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IMPLEMENTATION OF A HYDROGEN FUEL CELL IN A SMALL URBAN VEHICLE

Michal Cenkner*, Přemysl Toman, Josef Svoboda

Czech Technical University in Prague, Faculty of Transportation Sciences, Department of Vehicle Technology, Konviktská 20, 110 00 Prague, Czech Republic

* corresponding author: `cenknmic@cvut.cz`

Abstract. The transition to sustainable urban mobility is a key priority for Europe as countries seek to reduce greenhouse gas emissions and combat climate change. Electric vehicles (EVs) have become a popular trend offering a cleaner alternative to traditional combustion engines. However, despite their advantages, EVs face challenges related to the difficult extraction of raw materials for battery production, energy storage and long charging times. Hydrogen fuel cells (HFCs) are another possible alternative, offering longer range and shorter refueling times while maintaining zero local emissions. This paper discusses the integration of hydrogen fuel cell technology into a small urban vehicle and evaluates its potential in terms of sufficient power and efficiency. The study focuses on the design and implementation of the fuel cell system in a specific prototype vehicle, with the biggest challenge being the placement of the components and definition of sufficient power of fuel cell system integrated as range extender.

Keywords: Hydrogen fuel cell, urban vehicles, modular micro car, package study.

1. Introduction

In recent decades, Europe has focused heavily on ecological transformation to respond to climate change, pollution, and dependence on fossil fuels (European commission, 2021). An important part of this strategy is the Green Deal for Europe, which aims to achieve climate neutrality by 2050. A key element of this process is the transformation of urban mobility, which accounts for a significant share of greenhouse gas emissions. Overall, transport accounts for one-fifth of emissions, but three-quarters of this is attributed to road transport [1]. For this reason, small vehicles in cities, such as electric bikes, scooters, and smaller electric vehicles, are growing in importance [2], mostly in the regions that are prominent in EV sales. This brings a reduction in emissions [3] and optimization of transport.

With the growth of small vehicles, which are becoming an important tool for reducing emissions and improving transport efficiency in cities, comes the issue of supporting them, for example, by building infrastructure and introducing special zones [4]. These vehicles not only bring lower energy consumption and better use of parking spaces, but also reduce noise pollution and improve the quality of life of residents [5]. Electric vehicles are another key part of decarbonizing transport, although they face challenges such as limited range and the need for extensive charging infrastructure. Yet, they are developing rapidly in Europe, thanks, in particular, to support from governments and the European Union. An example is the project to cover the TEN-T road network in Europe with charging stations [4]. Another option is, for example, a method of motivating the driver to efficient driving through gamification of the human-machine interface [6, 7]. However, just the choice of powertrain can also influence driver's behavior, where a different vehicle behavior can encourage more dynamic driving [8]. In addition to electric vehicles, hydrogen vehicles, which use hydrogen as a fuel and produce only water vapor during operation, are beginning to gain ground. Hydrogen technology is promising, but it faces challenges such as insufficient infrastructure and the high costs of hydrogen production from renewable sources [5, 9]. A very interesting comparison [10] of the environmental impacts of using conventional electricity as part of the energy mix shows that hydrogen vehicles are even less environmentally friendly than conventional combustion vehicles, however they can be more ecologic if clean wind or solar electricity is used.

An example of a hydrogen vehicle is the Toyota Mirai, which is an effort to make practical use of hydrogen in passenger transport [11]. This car uses a fuel cell that converts hydrogen into electricity, allowing emission-free operation. Another interesting example of the incorporation of a hydrogen fuel cell into an urban vehicle is the Rasa from Riversimple. This vehicle is aimed at maximum efficiency, lowest possible driving resistance, and very low weight. The Rasa utilizes supercapacitors (shown in Figure 1) for acceleration and storing recovered energy from braking. As the car slows down, this electricity floods into the supercapacitors and is send back to the motors.

Hydrogen vehicles can become an important part of urban mobility, especially due to their rapid refueling and possibility of longer range, which is advantageous for, for example, taxis or public transport [3]. How-

Model	**Hydrogen consumption [kg 100 km^{-1}]**
Toyota Mirai	0,79
Hyundai Nexo	0,95 (data from manufacturer)
Honda Clarity Fuel Cell	0,84 (data from manufacturer)

Table 1. Hydrogen consumption of mass-produced hydrogen cars.

