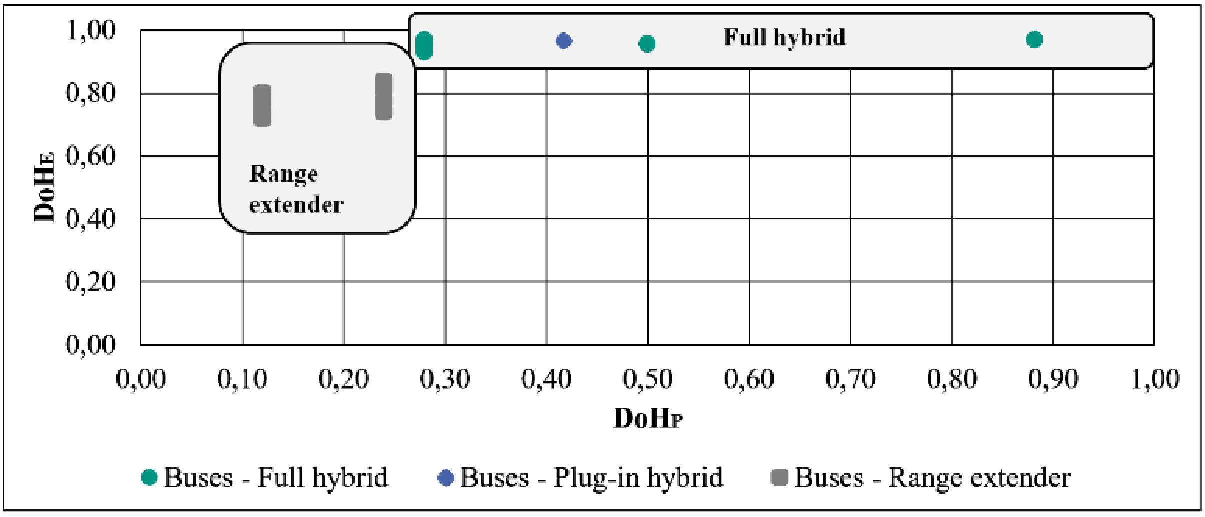

Fig. 3: Graphical representation of the two-dimensional degree of hybridization for buses with clusters of the investigated vehicles [24]

The presented DoH values do not provide a complete description of the drive system as they do not contain information about the actual power output and capacities. In the development of drive systems, the proposed two-dimensional definitions of the DoH can aid developers in sizing components in the early stages of product engineering. For instance, the average power to peak power ratio in different driving cycles can be converted into the DoH_P, a single value that can be used to determine the necessary power of the fuel cell system in relation to the peak power of the installed electric traction motors. Additionally, the DoH_E values can be utilized to evaluate the feasibility of offering an external charging option for an FCEV, at least for passenger cars and vans. Moreover, the DoH can be used as an optimization criterion to reduce computational effort compared to a complete parameterization of the drive system components. [24]

Optimization

A multi-objective optimization problem involves several objective functions that need to be either minimized or maximized. Typically, each objective conflicts with at least one other objective. When a state is reached where no individual solution can be improved further in terms of one objective function without worsening at least one other objective function, this is referred to as Pareto optimality. Such solutions are also known as non-dominated. When multiple objectives need to be satisfied in a single problem, a range of non-dominated solutions can arise. Traditional optimization methods propose converting the original multi-objective optimization problem into a straightforward single-objective optimization problem to minimize computation effort. However, this requires introducing more subjective information to influence the solutions. More advanced approaches strive to identify all solutions that are part of the Pareto front. Typically, these approaches are developed by mimicking biological or natural processes. Examples include Particle Swarm Optimization [26] and evolutionary algorithms, particularly genetic algorithms (GA). [27 – 30]

To objectively evaluate the quality of results obtained from multi-objective optimizations, a criterion is necessary. The hypervolume is a suitable quality indicator as it does not require prior knowledge of the Pareto front. This measure is calculated by comparing the Pareto front to a predefined, closed hypervolume space. The hypervolume space is defined by two reference points that span either a plane or three-dimensional space. A random set of sample points is uniformly distributed within the hypervolume space to form a net. Each sample point is then assessed to determine whether it is dominated by the Pareto front. The hypervolume is the ratio of sample points that are dominated by the Pareto front to the total number of sample points. A higher value typically indicates a better quality of the Pareto front, provided that the reference points and number of sample points are appropriately selected for the specific optimization problem. [31]

