HYDROGEN FUEL CELL RANGE EXTENDER POWERTRAIN SIMULATION STUDY FOR URBAN MOBILITY POWERED TWO-WHEELER

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Abstract: This study aims to evaluate the viability of hydrogen fuel cell (FC) technology as a range extender in powered two-wheelers (PTWs), focusing on choosing efficient FC size and under a time-limited, constant power delivery FC control strategy. The analysis presented in this study sheds light on the feasibility of hydrogen FC technology as an alternative energy source for mobility applications. In this study, a 1D powertrain simulation model was created, which enables the efficient analysing of both fundamental and advanced behaviour of individual vehicle subsystems and control strategies, even at the early conceptual design phase. The simulation results show that hydrogen FCs are a promising technology for range extension in urban mobility.

Key words: *light urban vehicles, fuel economy, powertrain simulation, fuel cell, hydrogen, electric powertrain*

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1. Introduction and Review

The rapid urbanization of the modern world has increased mobility demands while escalating environmental concerns. Transportation, as a major contributor to

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global greenhouse gas emissions, requires a shift to sustainable practices. Among urban transport modes, powered two-wheelers (PTWs) stand out for their affordability, compactness, and efficiency in congested cities. However, their widespread use raises concerns about emissions, pollution, and energy consumption. Integrating alternative energy sources into PTWs has become essential to reduce environmental impacts while maintaining their benefits. Studies show PTWs significantly contribute to particulate matter and nitrogen oxide emissions in urban areas, worsening air quality [1]. Small hydrogen vehicles, light-duty EVs, for city transportation are seen as an alternative to larger conventional vehicles and an asset to reduce greenhouse gas emissions (GHG) emissions in city centres [2]. To address these challenges, understanding the relationship between traffic emissions and even meteorological conditions is crucial, as it can help develop strategies to mitigate the environmental impact of transportation [3].

Decarbonizing transportation is vital in combating climate change. While electric passenger cars have advanced, PTWs lag in adopting clean energy, requiring targeted research to address their unique technical and infrastructural needs. Electric motorcycles face challenges like limited battery capacity, range anxiety, and insufficient charging infrastructure [4, 5]. Hydrogen fuel cell (FC) technologies for PTWs show promise but face significant infrastructural barriers [6].

Alternative energy solutions such as electric propulsion, hydrogen FCs, and biofuels offer promising pathways to reduce PTW emissions without compromising affordability. Hydrogen FCs stand out for their high energy density, zero emissions, and long range, making them ideal for urban mobility. However, hydrogen adoption in transportation depends on advancements in production, storage, and refuelling infrastructure [7].

Hydrogen-powered PTWs highlight the potential of innovative technologies in transforming urban mobility. Comparing hydrogen-powered PTWs with electric motorcycles and combustion engine models provides insights into their feasibility and sustainability. While electric motorcycles are more energy-efficient, hydrogen models offer longer ranges and faster refuelling, crucial for specific use cases [7, 8]. Comparative analyses of emissions, range, and infrastructure underscore the opportunities and challenges of integrating hydrogen into PTWs.

FCs have emerged as a promising technology for mobility applications. The main types of FCs considered for mobility include proton exchange membrane fuel cells (PEMFCs), solid oxide fuel cells (SOFCs), and alkaline fuel cells (AFCs). Among these, PEMFCs are the most widely adopted due to their high-power density, rapid start-up capability, and compatibility with hydrogen as a fuel source [9].

Hydrogen, stored in pressurized tanks, is the primary fuel used in fuel cell-based mobility. While it boasts a high energy density per unit mass, the low volumetric density of hydrogen poses challenges in storage and transportation. These challenges are being addressed through advancements in high-pressure composite tanks and cryogenic storage systems. The implications of using hydrogen include the need for robust refuelling infrastructure, enhanced safety measures, and standardization across the mobility sector, including the roads infrastructure [10, 11, 12, 13].

Efficient operation of FCs in mobility applications requires advanced control strategies to manage dynamic conditions such as variable load demands and transient states. Key parameters, including temperature, humidity, and reactant flow rates, must be precisely controlled to ensure optimal performance and longevity of the FC system [14]. Auxiliary components, such as air compressors, humidifiers, cooling systems, and power converters, play critical roles in supporting fuel cell operation and maintaining system stability.