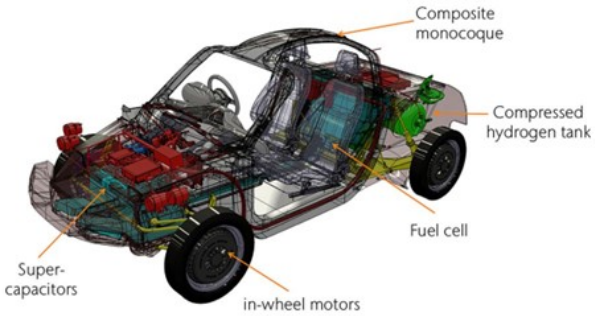


Figure 1. Package of the Rasa vehicle [12].

ever, this effort still requires a lot of research and development, but the results of the push can be seen by comparing two studies from 2020 [11] and 2023 [5]. At the same time, European cities are already experimenting with hydrogen buses and other means of transport that can contribute to climate goals.

Comparing the hydrogen consumption of several mass-produced hydrogen cars shows different levels of efficiency, with consumption depending on vehicle type, technology, and fuel cell specification. For example, the Toyota Mirai has a consumption of approximately 0.79 kg of hydrogen per 100 km according to the combined WLTP driving cycle (data from manufacturer). However, the record consumption of this vehicle was 0.55 kg per 100 km (data from manufacturer). The Hyundai Nexo, a hydrogen SUV, and the Honda Clarity Fuel Cell, a discontinued model, were compared. The results are shown in Table 1. These values show that hydrogen cars have similar fuel economy. The biggest differences appear depending on the aerodynamics, weight, and overall design of the vehicle.

An advantage of using hydrogen is its high energy density compared to batteries [13]. Hydrogen can be integrated into a vehicle's powertrain in several ways. The simplest is the conventional combustion of hydrogen in a conventional ICE [9]. This can be achieved by dispersing low-temperature hydrogen in the manifold, by using liquid hydrogen, which is injected directly into the cylinder after dispersion, or by adding it to gasoline. Burning the hydrogen in combustion engine is however comparatively ineffective approach. Therefore, the direction that has been chosen for this application, and fits with the idea of integration possibility to BEV, is to integrate hydrogen fuel cells as range extender. Their function is to convert energy from the electrochemical reaction of hydrogen and oxygen. The two main types of fuel cells are alkaline membrane fuel cells (AMFC) and proton exchange membrane fuel cells (PEMFC). PEMFCs are more suitable for automotive applications because of their faster power rise and lower operating temperature.

Our main goal is to use an already available fuel cell of a suitable type and test its performance characteristics and suitability for use in a small urban vehicle. The aim is to verify both the feasibility of incorporating the solution into the L7 vehicle platform and the overall potential of using the vehicle in a suitable driving mode.

2. Methods

2.1. Car platform description

In the context of this paper, our focus will be on evaluating the suitability of the implementation of a hydrogen fuel cell into a modular platform for a small urban electric vehicle. For evaluation, a research platform called Evgen (Figure 2) will be used that allows integration of different types of propulsion for testing purposes. This vehicle was originally designed as a BEV (Battery Electric Vehicle) of the L7 category, namely heavy quadricycles, and is therefore limited to a maximum weight of 450 kg and a maximum power output of 11 kW. The electric motor is located at the front with the front wheel drive.

2.2. Powertrain design

The entire proposed system architecture is shown in Figure 3 where the most important blocks (for the purposes of our paper) are marked in green. Red arrows indicate DC (AC) current flow.

To find a suitable fuel cell power the only one size of the hydrogen tank will be used with capacity for a 1 kg of hydrogen compressed to 350 bar. In order to use the fuel cell as a range extender, a PEM (Proton Exchange Membrane) Fuel Cell type was chosen mainly because of its compact dimensions, suitability for automotive applications and good power-to-weight ratio (see Figure 4). Another advantage is the possibility of use in a wide range of temperatures (up to 80° C). The limitation of this type of fuel cell is the necessity to humidify the polymer membrane with water and the high requirements for chemical purity of hydrogen and air [14].

Another key component in the schema is the DC-DC converter, which is used to regulate and manage generated electrical power. The output voltage of a fuel cell is not constant and depends on the load,

