

ADVANCING RENEWABLE HYDROGEN MOBILITY WITH AN URBAN HYDROGEN FUEL-CELL CONCEPT ELECTRIC VEHICLE INTEGRATING A MODULAR, RAPID-DISASSEMBLY CHASSIS

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Abstract

The shift to renewable and sustainable energy sources has enhanced the development of hydrogen fuel cell electric vehicles (HFCEVs). High manufacturing costs, intricate maintenance, and limited modularity limit their adoption. This study presents the design, numerical analysis, and experimental validation of a modular chassis for an urban concept HFCEV that aims to improve transportability, energy efficiency, and maintenance adaptability. The chassis allows for rapid disassembly. It reduces maintenance complexity, enhances scalability, and maintains structural integrity, while still complying with competition safety requirements. A proton exchange membrane fuel cell (PEMFC) stack was used to power an independent dual-motor drivetrain, eliminating mechanical transmission losses. Custom direct-drive gear was integrated and evaluated over 100 km of field testing. Findings showed that lower gearing of 1:23 provided optimum performance in acceleration and climbing at a current draw of 10 A, while a high gearing of 1:13 was best for speed-maintaining cruising at 24 km/h with 18 A. Using a 1:10 ratio was inefficient because it pulled more than 30 A without actually attaining the needed speed in terms of hydrogen consumption optimization. The PEMFC stack maintained a constant voltage over the relevant operating range, allowing controlled energy delivery with limited transient losses. The modular HFCEV's potential for flexible, efficient hydrogen-powered transportation underscores the need for modern hydrogen transport to address the problems posed by conventional vehicle designs. Overall, the proposed concept demonstrates that a rapidly disassembled modular chassis, integrated with an optimised dual-motor drivetrain and a PEMFC system, can deliver structurally energy-efficient urban hydrogen mobility.

Keywords: Hydrogen fuel cell electric vehicle, Modular chassis, Renewable energy, Sustainable mobility, Urban concept.

1. Introduction

The international transition toward renewable energy sources for transportation has made major strides in hydrogen fuel cell vehicle (HFCEV) technology. Concerns regarding climate change, energy security, and the need for CO₂ emission reductions have driven the development of HFCEVs as a viable alternative to battery electric vehicles (BEVs) due to their high energy density, rapid refuelling times, and zero-emission operation [1, 2].

Even though BEVs hold the majority share of the clean-energy transportation market, hydrogen-powered vehicles are superior for long-range applications due to their efficient refuelling, making them ideal for urban transport, fleet operations, and heavy-duty mobility [3, 4]. Recent analyses of fuel cell electric vehicles (FCEVs) further highlight their potential for long-range, zero-emission transport; while emphasising that system cost and energy management must be improved for broad deployment [5-7].

Despite potential advantages, hydrogen vehicles are, as of now, burdened by high manufacturing and maintenance costs, low modularity, and other issues [8, 9]. In the case of fuel cell vehicles (FCVs), the monocoque or single-frame chassis approach has its own set of issues, including limited transportability, repairability, and customization flexibility [10, 11]. With the progress of modular architecture, new chassis configurations are aimed at improving cost-effectiveness and adaptability by facilitating the integration of several energy sources and drivetrain layouts [8, 9].

Such modularity reduces the economic costs of vehicle assembly and logistics and enables more sustainable lifecycles [12]. At the vehicle level, modularity also affects ride, handling, and energy use because the arrangement of mass and structure influences rolling resistance, drivetrain packaging, and the ability to upgrade or reconfigure the powertrain as components age or are replaced [11-13].

The absence of modular vehicle architectures remains a fundamental impediment to the wider adoption of HFCEV, due to increased logistics costs, inefficient spatial arrangements, and complex assembly lines [8, 11]. Compared to electric vehicles, which use modular platform interfaces, hydrogen fuel cell vehicles are usually built as customized fleets with chassis and subsystems, which vastly complicates production and increases maintenance costs [13].

Furthermore, research on multi-module hydrogen fuel cell systems shows that some form of structural changeability significantly enhances upgradability and lowers the vehicle's lifecycle costs [4, 14]. Adding a modular chassis to an HFCEV will enhance its maintainability and transportability, reducing operating costs and improving fleet efficiency [10]. When combined with consciously sized fuel cell stacks and electric drives, modular platforms can therefore simultaneously target structural performance, energy efficiency, and operational availability, which is crucial for fleet-oriented urban mobility [2, 4, 8].