FCs are being deployed in various mobility applications, ranging from passenger vehicles and buses to heavy-duty trucks, trains, and even maritime and aerospace systems. In passenger vehicles, FCs provide a practical solution for achieving longer ranges and faster refuelling compared to battery electric vehicles (BEV). In heavy-duty applications, such as trucks and buses, FCs address the high energy demands and extended operation times effectively [15]. Emerging applications in trains and ships highlight the versatility of FCs in reducing greenhouse gas emissions across diverse transportation modes. Applications in small-scale vehicles, such as PTWs have been least researched due to the assumed size of the FC system.

Determining the sufficient size of a FC involves analyses of power demand, system efficiency, physical constraints, and dynamic response requirements. Power demand assessment considers peak and average loads for the application, such as acceleration needs in vehicles or steady-state loads in stationary systems. The FC's efficiency curve must align with expected operating conditions to avoid inefficiencies or stress from improper sizing. Physical and economic constraints, including space, weight, and cost, also play a critical role. Applications with dynamic loads may require hybrid systems to support transient performance. Finally, environmental and safety considerations, such as heat management and regulatory compliance, are essential in ensuring optimal and safe operation [11, 14, 4, 9, 10].

Hydrogen FC combined with the battery represent an advanced powertrain for range extension purposes. The FC serves as an on-board power supply that can supply both the battery pack and the electric motor. This combination thus represents a flexible system for powering the vehicle. The complexity of the system, on the other hand, is quite high and the sizing of a FC needs to match the FC characteristics as well as the battery pack capacity to achieve the optimized energy management, range and cost of the vehicle [16].

To simplify the process, the hydrogen FC was used in our case for charging the battery only. Thus, there is no communication between the electric motor and the FC. Using this configuration, the FC can be operated at (or close to) a nominal level without swift power demand surges. This setup improves the hydrogen consumption and longevity of the FC. The battery unit accounts for the peak power demands, and a DC/DC converter is used to meet the energy distribution control requirements. For hydrogen storage in mobility applications, compressed hydrogen or metal hydride canisters are typically used. The most perspective hydrogen FC technology is the proton exchange membrane (PEM), which offers advantages such as rapid start-up, low operating temperature, and high-power densities [15].

A suitable approach for the initial assessment of fundamental performance parameters and subsequent optimization in alternative powertrains is the use of 1D simulations. This simulation methodology enables the efficient modelling of both fundamental and advanced behaviour of individual vehicle subsystems and control strategies, even at the early conceptual design phase. Due to their computational efficiency and flexibility, 1D simulations are particularly valuable for determining key parameters, such as the power output of powertrain subsystems, and provide essential inputs for subsequent detailed simulations and physical testing [17].

This article focuses on evaluating the potential of hydrogen FCs as a range extender in PTWs, emphasizing the optimization of FC size under defined control strategy. Through a 1D powertrain simulation, the study aims to identify the most efficient FC configuration for maximizing vehicle mileage while ensuring effective energy management and cost efficiency.

2. Method

This chapter focuses on the sufficient FC size estimation in context of PTW in powertrain configuration as presented in Fig. 1. Described powertrain configuration is analysed as 1D powertrain simulation model created in computational SW Ignite[1].

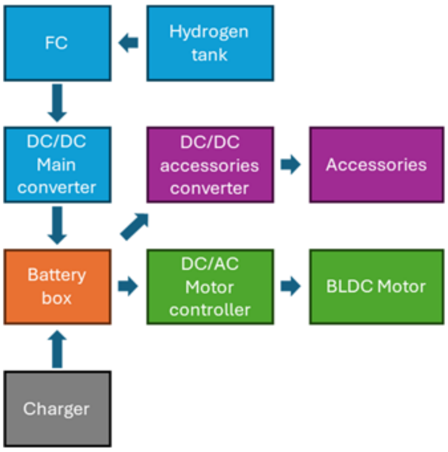

Fig. 1 *Powertrain description – FC as range extender.*

For the purposes of simulation, it is important to define main subsystems properties such as FC, battery box, powertrain including transmission, motor and its controller, and vehicle parameters. Main parameters of the simulated vehicle are listed in the Tab. I. For these purposes the 1D computational model contains block from Ignite powertrain library together with Modelica[2] scripted blocks describing the FC behaviour. The simplified FC range extender system is composed of hydrogen tank, FC and DC/DC converter. For the purposes of simulation, the time limited constant power delivery FC control strategy was implemented in the model. It means charging the battery with nominal current based on FC size (see Tab. I). The FC could not be restarted during the simulated riding.