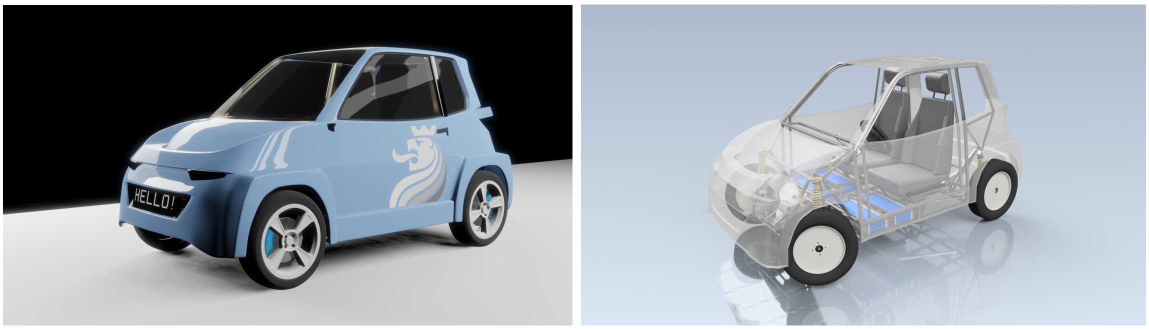


FIGURE 2. Modular vehicle called Evgen. Visualization on the right and vehicle frame on the left.

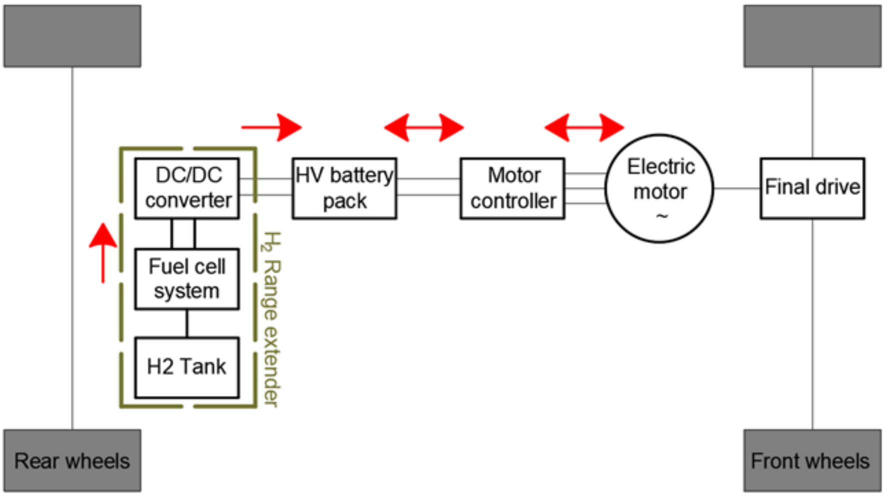


FIGURE 3. Powertrain schema.

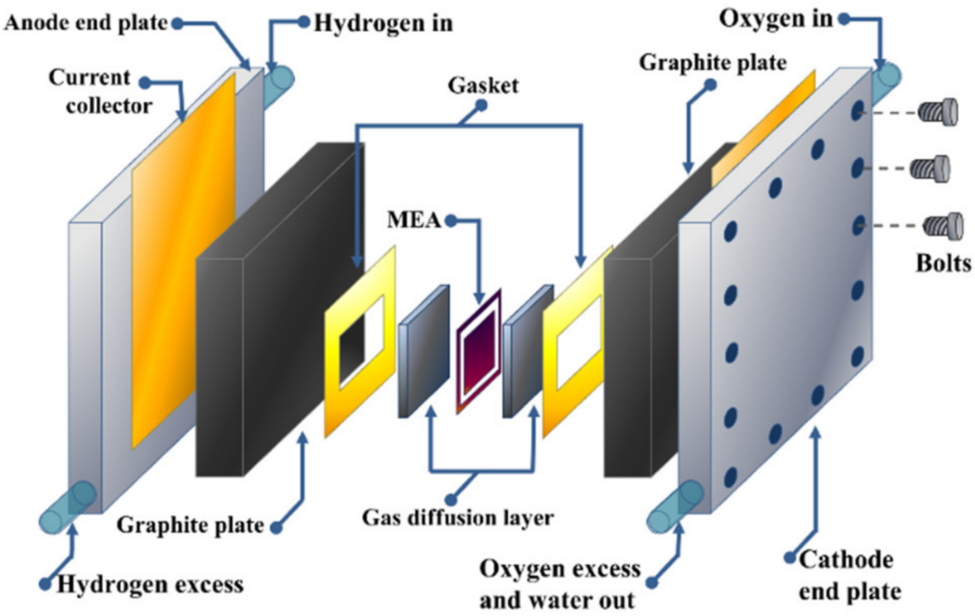


FIGURE 4. Assembly of the components of a single PEM Fuel Stack [15].

