Powertrain Design and Modeling for a Fuel Cell Hybrid ElectricVehicle

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ABSTRACT

The objective of this study was to develop a Fuel Cell Hybrid Electric Vehicle (FCHEV) powertrain with the aim of enhancing battery usage autonomy. The vehicle, which participated in the Eco-Marathon competition as a prototype, incorporates batteries, a Direct Current (DC) electric motor, and a Proton Exchange Membrane (PEM) fuel cell. The design permits the operation of the fuel cell to be conducted in a more efficacious and fuel-efficient manner. The study employs the MATLAB-Advisor software to construct powertrain models that are then validated in laboratory settings. These models are subsequently compared with the performance of the actual FCHEV prototype and adapted for use in automotive applications. The FCHEV power model calculates instantaneous energy consumption using input variables, such as vehicle speed, acceleration, and road gradient. Furthermore, Real Cycle drive was carried out to improve the trade-off between energy consumption, fuel cells, battery State of Charge (SOC) dynamics, and battery power smoothness, while ensuring that all essential limitations were met. The addition of a fuel cell to an electric car model enhances its range by 250%, significantly improving its adoption and usage.

Keywords-electric vehicle; fuel cell vehicle; fuel cell hybrid electric vehicle; advisor model; powertrain

I. INTRODUCTION

In recent years, the automotive industry has witnessed a considerable advancement in the field of hybrid vehicles, with a notable emphasis placed on the usage of hydrogen as a promising alternative fuel source. The evolution of hydrogen-powered vehicles has been substantial, spanning multiple decades. Prominent automakers, such as Toyota, Honda, and Hyundai, have already unveiled HFCVs to the public. Nevertheless, the widespread adoption of hydrogen vehicles is still in its infancy, facing significant challenges, such as high production costs and a lack of hydrogen fueling infrastructure [1]. Notwithstanding these impediments, the prospective benefits of hydrogen-powered vehicles render them a compelling alternative to conventionally fueled vehicles that use fossil fuels. These potential highlights the capacity of electric power and hydrogen, both as fuels, to make a significant contribution to the decarbonization of road transportation. Moreover, the capacity of electric power and hydrogen production to be derived from a range of primary energy sources, including biomass, solar and wind power, nuclear energy, and decarbonized fossil fuels, presents an opportunity to address the longstanding reliance on oil in the transportation sector [2]. A considerable number of governments and research organizations have proposed Fuel Cell Electric Vehicles (FCEVs) as a promising direction for achieving zero emissions. This study presents a fundamental approach for modeling the performance of fuel cell electric vehicles. The powertrain, which combines fuel cell technology and batteries, is analyzed using an in-house developed tool, the

Hybrid Battery Fuel Cell Vehicle Modeling Tool (HBFCMT), with the assumption of a specific control strategy [3]. The model maintains a consistent architectural framework, encompassing all relevant traction chain components. The schematic representation below delineates the fundamental building blocks used to create the hybrid hydrogen vehicle model, encompassing the battery, fuel cell, DC motor, gearbox (transmission), and wheels. Furthermore, a variety of controller blocks, including the drive cycle block, acceleration block, and grade block, are used to enhance the adaptability of the control system within the model. The combination of fuel cell technology and batteries offers a potential solution to address some of the key limitations of Battery Electric Vehicles (BEVs). Specifically, the integration of fuel cell technology can reduce the prolonged charging times and the substantial battery mass requirements typically associated with BEVs, particularly in applications involving high energy demands, such as buses and heavy-duty vehicles.

AN FCEV powertrain is primarily dependent on a fuel cell system for stationary power requirements. In contrast, an FCHEV employs a battery to provide power with enhanced dynamics and to recuperate energy during braking, with the fuel cell serving to augment the range of power. A sophisticated control system is necessary to regulate the distribution of power across the hydrogen cell and the power source, while ensuring that all component and system-level constraints are satisfied. This article examines two of the three alternative drivetrain technologies identified by the International Energy Agency (IEA) as potential solutions for developing a sustainable road transportation system with low emissions (IEA, 2008). The initial technology is the BEV, while the subsequent one is the FCEV. This study focuses exclusively on electric drivetrains, excluding the potential of biofuels as a viable alternative [4]. It comprised two integral components. The initial stage involved the skillful incorporation of the Fuel Cell Automotive Trainer, ensuring a seamless integration of this model into the simulation framework. This enabled the achievement of a precise and lifelike representation, which could then be subjected to an in-depth analysis. The second component of this research involved the construction of simulation models, which were created using Simulink and Advisor tools. These models served as a vital conduit for investigating the intricacies of hydrogen-powered vehicles, offering a comprehensive insight into their dynamics and evaluating their viability as a sustainable transportation solution. An FCEV is a vehicle that uses a fuel cell system to provide electric power for the electric motor, thereby reducing the environmental impact of transportation. FCEVs have a longer driving range and emit less carbon dioxide than BEVs. Additionally, Hybrid Electric Vehicles (HEVs) have a more limited carbon footprint and consume less fuel. The modeling procedure for an FCEV focuses on the key elements of the powertrain and longitudinal vehicle dynamics, with the objective of developing a comprehensive understanding of the powertrain, its simulation, and the control thereof. A comprehensive approach was deployed to assess the performance and potential of an FCHEV model. Firstly, a meticulous mathematical model of the FCHEV was developed. Subsequently, the Matlab-Advisor software was employed to refine the model parameters by means of an iterative comparison between the simulated results and the empirical data. Subsequently, the optimized model was subjected to a standardized drive test in order to assess its performance and efficiency. The acquired data enabled a quantitative comparison with the actual performance of the FCHEV in the real world, allowing for the identification of discrepancies and potential areas for further model refinement. It is noteworthy that the study underscores the intrinsic advantage of FCHEVs, namely their extended range in comparison to other electric vehicle power sources. This is due to the fact that fuel cells are capable of providing a continuous and reliable power output, coupled with their high energy density. Furthermore, the environmentally friendly nature of fuel cells, which emit no pollutants, aligns with the pursuit of sustainable transportation solutions. In conclusion, this study aims to make a meaningful contribution to the field of hydrogen vehicle modeling and simulation, thus facilitating the development of cleaner and more sustainable transportation systems for the future [5].