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[1] Realis Simulation. SW Ignite. Version 2024.1 Realis Simulation

[2] Unified Object-Oriented Language for Systems Modeling, https://modelica.org/

Item		Parameters	
Vehicle	Weight	Motorcycle	220 kg
		Rider	80 kg
	Aerodynamics	Drag coefficient C_d	0,6 [-]
		Frontal area	0,8 m^2
	Wheels	Tire radius	0,25 m
Powertrain	Electric motor	BLDC hub – electric motor	Rated power 8 kW Peak power 11 kW Rated torque 100 N.m Peak torque 210 N.m
	Transmission	Type	Direct transmission
		Gear ratio	1 [-]
	HV Battery	BB rated voltage	66,6 V
		BB rated discharge	58 A
		BB peak discharge	384 A
		Overall BB capacity	3,86 kW.hr
	Fuel stack	Fuel stack type	PEMFC
		Number of cells	Variable (25-150)
		Hydrogen tank capacity	288 g

Tab. I *Parameters of the simulated vehicle – 1D simulation inputs.*

The method described in this article generally targets the calculations of mileage of the vehicle while riding in a defined drive cycle. Drive cycles are used for standardized evaluation of vehicle energy consumption and emissions under various operating conditions. They enable objective comparison of results between different control strategies and validation of mathematical models. The main target drive cycle was defined as World Motorcycle Test Cycle[3] (WMTC) class 3 due to planned usage of the developed motorcycle prototype in urban, suburban and limited highway conditions [18]. In this study, other drive cycles (WMTC2, NEDC, WLTC3, and HWFET) were also utilized, especially for comparison and verification of the created 1D simulation.

The computational model contains the drive cycle rider block that contain proportional-integral-derivative (PID) regulator to reach the defined drive cycle velocity with the 1D computational model setup. The simulation process includes testing of variety of FC sizes with the variable number of cells. In this way, each FC size was assigned parameters for efficiency, continuous power delivery, hydrogen consumption, operating time, and output currents. In this process, parameters such as efficiency, continuous power delivery, hydrogen consumption, operating time, and output currents were assigned according to each FC size. As the vehicle uses FC as range extender it was crucial to define parameters of the battery box

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[3] Regulation (EU) No 168/2013 of the European Parliament and of the Council

that is being continuously supported with the FC while riding (see Tab. I). Goal of this approach is to define powertrain configuration that effectively reaches the highest possible mileage with the smallest possible FC size.

The second variable in the presented approach is the drive cycle itself. Even though the main target drive cycle is defined, it is important to estimate behaviour in different driving conditions. In this way the simulation process considers six drive cycles as presented in Fig. 7.

Each powertrain configuration, integrating different FC sizes and drive cycles, is simulated independently while maintaining common external conditions. This ensures identical initial conditions, including a 99% battery state of charge (SOC), a fixed amount of hydrogen in the tank, and the FC activation point set at 80% SOC, representing the moment when the FC starts operating. Each simulation concludes when the battery SOC drops to 5%. These conditions represent necessary time that the FC system needs under real conditions for proper start of operation.

3. Results

The Results section presents the outcome of the 1D powertrain simulation approach described in the Method section. Fig. 2 illustrates the influence of FC size on the vehicle's overall mileage. The analysis shows that FC sizes ranging from 35 to 93 cells achieve a similar maximum mileage of approximately 120 km. The parameter "Mileage when FC stops" indicates the distance traveled before the hydrogen in the tank is fully consumed, after which the vehicle operates purely as a BEV for the remainder of the simulation.