PEMFC simplified models	Units	FC25	FC50	FC75	FC90	FC93	FC95	FC100	FC108
Number of cells	[-]	25	50	75	90	93	95	100	108
Efficiency continuous	[-]	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Power continuous raw	[kW]	1.5	3	4.5	5.4	5.58	5.7	6	6.48
Efficient power	[kW]	1.05	2.1	3.15	3.78	3.906	3.99	4.2	4.536
Voltage	[V]	13-25	25-50	28-75	45-90	47-93	48-95	50-100	54-108
H2 consumption	[g h^{-1}]	108	216	324	388.8	401.76	410.4	432	466.56
Operating time (1 kg H2)	[hour]	9.26	4.63	3.09	2.57	2.49	2.44	2.31	2.14

Table 2. PEMFC simplified model properties 1/2.

PEMFC simplified models	Units	FC110	FC112	FC116	FC125	FC132	FC150	FC175	FC200
Number of cells	[-]	110	112	116	125	132	150	175	200
Efficiency continuous	[-]	0.7	0.7	0.7	0.7	0.7	0.7	0.7	0.7
Power continuous raw	[kW]	6.6	6.72	6.96	7.5	7.92	9	10.5	12
Efficient power	[kW]	4.62	4.704	4.872	5.25	5.544	6.3	7.35	8.4
Voltage	[V]	55-110	56-112	58-116	63-125	66-132	75-150	88-175	100-200
H2 consumption	[g h^{-1}]	475.2	483.84	501.12	540	570.24	648	756	864
Operating time (1kg H2)	[hour]	2.10	2.07	2.00	1.85	1.75	1.54	1.32	1.16

Table 3. PEMFC simplified model properties 2/2.

High Voltage battery pack cells	Units	LiFePO4 3.2 V 105 Ah	Li-on 3.7 V 58 Ah	LiPol 3.7 V 24 Ah
High Voltage Battery Box rated voltage	[V]	96	96.2	96.2
Voltage cell max	[V]	3.7	4.2	4.2
Voltage cell cut-off	[V]	2.5	2.75	3
Voltage cell rated	[V]	3.2	3.7	3.7
Continuous cell discharge current	[A]	105	58	200
Max discharge cell current	[A]	210	384	360
Cell weight	[g]	2000	946	430
Capacity/weight ratio	[A hr kg^{-1}]	52.5	61.3	55.8
Battery box configuration	[-]	30S1P	26S1P	26S1P
Battery box capacity	[kW hr]	10.1	5.6	2.3
Battery box cells weight	[kg]	60	24.596	11.18

Table 4. Three possible variants of HV battery.

temperature, and other factors. A DC-DC converter helps regulate the voltage to provide a voltage required for downstream components, mainly the high voltage (HV) battery and the electric motor [16, 17].

2.3. Powertrain simulation

This chapter describes the approach to define a hydrogen fuel cell with sufficient power in combination with minimized battery pack capacity versus the conventional BEV solution. For these purposes, we created simplified models of PEMFCs and battery packs. The possible Fuel Cells (FCs) are shown in Tables 2 and 3.

The examined vehicle is equipped with LiFePO4 battery cells, as shown in the table below. One of the goals of the fuel cell integration powertrain simulation assessment is to minimize battery pack. For this purpose, we created 3 possible variants of such a solution compatible with our vehicle platform (see Table 4).

The simulation model was created in the Realis Simulation software. The one-dimensional powertrain model consists of BEV fitted with PEMFC as range extender. The basic parameters of the examined vehicle are listed in the Table 5.

The powertrain was examined under the WLTC class 3 drive cycle. In every simulation scenario, the PEMFC is activated when the battery reaches SOC 80 %. This simulation part takes into account the fact that PEMFC need non-negligible amount of time for start. The PEMFC is used as a range extender constantly supporting BEV battery pack. This control strategy was defined to define the optimal size of the PEMFC. Using more complex control strategy allow to define wider group of suitable PEMFC system sizes. In this article, we operate with simplified PEMFC systems variants, and the results aim to sufficient variants definition even with basic control strategy. The

Powertrain model basic parameters	**Units**	**LiFePO4 3.2 V 105 Ah**
SOC initial	[%]	0.99
Frontal area	[m^2]	2.1
Wheel radius	[m]	0.3
Rolling resistance coef.	[-]	0.015
Max power	[kW]	20
Mass (vehicle + rider)	[kg]	600
Cx	[-]	0.4
Overall transmission ratio	[-]	9
Max torque	[Nm]	50
Transmission efficiency	[-]	0,9

Table 5. Basic parameters of the examined vehicle for simulation purposes.