II. FCHEV CONFIGURATION AND COMPONENTS

An electric vehicle that relies solely on the fuel cell (FCEV) is less efficient than the regular battery-based electric vehicle [6]. This provides a rationale for integrating the fuel cell as an additional power source for the electric vehicle, which is represented by a hybrid architecture in the proposed model. The complete configuration of the FCHV is presented in Figure 1. The system is divided into multiple discrete subsystems, including the Fuel Cell Stack (FCS), battery, DC-DC converter, DC-AC converter, AC machine, gearbox, and power transmission to the wheels.

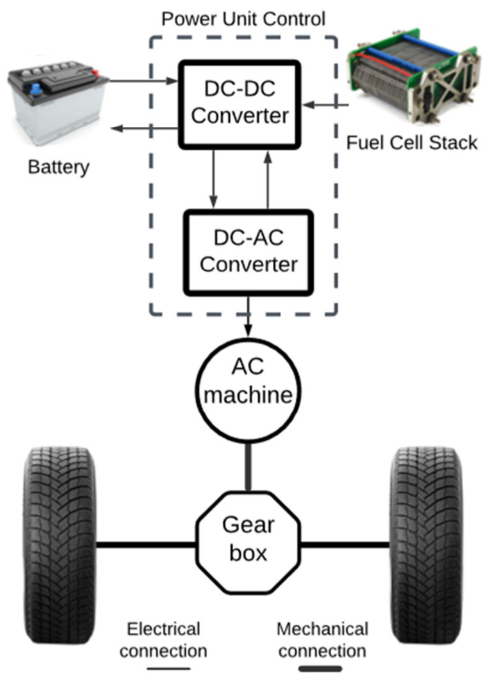

Fig. 1. FCHEV Power train configuration.

The DC-DC converter and the DC-AC converter collectively comprise the Power Unit Control (PUC). The PUC is configured with the battery as the primary source and the FCS as the secondary source. The FCS is employed to facilitate the charging of the battery, when necessary, under the direction of the PUC. The DC-DC converter fulfills two distinct functions. When supplying power to the motor, it acts as a boost converter, increasing the voltage to the desired level for the DC-AC converter. Conversely, when charging the battery, it operates as a buck converter. The DC-AC converter drives the AC machine at 200 V as a motor and recharges the battery when the AC machine is functioning as a generator due to regenerative braking. The AC motor is a permanent-magnet synchronous electrical machine with a rated power output of 10 kW. Subsequently, an automatic gearbox transmits the power to the wheels. An FCHEV employs a battery system as the primary source of power for electricity generation, with the FC serving as an auxiliary source. The electric motor is driven by the aforementioned electric energy, which is then converted into mechanical power and used to propel the wheels through a transmission system. The objective of this research is to enhance the understanding of battery consumption and improve the efficiency of FCEVs. The findings of the conducted investigation will facilitate the advancement of more efficient and sustainable FCEV powertrains.

A. Fuel Cell Technologies

Fuel cells are classified into a number of categories based on the electrolytes present. The operating temperature and electrolytes are presented in Table I. Proton Exchange Membrane Fuel Cells (PEMFCs) use hydrogen as the fuel and oxygen as the oxidant. The anode is supplied with hydrogen, which is then oxidized, resulting in the loss of electrodes. Concurrently, positive hydrogen ions (protons) traverse the electrolyte via the membrane to the cathode, while electrons flow around the external circuit to the cathode. The oxygen is conveyed to the cathode, where it is reduced by the absorption of electrons and ions from the hydrogen, thereby generating water, as shown in Figure 2.

TABLE I. FUEL CELL TECHNOLOGIES

Temperature (°C)	Fuel Cell Technologies	Electrolyte (Solid or Liquid)
60–100	PEMFCs	S
80–230	Alkaline fuel cells (AFCs)	L
60–200	Phosphoric acid fuel cells (PAFCs)	L
600–1,000	Molten carbonate fuel cells (MCFCs)	L
1,000–1,200	Solid oxide fuel cells (SOFCs)	S
100	Direct methanol fuel cells (DMFCs)	S

PEMFCs are the optimal choice for the fuel cell technology in the automotive sector, as they are capable of functioning at low temperatures, they exhibit the highest power density of all fuel cell types, and use a stable solid electrolyte that remains unchanging regardless of motion or condensation. Additionally, their potential for exceptional performance and lack of toxins and greenhouse gas emissions further justifies their suitability for automotive applications. The use of hydrogen-powered vehicles represents a promising solution for reducing the environmental impact of transportation while still providing the convenience and performance of traditional gasoline-powered vehicles. A comparative analysis has been conducted between the usable specific energy and useful energy density of various battery types and a PEMFC. This comparison encompasses the storage of hydrogen tanks and the batteries used for regenerative braking and power enhancement in electric vehicles. It has also yielded a compelling comparison between hydrogen systems and batteries [7].