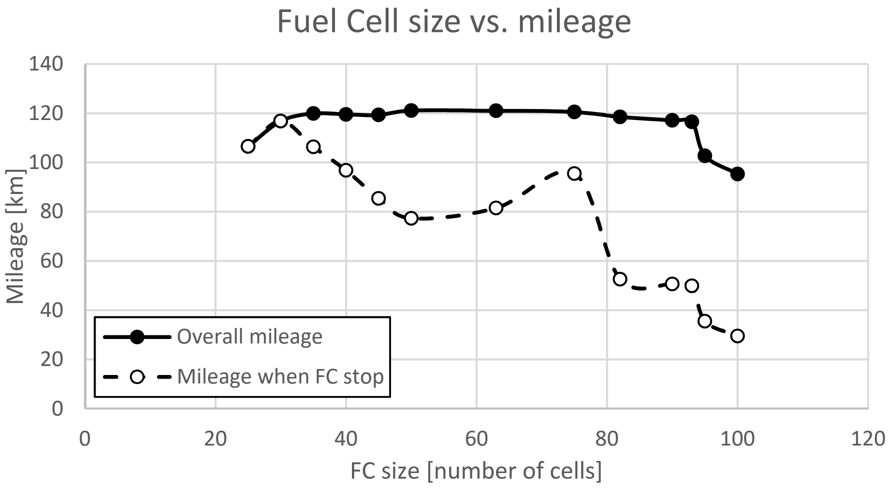

Fig. 2 *Fuel cell size effect on the overall mileage of the vehicle as function of WTMC 3 drive cycle.*

Another view on the results brings the Fig. 3 analysing in detail the amount of effectively used hydrogen and the battey SOC level when the FC stopped operation.

These results reveal the problematic feature of insufficient power of FC sizes smaller than 35 cells and excess power used with FC with more than 75 cells. This figure also shows that using FC sizes from 50 to 63 cells results in the highest battery SOC level when the FC stops.

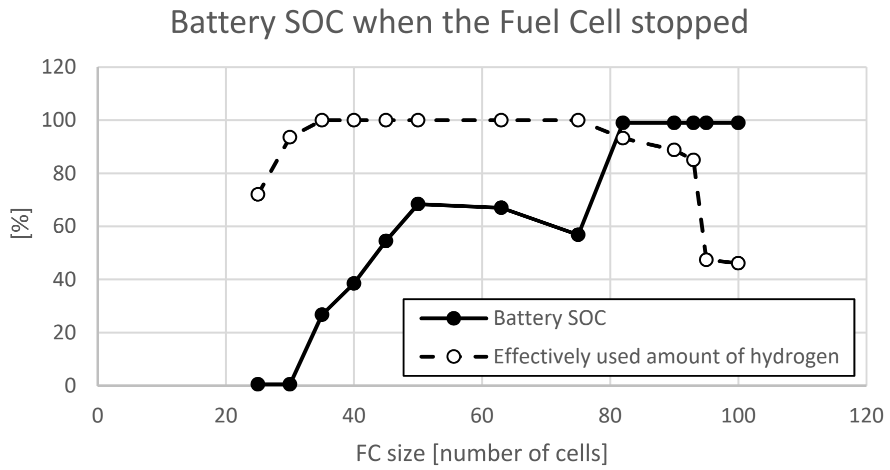

Fig. 3 *Battery SOC level when the FC stopped due to low hydrogen level accompanied by the effectively used amount of hydrogen in context of drive cycle WMTC 3.*

Following Fig. 4 presents the example of FC with 50 cells performance in WMTC 3 drive cycle. This FC size represents the sufficient power delivery of FC together with efficient usage of hydrogen even using time limited contentious power delivery strategy of FC as range extender. Fig. 4 reveals the trend of battery charging possibility in low speed sections of the drive cycle.

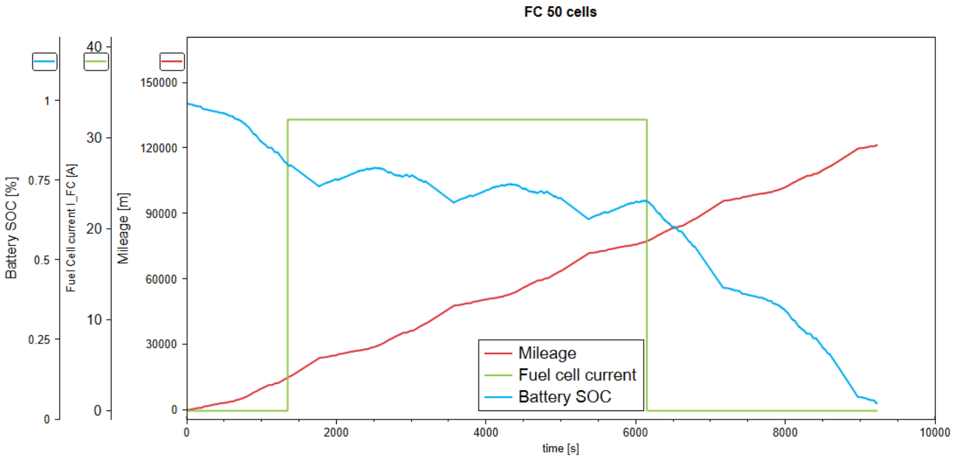

Fig. 4 *Fuel cell with cells 50 performance under WMTC 3 drive cycle in context of battery SOC and mileage.*