Drive System Design Methods

Numerous design methodologies for FCEVs and fuel cell drive systems have been published in recent years. One of the earliest systematic design methodologies for FCEV drive systems is described in [32]. Subsequent research has utilized various optimization methods, such as particle swarm optimization or dynamic programming, to focus on component sizing or cost reduction in FCEV drive systems and to compare different optimization methods [33, 34]. In [35], previously published design approaches for FCEV drive systems were enhanced by including the optimization of energy management strategy. The design of fuel cell drive systems and associated energy management strategies remains a major focus of current research. New methodologies for conceptual design of FCEV drive systems are described in [36, 37], which utilize full factorial design to identify optimal solutions. In [38], the author optimizes the concept design of electrified drive systems, including fuel cell drive systems, with a focus on affordability and a balance of driving performance and low energy usage. Although multiple gearbox types were considered, the optimization procedure only examined one drivetrain topology with a single electric machine. In [39], a framework for optimizing FCEVs employing various energy storage systems is presented. Several approaches to enhancing power management strategy were investigated, and fuel cells and electric energy storage systems were dimensioned in detail, taking battery aging and lifespan costs into account. In [40], an approach for automatically synthesizing and evaluating drivetrain topologies is presented, which supports developers of hybrid drive systems.

Integrated Optimization of Fuel Cell Drive System Design and Energy Management Approach

The authors introduced a methodology for the automated specification of FCEV drive systems [41] and refined this approach by integrating the optimization of the energy management strategy (EMS) in [12, 13]. The integration of the EMS was implemented using three different approaches, which were evaluated based on their optimization performance and results. The study concludes that a single-loop approach, simply integrating the EMS parameters into the drive system specification optimization loop, is the most appropriate for the given challenge, as it has lower complexity and requires less computational effort, while yielding better results compared to optimizing the drive system specification without optimizing the EMS. This emphasizes the importance of considering the EMS in the drive system design process. None of the approaches with two loops were able to produce drive systems with superior performance in terms of acceleration, efficiency, and cost while massively increasing the necessary computational effort. Fig. 4 gives an overview of the development of the hypervolume of the approaches A0 (optimization of the drive system specification in a single loop) and A1 (integrated optimization of the drive system specification and the EMS in a single loop) for different population numbers (250 and 125 respectively). It can be seen, that the optimization seems to converge in both cases. Furthermore, the difference between both approaches regarding the hypervolume is neglible. [13]

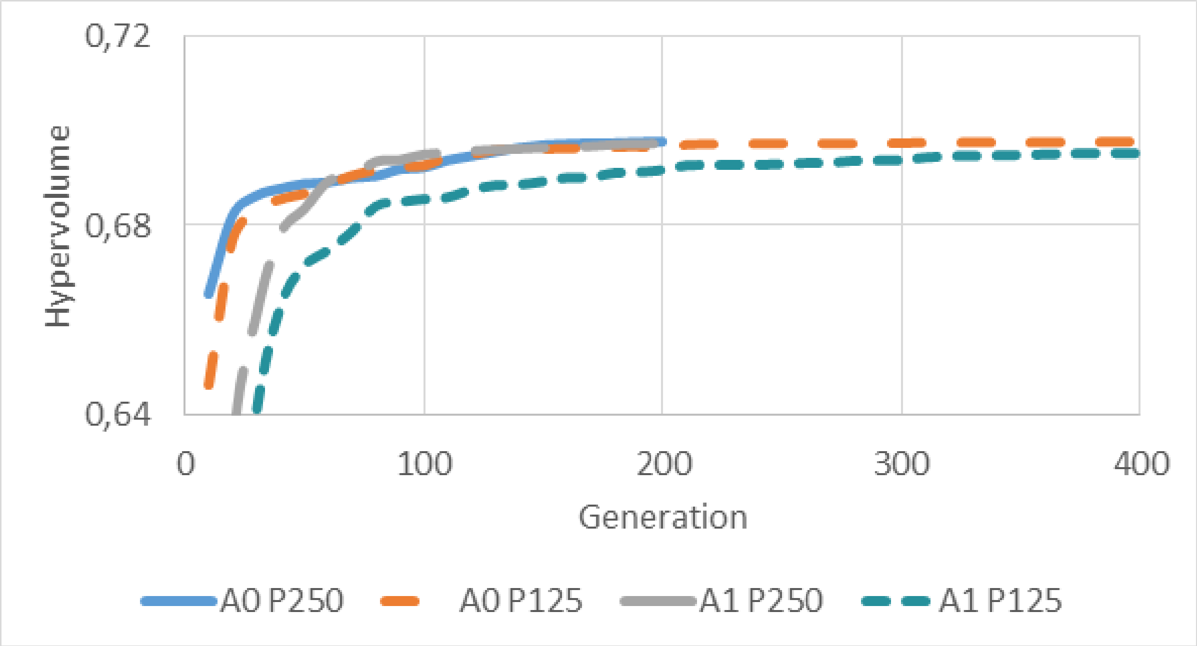

Fig. 4: Hypervolume comparison of different approaches towards the integration of EMS optimization in the drive system specification optimization with different population sizes [13]

Fig. 5 depicts the approach proposed by the authors, which takes into account the vehicle class for which the drive system is being developed, as well as other performance requirements that are indicated by the expected usage profile.