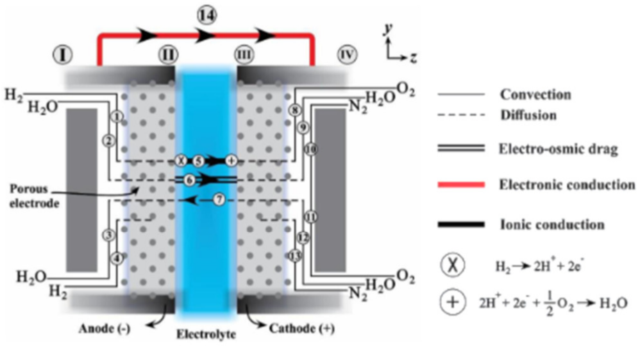

Fig. 2. The schematic of a PEM cell model.

It is important to note that the connection between the membrane and the anode electrode and cathode electrode is referred to as the second section and the third section, respectively, in Figure 2. The final term $s^{C}_{H_2O}$ is the rate at which water is generated per unit area (mol m^{-2}s^{-1}) at the cathode, as presented in section III of Figure 2. In order to extend the aforementioned relationship to encompass the entire cell, it is necessary to consider the role of hydrogen and oxygen, $n^{A}_{H_2}$ and $n^{C}_{O_2}$ can be written as:

$$n^{A}_{H_2} = \frac{N_{H_2,1} - N_{H_2,4}}{A_{elec}} \tag{1}$$

$$n^{C}_{O_2} = \frac{N_{O_2,8} - N_{O_2,13}}{A_{elec}} \tag{2}$$

B. Battery modeling

The accurate prediction of battery dynamics in HEVs remains a significant challenge due to the complex and interconnected nature of the key variables influencing performance. These variables, primarily the SOC, include voltage, current, and temperature, which exhibit strong non-linearity and interact dynamically with each other. Consequently, HEV vehicle simulators rely on robust battery models capable of accurately anticipating changes in SOC based on the anticipated electrical load. The SOC itself represents the proportion of electrical charge stored in the battery relative to its total capacity, serving as a critical indicator of energy availability. The SOC is defined by the following [8]:

$$SOC(t) = \frac{Q(t)}{Q_{nom}} \tag{3}$$

where Q_{nom} is the nominal charge capacity and $Q(t)$ is the amount of charge stored at the moment. The SOC dynamics are described by:

$$SOC(t) = \begin{cases} -\frac{1}{\eta_{coul}}\frac{I(t)}{Q_{nom}} \; if \; I(t) > 0 \\ -\eta_{coul}\frac{I(t)}{Q_{nom}} \; if \; I(t) < 0 \end{cases} \quad (4)$$

where I is the battery current, with positive values indicating discharge, η_{coul} is the Coulombic or charge efficiency, which accounts for charge losses arising from various operating parameters, mainly current intensity and temperature. The temperature at which a battery operates has a direct effect on its lifespan. The battery's design life is contingent upon an average annual temperature of 77 F (25 ºC). As temperature rises above 77 F, the battery's capacity to sustain a greater current is enhanced. However, this is accompanied by a reduction in battery lifespan. The SOC equation makes reference to only two terms, I and Q, which are the primary factors influencing the charge. In addition, a number of other factors affect the charge, including resistance and temperature. These factors are reflected in the SOC equation, which incorporates the parameter η and is dependent on other variables, such as temperature and resistance. An increase in resistance results in a greater loss of energy in the form of heat, which in turn has a direct impact on the lifespan of a battery. The Arrhenius equation defines the relationship between temperature and the rate at which a chemical reaction occurs in a battery. It demonstrates that the rate of reaction increases exponentially as temperature rises:

$$K = Ae^{-\frac{Ea}{RT}} \text{ or } \quad ln\,K = \frac{Ea}{RT} + lnA \quad (5)$$

where K is the chemical reaction rate, A is the pre-exponential function, E_a is the activation energy, R is the gas constant, T is the temperature in Kelvin. If the capacity is assumed to be a constant, known value, calculating the SOC by integrating (4) appears to be a relatively straightforward process. In practice, battery capacity and coulombic efficiency are subject to variation depending on a number of parameters. Consequently, the numerical integration is only reliable in simulation in the absence of measurement error and noise. This makes reliable SOC estimation a significant portion of the actual Battery Management System (BMS) [8]. A battery circuit model may be employed to establish a correlation between the battery current and voltage and the power exchanged with the remainder of the powertrain. An additional benefit of incorporating a battery pack in the engine drive train of an FCHEV is the capacity to capture and store electrical energy generated by the vehicle's mechanical inertia during the braking process, which is known as regenerative braking or electric braking.

III. FCHEV MODEL

The FVHEV powertrains operate on electricity generated by hydrogen fuel cells, which convert hydrogen gas into electrical energy, emitting only water as a byproduct. This results in the generation of noxious emissions, hence rendering them a highly sustainable and environmentally friendly option. The entirety of the aforementioned HFCEV components, as previously delineated, are taken into consideration for the model under development in this study. This work presents the development of a high-fidelity FCHEV model in MATLAB Simulink for the purpose of investigating energy management strategies and performing various design optimizations. The model incorporates switchable fuel cell representations, enabling a comprehensive electrochemical analysis or efficient simulation via pre-mapped performance curves. This versatility enables a multitude of applications, including studies of component sizing trade-offs, optimization of operating parameters, and hardware-in-the-loop evaluation. Figure 3 shows the model's architectural configuration and its capacity to emulate the FCHEV's operational characteristics across a spectrum of operating conditions.