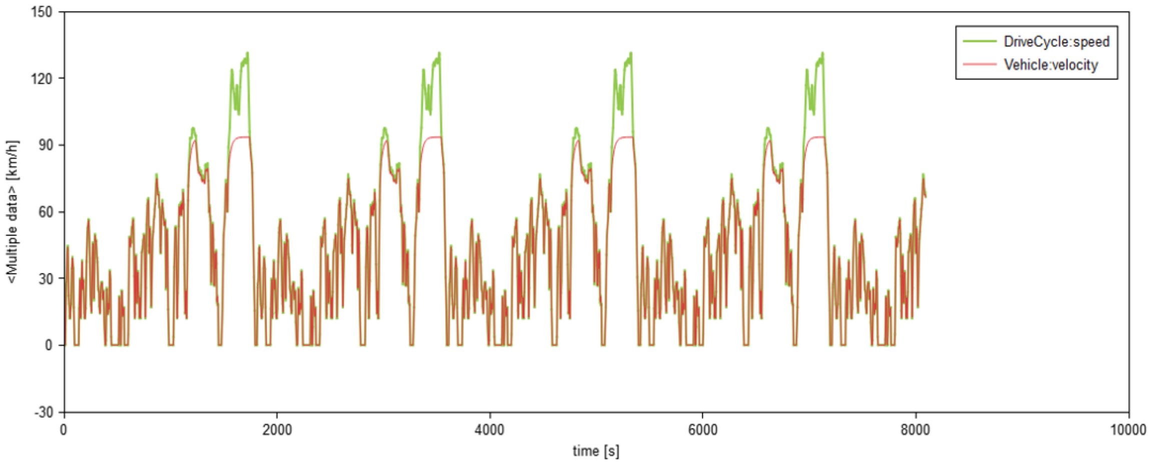


Figure 5. Examined vehicle performance in context of WLTC class 3 drive cycle.

simulation ends when the battery reaches SOC 5 %. In scenarios with BEV+PEMFC model counts with battery cells LiPol 3.7 V 24 Ah and BEV simulation takes into account all variants listed in Table 4.

3. Results

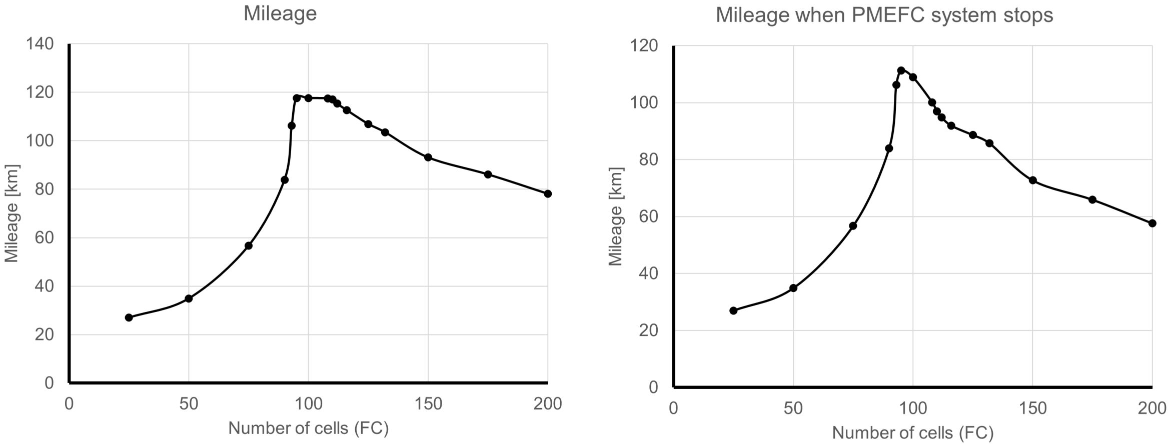
In this chapter, we present results of series of powertrain simulations of BEV and BEV equipped with PEMFC as range extender. First Figure 5 reflects the vehicle performance under WLTC class 3 test cycle. We observe that our vehicle reaches maximal velocity 95 $\mathrm{km\,h^{-1}}$.

The powertrain simulation assessed various PEMFC integrations. The following Figures 6a–6c present the overall mileage of the vehicle and the mileage when the PEMFC systems stop when all the hydrogen is depleted. The maximum mileage in the tested scenarios is 117.6 km.

According to the proper usage of hydrogen in tanks Figure 7 shows the proper usage towards driving performance. The blue highlighted section of the figure presents PEMFC sizes with insufficient power. In this testing section, values represent how much hydrogen was used and the rest of hydrogen stays in the tank. The green highlighted area defines the optimal size of PMEFC according to the parameters of the examined vehicle in the context of WLTC class 3 drive cycle. In this area, all the hydrogen is used for driving performance and fuel cell sufficiently supports the vehicle battery. The last orange highlighted area of the figure represents testing scenarios with PEMFCs with higher than needed power according to our defined basic and simplified PEMFC control strategy. The values in this section represent the amount of hydrogen used for driving performance. The rest of hydrogen was consumed into losses.