Further results provide a detailed analysis of the simulation output for a specific FC size. Fig. 5 illustrates the vehicle's performance in the WMTC 3 cycle, which reflects its intended use in urban and suburban areas, with limited highway capabilities at a maximum speed of 80 km/h. In the testing scenario, highway segments are represented by the vehicle operating at its peak speed. Additionally, the study examines the vehicle's performance without the FC as a range extender. Fig. 6 demonstrates how the simulated model would behave in BEV-only mode. Under these conditions, the vehicle achieves a total mileage of 67 km before depleting its battery.

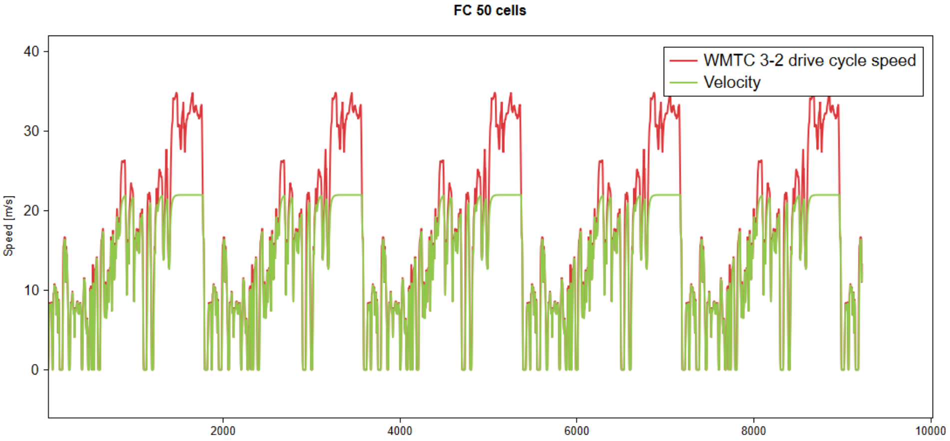

Fig. 5 *Vehicle performance from the velocity point of view during the WMTC 3 drive cycle.*

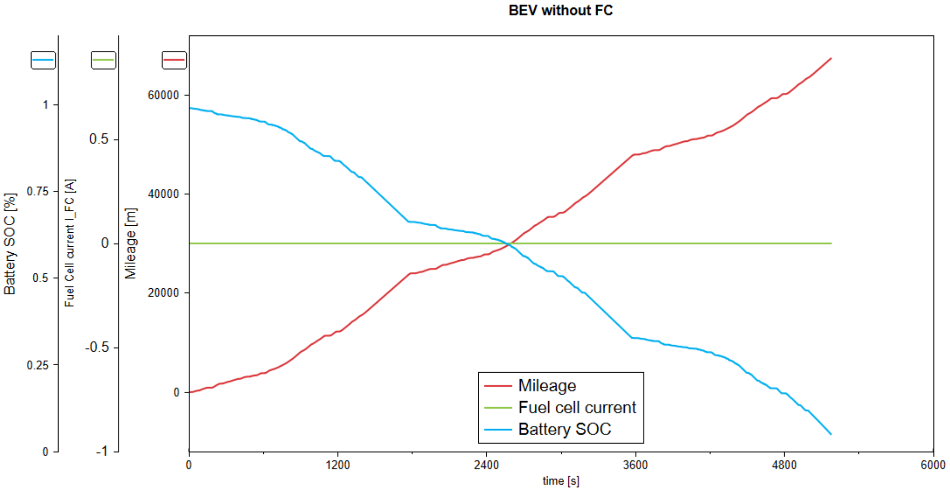

Fig. 6 *Simulation results of vehicle as BEV without FC range extender.*

In the final part of the results, the influence of different drive cycles is presented including the riding under full load during the whole simulation time. The Fig. 7 shows mileage in particular drive cycle with and without the FC as range extender. From this point of view, we are able to define that under similar drive cycles like WMTC 3 and WLTC the vehicle reaches similar mileage. From the point of view of hydrogen usage efficiency in cycles WMTC 2/3, WLTC and HWFET all the hydrogen is used properly under the described control strategy. In the simulation under full load drive cycle the amount hydrogen was not fully used, because the battery reached SOC 5% before the hydrogen was fully consumpted. On the other hand in the simulation scenario with NEDC drive cycle the power demand was significantly lower and part of the hydrogen was consumed to losses, when the battery SOC reached 100% and due to defined control strategy the FC could not be stopped and restarted.