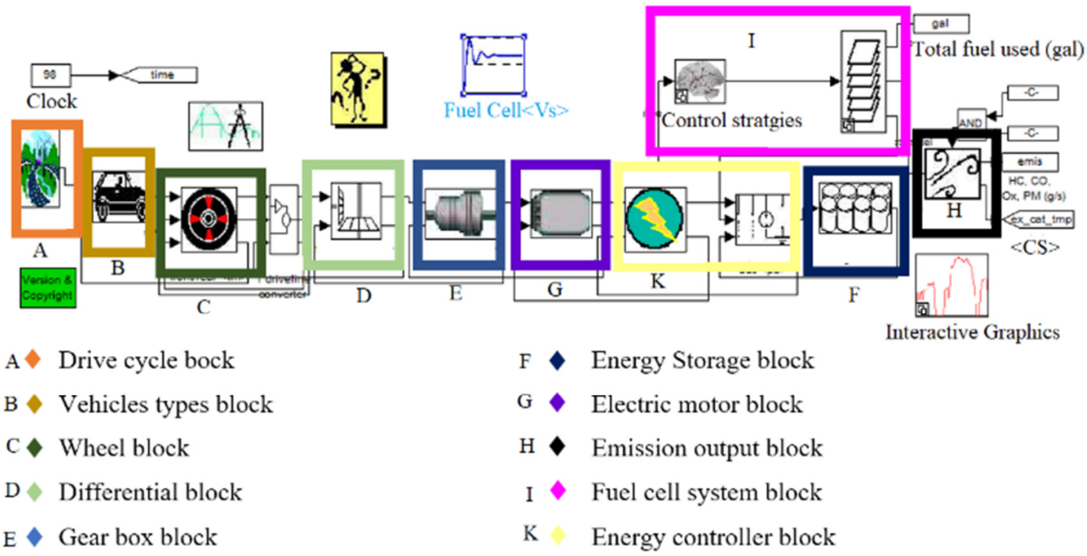

Fig. 3. Advisor fuel-cell model.

The model provides a readily accessible and functionally equivalent counterpart to the real-world system, thus serving as a valuable tool for design and optimization. The FCHEV model in MATLAB Simulink constitutes of interlinked modules, which represent the essential components of the system. These include a storage unit, drive cycle block, fuel cell system, energy controller, wheels, and gearbox. The Advisor block facilitates the process of parameterization of the model and allows for comprehensive analysis and simulations. These capabilities enable the optimization of the FCHEV's performance through the iterative evaluation of potential improvements and the refinement of component characteristics. Cones have been identified as compounds of interest, exhibiting a range of biological and photochemical properties, as depicted in Figure 2. The characteristics of the fuel cell automotive trainer, as presented in Table II, were employed as input to the proposed model, using Advisor software, as displayed in Figure 4. Due to the paucity of the available models of fuel cell vehicles in Advisor, the same configuration and identical components are used but with an augmented power output, relative to the actual vehicle. Some metals are capable of being combined with hydrogen to form stable compounds that, under specific pressure and temperature conditions, can undergo decomposition. The aforementioned metals include iron, titanium, manganese, nickel, lithium, and their respective alloys. Metal hydrides are stable under normal temperature and pressure conditions and can only release hydrogen when necessary [9].

TABLE II. CAR CHARACTERISTICS INPUT

Characteristic	Values
Power of electric Motor	90 W
Efficiency	86 %
Number of batterie module	6 (series)
Total voltage	8.2 V
Type of batterie and energy capacity	NIMH 3,300 mAh
Maximum speed of electric motor	1,250 rpm
PEMFC rated power	300 W
Max speed	27 km/h
Wheel diameter	33 mm
Total mass, M	1.5 kg

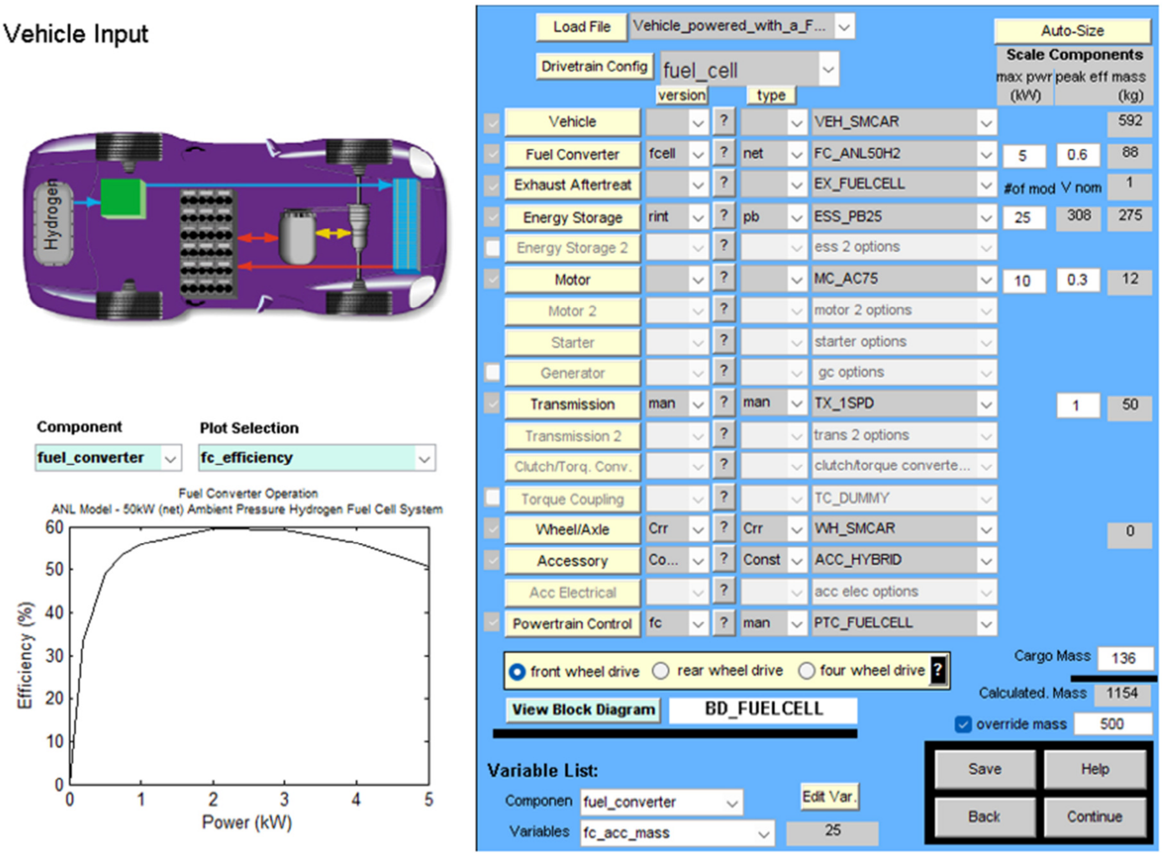

Fig. 4. Advisor interface of the FCHEV model inputs and parameters.