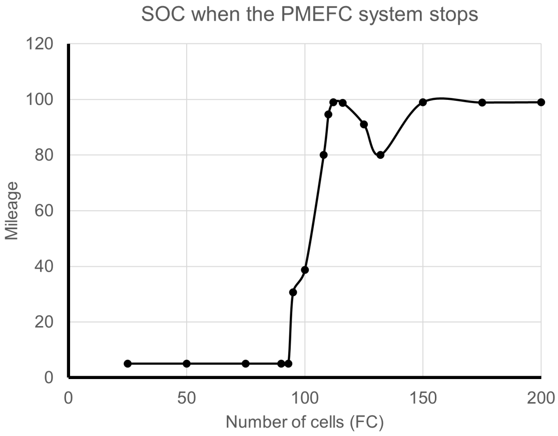
The following Figures 8 to 10 presents the output of three integrated PEMFC systems – 75, 108 and 200 cells. First example shows the situation when the battery SOC reaches 5 % earlier than the hydrogen is consumed. The second example presents the situation where all the hydrogen is consumed while driving the vehicle. When the PEMFC system stops due to running out of hydrogen, the battery is charged at SOC level 80.1 %. The third example describes the situation where the SOC while driving the vehicle with activated PEMFC system reaches 100 %. The rest of the power is under defined PEMFC control strategy directed into losses.

In the end, the powertrain simulations were compared with the performance of the BEV variants. The first variant was the same battery size as in the simu-



(a). Overall mileage of the whole powertrain system.

(b). Mileage when the PEMFC system stops.



(c). Vehicle battery pack SOC when the PMEFC system stops operation.

Figure 6. Configurations with different numbers of cells.

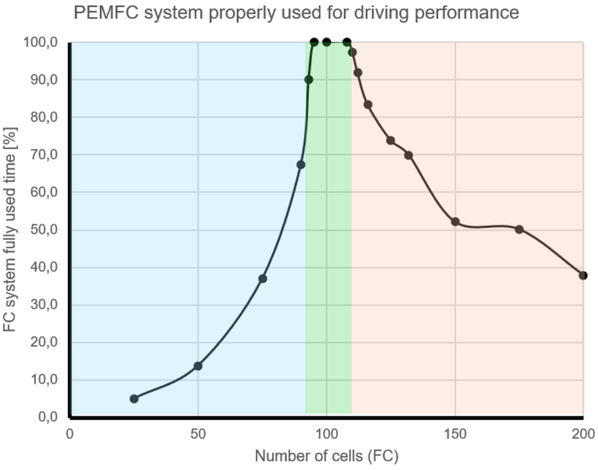


Figure 7. Proper usage of hydrogen and PMEFC systems for driving performance.

lation with PMEFC. The mileage in this variant was 20.5 km. The second variant simulation test was conducted with a midsize battery with Lion NMC 58 A.hr cells. In this variant, the mileage reached 51.8 km. In the last test we performed simulation with original LiFePO4 105 A.hr cell battery pack with resulting mileage of 97.7 km.

4. Discussion

In this article, various scenarios of integration PEMFC system as range extender into small urban BEV were assessed. Performed vehicle powertrain simulation reflects WLTC class 3 drive cycle as presented in Figure 5. The goal of the simulation process was to define a sufficient size of the PMEFC stack in the context of a defined PMEFC control strategy. All simulations were performed with the same amount of 1 kg hydrogen in the tank. This amount of hydrogen was defined due to compatibility with current hydrogen refill stations that are often constructed with the limitation of minimal 1 kg hydrogen refueling.

The method described in this article proved the potential of definition of such sufficient fuel cell system power. Figures 6a and 6b show the effect of the PEMFC system sizes in the context of vehicle mileage. Using this approach, we are able to define sizes of PMEFC systems suitable for examined small urban vehicle – sizes FC98, 100 and 108. In more detail in this narrower group of systems in Figure 7 we