This research addresses the challenges of the urban concept of HFCEV through a fully modular chassis architecture. As proposed, the modular design enables the vehicle to be disassembled into seven basic parts, thereby enhancing transportability, repairability, and customization options [11, 15]. The present work intentionally separates the driver cell, powertrain compartment, suspension arms, and steering module into independently serviceable assemblies. Such design also

adheres to contemporary practices of lightweight automobile manufacturing, where modularity offers greater structural flexibility without compromising energy efficiency [9, 16].

The goal is to design a modular, lightweight disassembly chassis for hydrogen vehicles that optimizes transportability, ease of maintenance, and structural flexibility. This work also aims to improve the integration of hydrogen fuel cells with an autonomous motor system to enhance energy efficiency and minimize power losses within the drivetrain. Moreover, it analyses the impact of custom direct gear-ratio assignments of 1:23 and 1:13 for low and high gears, respectively, on the vehicle's energy efficiency and power control [2, 4].

By experimentally characterising power, current draw, vehicle speed, and hydrogen consumption across different fixed gear ratios, the study directly links system-level component design decisions on chassis modularity and drivetrain configuration to the vehicle's overall performance. The study focuses on the construction and customization of modular chassis systems for hydrogen fuel cell vehicles to advance eco-friendly transportation paradigms [3, 8].

The primary contributions of this work include the development of a modular system designed for rapid disassembly, with a dual-hub-motor powertrain featuring two optimized fixed gear ratios specifically engineered for efficient, low-speed urban driving. Furthermore, the research provides an experimental evaluation of the fuel cell's performance, detailing its load response and overall energy consumption. Finally, a CFD-based assessment was conducted to accurately quantify the aerodynamic drag penalties arising from the modular joints and the vehicle body segmentation.

2. Literature Review

2.1. Modular chassis design for hydrogen fuel cell electric vehicles

The design and modular chassis have become increasingly popular in HFCEVs due to their fuel efficiency, operational efficacy, and adaptability. Modularity enables easier maintenance and disassembly and supports upgradeable energy integration, which is crucial for commercial fleets and urban mobility [9].

Certain chassis parts that can be replaced or removed allow the use of lightweight materials, thereby reducing lifecycle costs and energy use, and improving durability and material use [8]. Studies show that production costs can be reduced by up to 30%, logistics improved, and the vehicle's lifespan prolonged with modular chassis design and component-based maintenance [14]. These modular spaceframe architectures have also been reported to facilitate transport to events and rapid repair between runs while maintaining adequate stiffness for safe handling [11].

Research on multi-module fuel cell systems shows promise for improving durability and energy performance, and for lessening the effects of stop-and-go driving common in urban settings [4]. In addition, lightweight chassis production techniques have improved energy efficiency, with some studies reporting energy use of 70 km/kWh with no CO₂ emissions [11].

These studies suggest great potential for modular lightweight chassis designs in next-gen hydrogen-powered vehicles, especially for shared mobility, last-mile

delivery, and autonomous transport [12]. Recent work also emphasises that modular vehicle platforms can be combined with different fuel cell system sizes and battery buffers over the vehicle lifetime, allowing gradual upgrades without complete vehicle replacement [5, 6].

2.2. Hydrogen fuel cell efficiency and modularity

Hydrogen fuel cells are considered one of the cleanest and most sustainable energy alternatives for vehicles, offering faster refuelling, high energy density, and zero emissions [2]. Nonetheless, fuel cell degradation and system efficiency losses, particularly in long-haul and urban transit applications, remain problematic [3]. One of the study's scopes is the application of multi-module fuel cells, which have the potential to increase power output while reducing the operational life of the system's components [8].

Some control approaches applied to modular fuel cell systems significantly improve system endurance by 471% while increasing hydrogen consumption by only 3.8% [4]. Complementary to this, recent reviews on FCEVs and PEMFC technology highlight the role of intelligent energy management, hybrid energy storage, and health-conscious control strategies in extending stack life and improving overall vehicle energy efficiency [5-7].

For smaller vehicles, the range is boosted by more than 50%, while for larger vehicles it is increased by 25%. Fuel cell range extenders also improve the flexibility of urban fleet operations [2]. Work on the integration of multi-module hydrogen fuel cells shows that modularized distribution improves power distribution efficiency and increases the number of possible start/stop cycles [9]. It is well-established that these cycles accelerate fuel cell deterioration.

Modular design greatly aids adaptive urban mobility solutions because it requires low effort to configure and scale hydrogen fuel cells for demand control. Geometric variability enables the optimisation of energy and fuel consumption for the vehicle's operating conditions [1]. In parallel, optimisation studies on EV and extended-range EV powertrains with multiple motors and gear ratios show that appropriate sizing and gearing can reduce energy consumption by several percent while maintaining or improving dynamic performance [17, 18], supporting the approach of coupling modular fuel cell systems with custom drivetrains.