The capacity of hydrogen storage is significantly affected by the surface area of the substance on which the hydrogen molecules are absorbed. Fuel cells represent one of the most advanced power sources for transportation applications. When compared to Internal Combustion (IC) engines, fuel cells demonstrate superior energy efficiency and produce fewer emissions [10]. This is due to the fact that they transform the free energy in the fuel directly into electrical energy without necessitating combustion. However, vehicles powered purely by fuel cells have significant drawbacks, including a heavy and bulky power unit due to the low power density of the fuel cell system, a long starting time, and a delayed power response

[11]. Moreover, in applications involving propulsion, the high-power output at high speeds and the low-power production at low speeds result in a reduction in efficiency. The combination of a fuel cell system and a peak power source represents a viable method for overcoming the limitations of fuel-cell-only vehicles. A fuel cell HEV is not analogous to traditional ICE vehicles or ICE-based hybrid drivetrains. Accordingly, a wholly novel design process is imperative. This work addresses the design of fuel cell hybrid electric drivetrains, presenting a comprehensive systematic approach and a control strategy.

IV. EXPERIMENTS ON FCHEV

The experiment bench comprises an FCHEV setup, which includes the aforementioned set of components. The same characteristics, presented in Table II, are employed to conduct the tests and evaluate the performance of the FCHEV. Figure 5 portrays the experimental apparatus used in this investigation. Furthermore, additional electric and electronic devices have been integrated into the FCHEV to facilitate control and monitoring functions, which are executed by a Microcontroller Unit (MCU). The FCHEV is controlled and monitored via an Arduino YUN board and a LabVIEW interface. The LabVIEW dashboard is also shown in Figure 5. A variety of driving cycles are programmed in LabVIEW in accordance with the prescribed standard. The currents, voltages, and displacements acquired during the tests are recorded on the computer with an accuracy of 10 bits and a sampling rate of 15 ksps. The Arduino YUN board is equipped with an embedded web server, which enables the retrieval of comprehensive process variables associated with the FCHEV and facilitates communication between the board and the computer. The current and voltage are obtained directly from the battery. The speed and torque are determined by measuring the variables from the transmission shaft. The instrumentation setup is a sensory system used to ascertain the energy chain of the mechanical and electrical components. The software permits the calculation of various parameters, including speed, acceleration, torque, absorbed power, power consumption, energy, yield, and so forth.

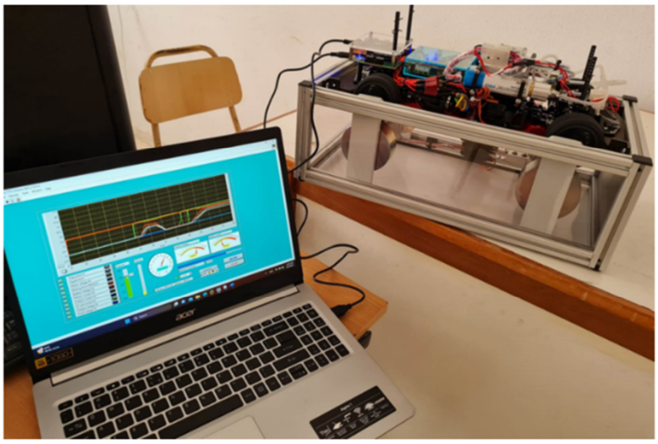

Fig. 5. Bench experiment of the HFCEV in the laboratory.

V. RESULTS AND DISCUSSION

The constructed model is capable of providing a meticulous characterization of a real-world FCHEV, culminating in a high-fidelity Simulink-MATLAB representation. A comprehensive testing program, including Advisor-based evaluations, confirmed the accuracy of the model and enabled a detailed performance analysis. It is noteworthy that this analysis highlights the distinct advantages of FCHEVs. These include rapid refueling comparable to conventional internal combustion engines, exceptional acceleration and responsiveness characteristic of electric propulsion, and, most importantly, significant environmental benefits through the usage of green hydrogen as a clean fuel source [12].

A. Driving Cycles

As previously stated, the advantages of hybrid vehicles are contingent upon the manner in which the vehicle is used. The primary advantages of hybridization pertain to the recuperation of kinetic and potential energy that may have been dissipated in the braking system, as well as the capacity to operate the motor within its optimal efficiency range. If the engine demonstrated consistent efficiency and the vehicle operated at a constant speed on a flat road, a hybrid electric configuration would offer no advantage [13]. A driving cycle is defined as the collective term for the driving behavior exhibited by a car throughout a trip and the features of the route it travels on. In its most fundamental sense, a driving cycle can be defined as a chronological account of the speed of an automobile, and consequently, its acceleration, as well as the incline of the road. The road load, defined as the force exerted by the vehicle on the road during the driving cycle, is a function of both the vehicle's specifications and other factors [14]. It is important to note that each component of the energy balance is dependent on both the driving cycle, including speed, acceleration, and gradient, and the characteristics of the vehicle itself, involving mass, frontal area, and coefficients of aerodynamic and rolling resistance. It is, therefore, essential to specify the fuel consumption of a vehicle in relation to a specific driving cycle. However, when a specific driving cycle is considered, the absolute value of the traffic load and the dimensions of its parts are influenced by the features of the vehicle. The necessity for a uniform methodology to evaluate the emissions and fuel consumption of all automobiles currently in circulation, coupled with the need for a reliable foundation upon which to base their comparison, has led to the implementation of a restricted set of regulated driving cycles. Any vehicle that is to be sold must undergo testing, in accordance with the prescribed procedures, using one or more of these standard cycles, which are distinct for each global region. Examples of standard cycles are shown in Figure 6, which also includes a basic energy analysis comparison [15].