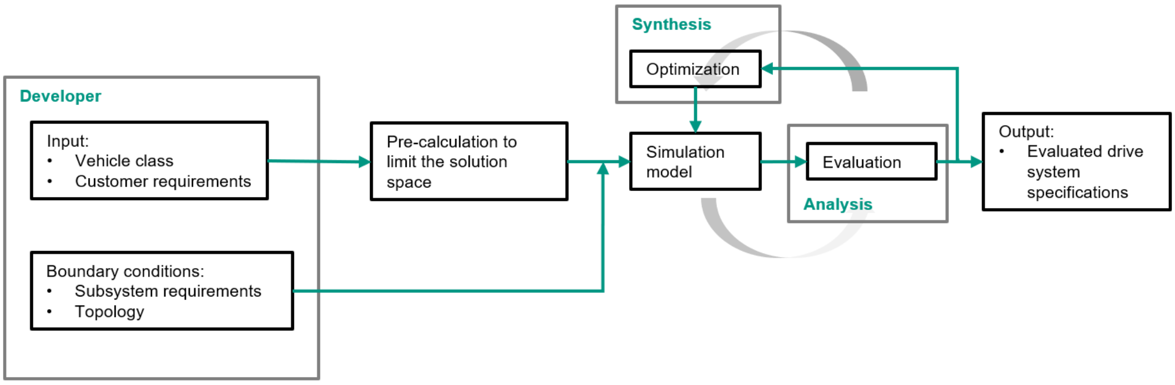

Fig. 5: Design approach (schematic) [41]

To assist developers in selecting optimal FCEV drive system configurations that meet customer demands, a scalable techno-economic FCEV model is combined with a multi-objective optimization heuristic that utilizes NSGA-II. This methodology also enables the assessment of how changes in various factors, such as modified requirements or drive system component costs, would impact the system. The optimization process considers several evaluation objectives, including the drive system cost, vehicle acceleration capability, and hydrogen consumption (determined by the drive system's efficiency during different driving cycles). [12, 13, 41]

Results

The results of the optimization approach are shown in Fig. 6. Depending on the choice of the developer, it is possible to consider two, three or more optimization criteria in the process.

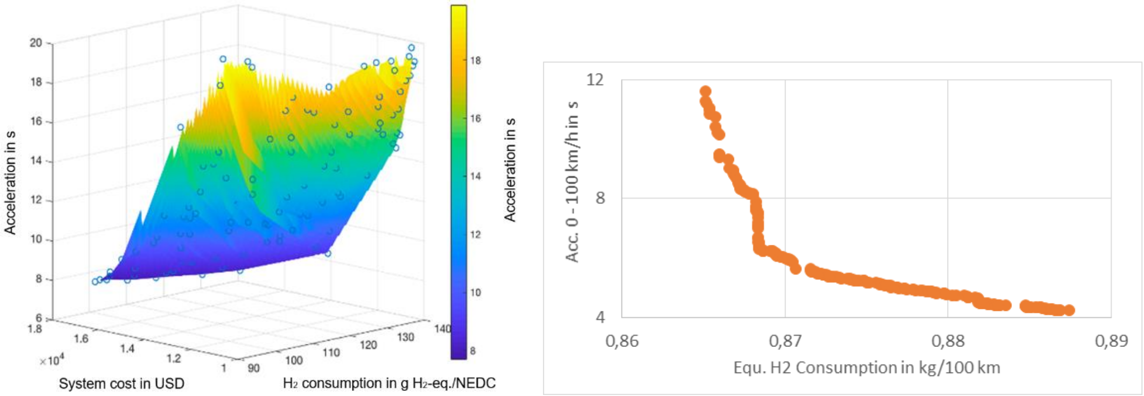

Fig. 6: Graphical representation of optimization results. Left: optimization criteria acceleration performance, equivalent hydrogen consumption and system cost; Right: optimization criteria acceleration performance and equivalent hydrogen consumption

Based on the optimization results, the developer can choose specific drive system specifications for further evaluation and development.

Conclusion and Outlook

In this manuscript, an overview over the degree of hybridization (DoH) in fuel cell electric vehicles (FCEV) is given. The two-dimensional definition of the DoH and resulting vehicle clusters are presented. Furthermore, methods for the design of FCEV drive systems are described and one specific approach towards the integrated optimization of drive system and energy management strategy (EMS) is presented. This approach will be expanded utilizing another optimization criterion by coupling the drive system and EMS optimization with a vehicle sales prediction utilizing an artificial neural network that has been developed by the authors [42]. Therefore, it will be possible to determine an “optimal” vehicle configuration for maximizing sales performance, considering the vehicles customer benefits.

In this manuscript, passenger cars with fuel cell drive systems have been focused. As fuel cell drive systems are more likely to be used in heavy-duty applications in the near future, the tool based on the optimization method will be expanded with truck and bus chassis models, requirements and drive cycles relevant to commercial vehicles.

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