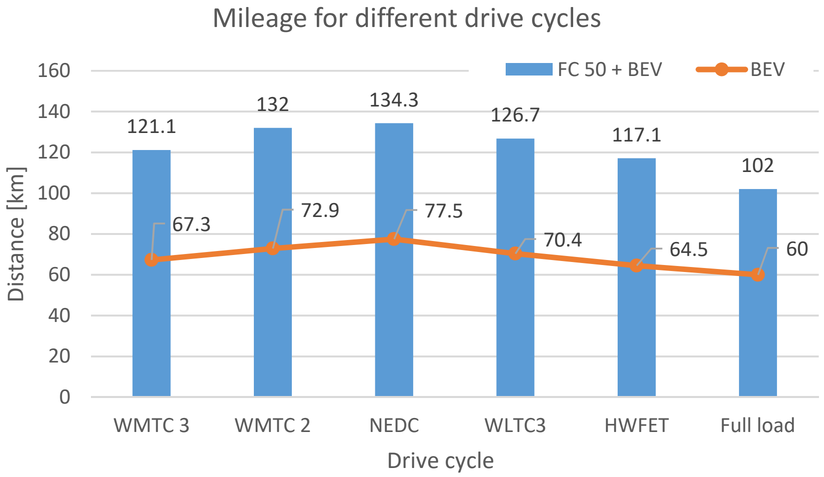

Fig. 7 *Mileage of the tested vehicle with the FC with 50 cells under different drive cycles.*

4. Discussion

The analysis presented in this study sheds light on the viability of hydrogen FC technology in PTWs, focusing on its performance as a range extender in combination with battery electric propulsion. It is important to note that the study focuses on optimizing the hydrogen consumption and FC performance under a time-limited, constant power delivery strategy. As observed in the results of the 1D simulations in Fig. 2, FCs with sizes between 35 and 93 cells provided similar high mileage (around 120 km) for the simulated powertrain configuration. Beyond this range the overall mileage decreased on both sides of the FC size spectrum. These results are applicable for the defined simulated FC control strategy. In general, the approach of the presented 1D simulation method is to find the smallest efficient applicable FC size.

Another perspective on FC performance is presented in Fig. 3, which illustrates the effectively utilized amount of hydrogen. The analysis indicates optimal performance within the 35 to 75-cell range, where hydrogen usage is most efficient. In FCs with a higher number of cells the hydrogen was not used effectively under the defined control strategy and part of it was spent into losses. On the other hand, the figure shows the issue of undersized FCs (less than 35 cells). When the FC is too small to meet the power demands, the system cannot adequately support the battery, leading to faster depletion of the battery and suboptimal performance. Another insight from the simulation is the impact of the FC on the battery SOC level when the FC stops operation. In FC size range of 50 to 63 cells, the battery SOC is better maintained, leading to more efficient use of the energy stored in both the battery and the hydrogen tank.

The vehicle's performance under different drive cycles revealed valuable insights. Notably, the simulations indicated that in more dynamic drive cycles, such as the full load cycle, the vehicle could not fully utilize the hydrogen before the battery reached its discharge threshold (SOC 5%). In contrast, under standard urban and suburban conditions, the hydrogen was consumed more efficiently, aligning with the expectations of real-world usage.

Generally, it is important to mention that the size of the FC define its output power possibilities. In this scenario, a low number of FC cells fails to provide sufficient support for the battery, while an excessively high number of cells can result in surplus energy that cannot be utilized efficiently.

5. Conclusion

The growing need for sustainable urban mobility calls for alternative energy solutions for PTW. Hydrogen FCs, with their high energy density and zero carbon dioxide emissions show promise as a cleaner alternative source of energy in urban mobility. However, challenges like infrastructure development, fuel storage and purity of hydrogen itself should be addressed. Continued advancements in hydrogen technologies, along with powertrain optimization through simulations, can enhance the feasibility of hydrogen-powered PTWs.

This study examines the usability of hydrogen FC technology as a range extender in PTW, focusing on choosing efficient FC size and under a time-limited, constant power delivery FC control strategy. In this way a well-sized FC helps maintain battery SOC more effectively, especially in more dynamic drive cycles. Selecting the optimal FC size is crucial to ensure both performance efficiency and cost-effectiveness, avoiding energy waste or underperformance.

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