The objective of these driving cycles is to provide an accurate simulation of both urban and extra-urban driving conditions. The New European Driving Cycle (NEDC) is a synthetic one, whereas the others are designed to reproduce the speed of vehicles on actual roads. However, with the exception of US 06, the acceleration levels are well below the capabilities of any modern car. Consequently, the fuel consumption results are typically optimistic and unable to reproduce real-world driving conditions. It is recommended that the regulatory cycles be regarded as a conventional benchmarking tool, rather than as an accurate reflection of real-world operational conditions. Indeed, it is impracticable to anticipate the manner in which an automobile will operate, given that each vehicle has a distinct usage pattern and that each passenger possesses a unique driving style. To obtain more precise estimates of the actual fuel consumption of a specific vehicle, automobile manufacturers may develop their own testing protocols, as illustrated in Figure 7 [16].

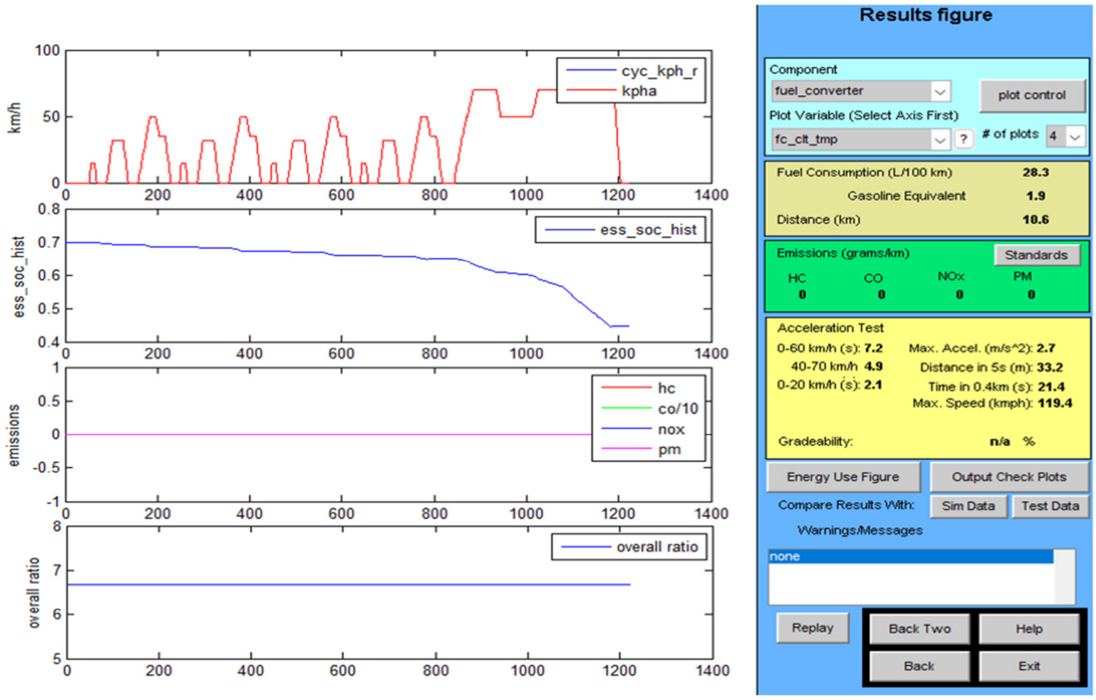

Fig. 6. FCHEV in Advisor parameter configuration.

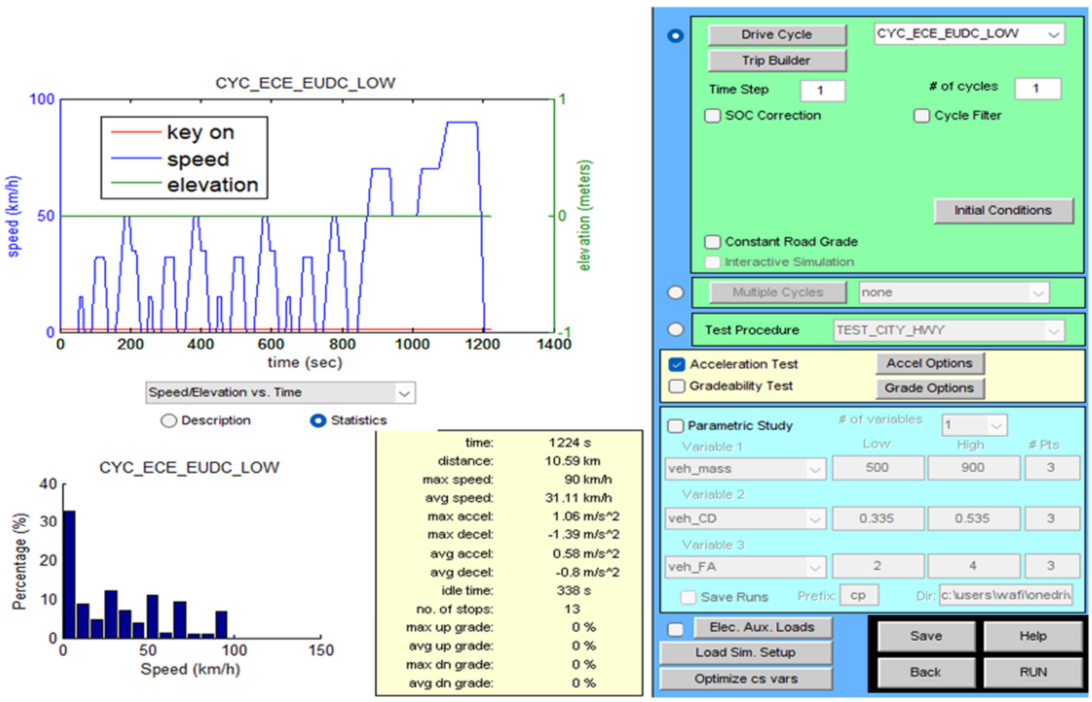

Fig. 7. New European drive cycle configuration.