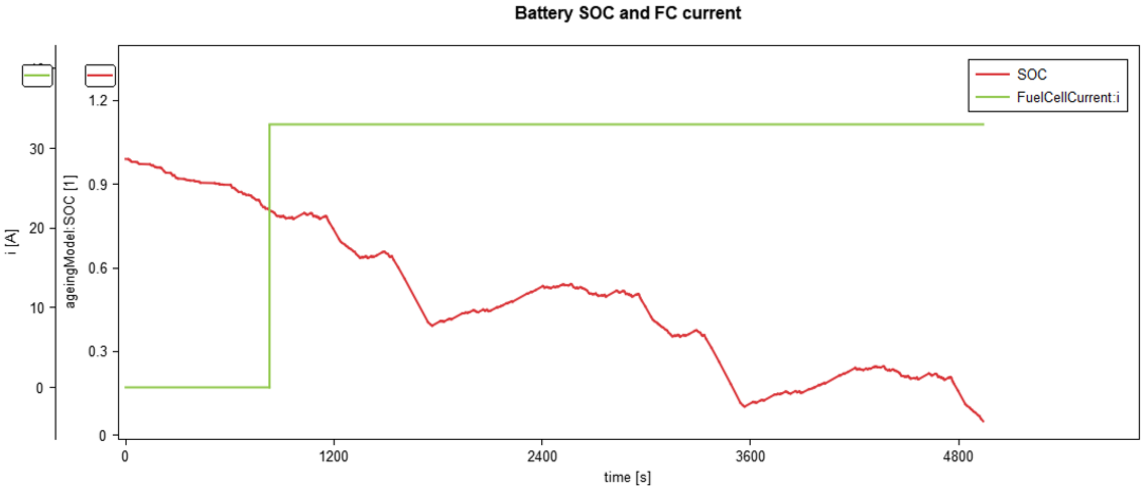


Figure 8. Powertrain simulation output with PEMFC – 75 cells.

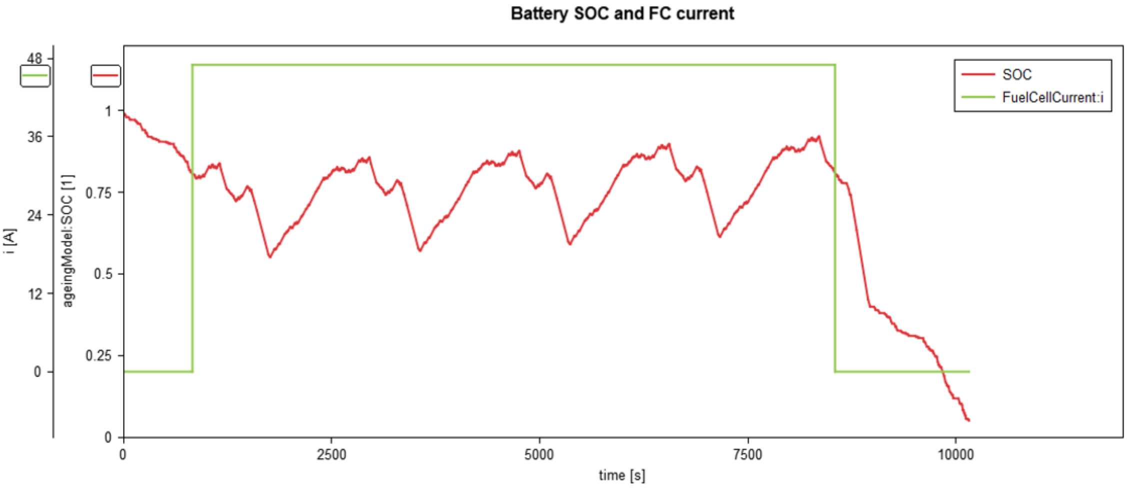


Figure 9. Powertrain simulation output with PEMFC – 108 cells.