B. Advisor Model without Fuel Cell

In this section, the same modeling methods used for the initial vehicle are employed, with a notable distinction: the fuel cell is deactivated, resulting in the data shown in Figure 8. The disabling of the fuel cell in the second vehicle model demonstrated that the maximum speed remained unaltered, maintaining a value of 28.3. However, a consistent decrease in the battery level was observed, indicating that energy consumption increased without the fuel cell's assistance. This underscores the significance of the fuel cell system in preserving battery stability and optimizing energy utilization within the vehicle.

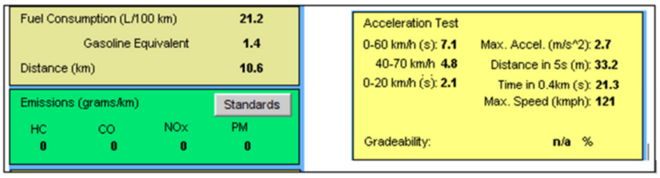

Fig. 8. Output results for Fuel-Cell vehicle.

The Advisor model provides a block diagram representation within the Simulink environment, which serves as a visual representation of the system, providing a comprehensive overview of the model's structure and components. The application of Simulink allows users to readily analyze and modify the connections between disparate blocks, thereby facilitating the effective modeling and simulation of intricate systems [17]. The second drive cycle interface was used in the course of the experiment. A variety of parameters, including speed and current, were recorded and data were subjected to analysis in order to evaluate the vehicle's performance. This work encompassed an exploration of hydrogen vehicles, an investigation of their environmental benefits, and the development of simulation models using Simulink and Advisor tools. A comprehensive research and analysis process was conducted, which highlighted the potential of hydrogen vehicles as a cleaner and more sustainable mode of transportation. In the initial trial, the vehicle's battery was fully charged prior to the commencement of the test. The test was conducted for a period of 24 min during which the vehicle maintained a constant speed of 23 km/h until it came to a stop, as presented in Figures 9 and 10. This information provides supplementary context regarding the test conditions and the vehicle's performance during the test. In conclusion, the tests conducted on the vehicle demonstrated the impact of integrating a fuel cell into its powertrain [19].

The preliminary trial, carried out in the absence of a fuel cell, yielded a duration of 24 minutes, during which the vehicle maintained a constant velocity of 23 km/h. However, in the second test, which involved the use of a fuel cell, the vehicle exhibited an extended duration of 58 minutes under the same speed conditions. This improvement underscores the potential of fuel cell technology to augment the vehicle's autonomy and indicates its capacity to serve as a sustained power source for extended durations when compared to relying solely on a battery. The FCHEV offers three principal advantages over BEVs: rapid refueling (5-10 minutes), accelerated warming in cold weather conditions, and an extended driving range with a full tank. This is attributable to the vehicle's range and charging technology, as well as its capacity to attain full power more rapidly [20].

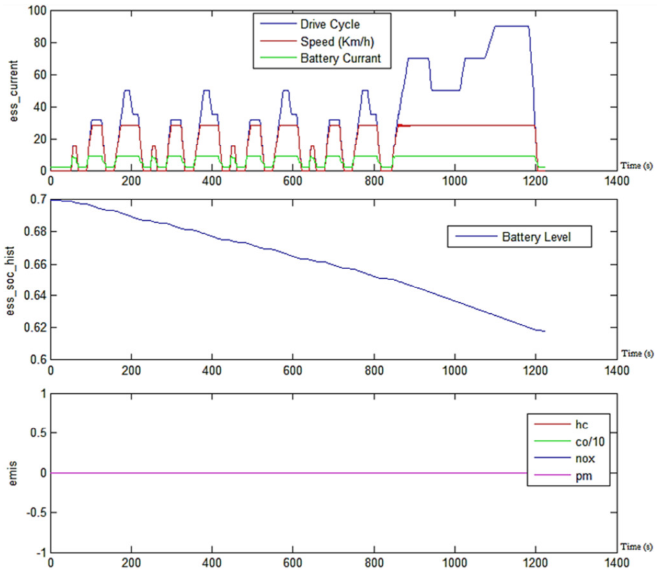

Fig. 9. Fuel results without fuel cell.

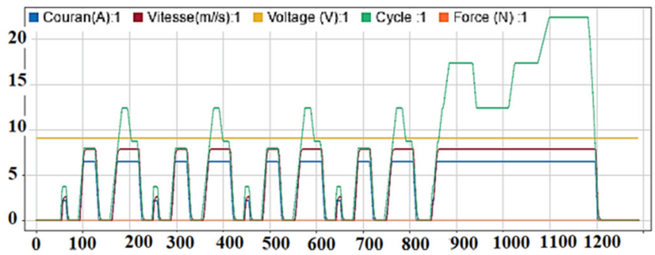

Fig. 10. Experiment simulation NEDC.

C. Hybrid Fuel Cell Vehicle Investigation

The findings of both the simulation and the design demonstrate that the FCHEV exhibits a markedly superior fuel efficiency while maintaining a similar efficiency compared to a vehicle that is powered solely by a fuel cell system. The equalization of the maximum electric current of the battery, as presented in Figure 11, represents a key benefit of the hybrid energy storage. This results in an enhanced control of the heat within the batteries, an extended battery lifespan, and a rapid power response due to the extremely low resistance within the fuel cell [21, 22]. It is possible to use alternative sophisticated configurations of hybrid energy storage in order to enhance efficiency. The chart's behavior in the driving cycle remains consistent between the actual test and the advisor model. Furthermore, there is a notable degree of similarity in the current activity between the two, indicating a strong correlation in performance. The most prevalent configuration is that of a hybrid power system, which consists of fuel cells and batteries. Batteries offer several advantages, including high energy density, minimal maintenance requirements, and cost-effective pricing [23]. This paper offers a substantial contribution to the field of sustainable transportation, focusing on the development of an FCHEV powertrain to enhance battery usage autonomy. The research integrates a fuel cell into an electric car model, resulting in a 250% increase in range and vehicle autonomy, thereby enhancing the adoption and usage of the vehicle. This study is distinguished by its use of MATLAB-Advisor to develop powertrain models that are validated in laboratory settings and adapted for automotive applications. This approach underscores the significance of ensuring the optimal operation of the fuel cell, which could potentially enhance efficiency and fuel consumption rates.

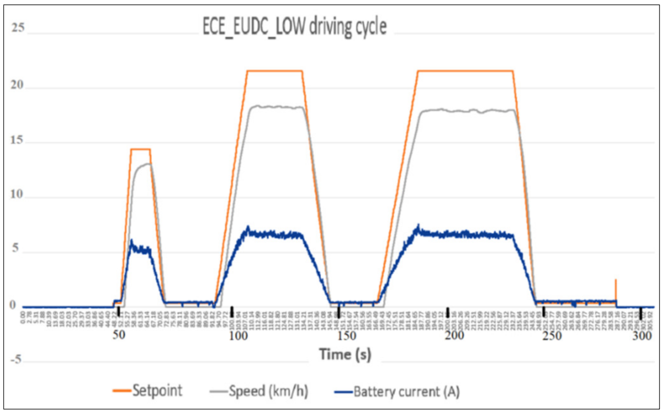

Fig. 11. Real test for European drive cycle output.

A comparison of this work with other papers reveals that it is aligned with the broader research landscape, which encompasses energy management in HEVs, the assessment of environmental and energy usage of alternative motor fuels, and the design and modeling of powertrains for FCHEVs. For example, authors in [1] address the topic of energy management in HEVs, emphasizing the significance of efficient power distribution in such vehicles. Additionally, authors in [4] focus on the design and modeling of the powertrain of an FCHEV, which contributes to the existing research on FCHEV powertrain design and modeling. Moreover, authors in [5] explore the modeling, simulation, and control strategy optimization of an FCHEV, underscoring the significance of control strategies in enhancing the performance of such vehicles. A comparison of these works demonstrates that the study of FCHEV powertrain design and modeling contributes to the body of knowledge surrounding sustainable transportation solutions, particularly in the context of hydrogen fuel cell and BEVs. It demonstrates the potential for advancements in energy efficiency and autonomy in future mobility systems. The paper concentrates on the utilization of a modeling tool for the analysis of fuel cell powertrain performance, demonstrating a 6.1% discrepancy in hydrogen consumption in comparison to the test data [1]. In contrast, another paper introduces a neural network-based Maximum Power Point Tracking (MPPT) controller for a PEMFC in FCEVs, emphasizing the significance of high-voltage gain DC-DC converters and an IBC for system efficiency. Moreover, a study on solar-assisted FCEVs proposes the integration of fuel cells with an electrolyzer and solar power, using a quadratic bidirectional buck-boost converter and an MPPT algorithm for optimal power management [3]. Moreover, a paper builds upon the Fully-Analytical Fuel Consumption Estimation (FACE) method for FCHEV, demonstrating a precise hydrogen consumption estimation with an error of less than 7% RMS when compared to experimental data.

VI. CONCLUSIONS

This paper has studied the potential of hydrogen fuel cell and Battery Electric Vehicles (BEVs) for a future sustainable mobility system. The main focus was on a quantitative comparison between real experiments and the ADVISOR model. The practical aspect of hydrogen vehicle testing using real tests conducted on an actual vehicle through the implementation of LabVIEW software was presented. By comparing the results of the real tests and the ADVISOR model, the current study was able to evaluate the accuracy and reliability of the model in predicting real-world results. Ultimately, this research provided important insights into the performance and effectiveness of the model. In addition, the integration of a fuel cell into an electric vehicle increased its autonomy by 250% (without a fuel cell, the vehicle's autonomy test lasted 24 minutes at 23 km/h, while the second test with a fuel cell lasted 58 minutes). The integration of a fuel cell in its powertrain resulted in reduced emissions and increased range, offering superior autonomy compared to alternative energy sources for electric vehicles, making it a promising technology for future sustainable transportation.

According to the analysis, Fuel Cell Electric Vehicles (FCEVs), Battery Electric Vehicles (BEVs) and Fuel Cell Hybrid Electric Vehicles (FCHEVs) have higher costs in 2023 compared to conventional Internal Combustion Engine (ICE) powertrains. However, by 2028, a significant reduction in investment costs is expected, with FCHEV being the most cost-effective option. The current study proposes the integration of hydrogen FCEVs with BEVs equipped with fuel cell range extenders. Thus, the conducted research suggests that BEVs and hydrogen fuel cell vehicles should not be seen as conflicting alternatives, but should be both, instead, actively pursued and supported for policy purposes.

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