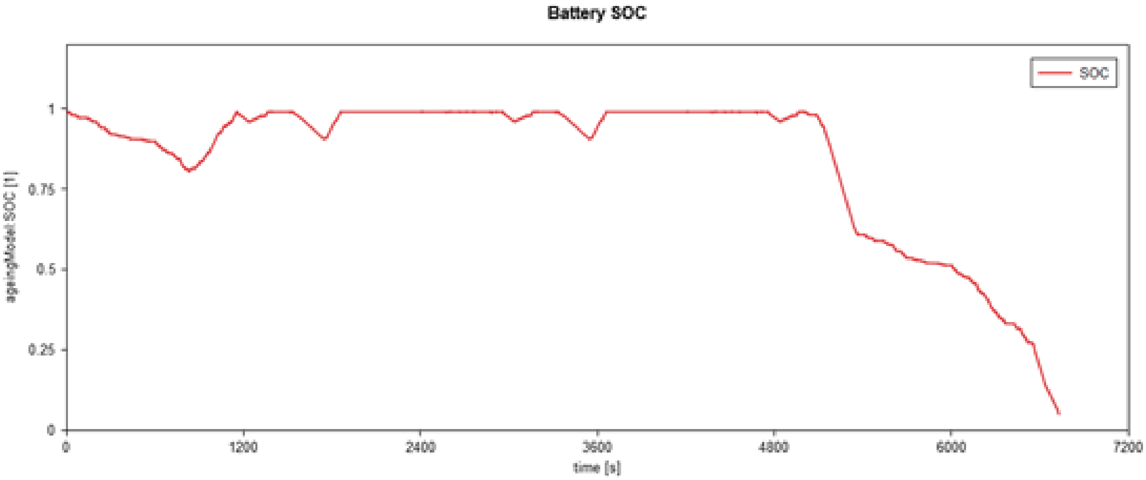


Figure 10. Powertrain simulation output with PEMFC – 200 cells. Highlighted area indicates losses in the system.

observe differences of SOC when the fuel cell system stops operation (see Figure 6c). This fact is strongly affected in this approach with the defined drive cycle – for example FC 132 in Figure 6c which indicates that the SOC of the battery was significantly lower at the termination of PEMFC than in the other – adjacent cases (only 80 % SOC). This situation is due to the fact that the PEMFC termination occurred at a time when the battery was under more load, depending on the position within the driving cycle – here it was the end of a motorway section. Figures 6a, 6b and 7 also show trends in context of PEMFC power – too low and even too high-power leads to inefficient operation.

Figures 8 to 10 brings the closer look on the behavior of the battery system while driving in terms of SOC. As the whole PEMFC system was designed as a range extender, the battery pack itself is able to provide sufficient power for the vehicle. Increasing the sizes of the PEMFC systems extend the mileage of the entire powertrain system until the suboptimal size is reached. In detail, we observe that the sufficient power of the fuel cell system is able to keep battery SOC in constant zone, e.g. between 50 % and 90 %. If the fuel cell system has higher than sufficient power, it handles the battery SOC in a narrower range between e.g. SOC 90 % and 100 %. Because while driving under defined drive cycle the is in certain situation low demand for power the rest of the fuel cell system power is directed into losses. This negative effect could be eliminated with a more complex PEMFC control strategy. However, the smaller size of the PMEFC is sufficient and provides the same overall mileage, because the same amount of hydrogen is used. The main differences that would occur using higher than sufficient PMEFC system power would lead to different battery SOC when the fuel cell system stops operating because based on control strategy the vehicle would occur in different parts of the drive cycle.

Comparing the potential of PEMFC system integration with described small urban BEV concept, we observe the difference in mileage 117.6 km with optimal fuel cell size and 97.7 km with original battery. Integrating the fuel cell system, the battery capacity was reduced to 23 % from 10.1 kW.hr to 2.3 kW.hr. This reduction represents a weight reduction of 50 kg in the case of battery cells. However, the weight of the fuel cell and all other necessary components of the system must be taken into account, so the resulting weight savings may be insignificant. This is another parameter that should be considered while choosing the right size fuel systems from predefined cells using approach assessed in this article.

In terms of package study, the Figure 11 presents possibility of fuel cell system integration into current concept considering real dimensions of all subsystems.

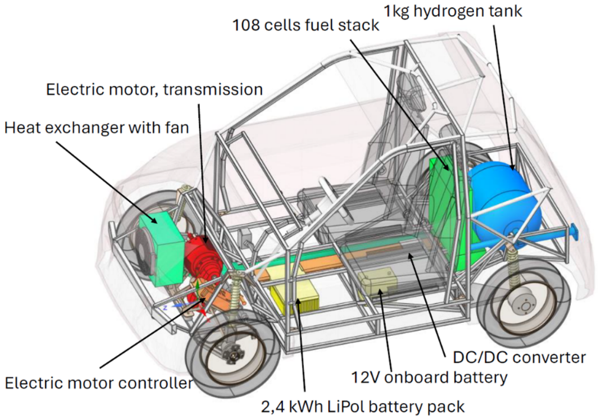


FIGURE 11. Raw 3D package model of the implemented powertrain.

5. CONCLUSION

In this paper, the implementation of the hydrogen fuel cell system in a small urban vehicle was analyzed from the point of view of dimensioning the power of the required hydrogen fuel cell, which is used in the powertrain as a range extender. Using a 1D multiparametric powertrain simulation within a standardized WLTC class 3 cycle, the suitable fuel cell power was found and then compared to a pure battery electric vehicle. Based on the results of the simulations, a raw 3D package model was also created, where the simplified geometry of all essential components of the powertrain system is implemented.

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