2.3. Aerodynamics and energy consumption in modular designs

At urban speeds of about 25 km/h, aerodynamics has minimal impact compared to the vehicle's drivetrain efficiency [8]. Nonetheless, modular chassis designs still require some refinement to minimize structural dynamic accommodation and limit airflow interference with system components [3]. Studies on modular chassis systems for HFCEVs indicate that modular segmentation and joints significantly degrade aerodynamic efficiency, increasing drag and resistance, with a drag coefficient (C_d) estimated at 0.6-0.75 [11].

These drag coefficients are generally for lightweight hydrogen prototype vehicles with a modular chassis, rather than for fully seamless production vehicles or light commercial vehicle studies reported in the literature. While an insignificant increase in drag may be tolerable at lower speeds, smoother contour fairings that taper, gap at joints, and streamline exposed transitions improve airflow, energy

efficiency, and stability [13]. Recent extensive studies on road vehicle drag reduction have shown that attachable fairings, underbody fairings, and well-designed square-back rear tapering can lower the drag coefficient, which is very important for modular road vehicles with detachable parts [18].

A study on hydrogen vehicles found that enhanced modular chassis aerodynamics may yield a 10-15% increase in fuel economy, highlighting trade-offs between modularity and aerodynamics [4]. Further studies reveal that certain design elements, such as underbody fairings, streamlined gap-closing panels, and others, can reduce vortex shedding and, as a result, reduce losses due to airflow disturbances [10]. Additionally, future modular HFCEV designs require aerodynamic design to reduce energy consumption and maintain versatility [11].

2.4. Sustainability benefits of modular hydrogen vehicles

From a sustainability perspective, hydrogen modular cars offer advantages such as reduced material consumption, lower emissions, and longer vehicle life [15]. Research on lightweight modular vehicle chassis design indicates that part consolidation strategies can enhance material efficiency by reducing vehicle weight and raw material use [11]. The use of chassis elements constructed from recyclable aluminum and lightweight body panels made of foam composites supports the automotive industry's circular economy.

In addition, modular chassis designs support maintenance, as certain components can be serviced or replaced without fully disassembling the vehicle [9]. This approach improves the vehicle's overall durability while also minimizing repair costs and downtime in fleet operations [1]. There are allegations about the sustainable energy efficiency of modular HFCEVs. It is claimed that multi-module fuel cell systems can decrease hydrogen consumption in urban vehicles and thereby improve emissions-free propulsion [8]. Recent critical reviews of sustainable hydrogen FCEVs underline that modular system architectures and easy component replacement can reduce embodied emissions by extending vehicle lifetimes and facilitating technology upgrades without scrapping entire vehicles [6, 7].

As Wu et al. [2] note, modular hydrogen vehicles have the potential to reduce emissions by up to 15% compared with traditional HFCEV frameworks, suggesting they may be a sustainable solution for urban transport. The vehicle design is said to possess the requisite technological and economic adaptability for widespread deployment, along with operating cost-effectiveness, environmental sustainability, and energy efficiency, thus satisfying decarbonization objectives and the future of hydrogen mobility [3]. In this context, the present work contributes by demonstrating a tangible implementation of such a modular concept, including quantified assembly/disassembly times and durability results for a hydrogen-powered urban prototype.

3. Method

The construction of the HFCEV is based on a systematic approach that includes vehicle design and modular chassis fabrication, integration of hydrogen fuel cell and drivetrain components, CFD analysis of aerodynamics, and energy-efficiency testing. The design prepares the vehicle for maximum transportability, ease of use, and environmental impact by employing a modular chassis configuration with

hydrogen fuel-cell outriggers to complement vehicle dynamics and system flexibility. Figure 1 shows the overall development block diagram with the subsystems of interest and their interconnections.

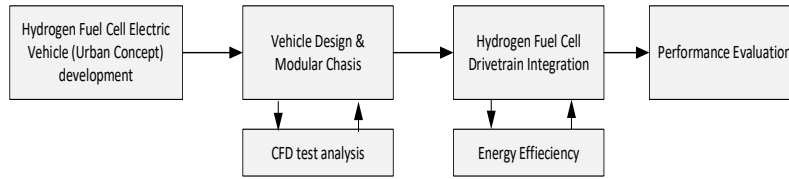


Fig. 1. HFCEV development block.

3.1. Vehicle design and modular chassis development

The HFCEV chassis emphasizes lightweight construction, structural integrity, and modularity for easy disassembly and maintenance. As depicted in Fig. 2, the fully modular chassis comprises seven modular constituents. It includes the core driver enclosure, a cabin that optimises safety and aerodynamics, a bulkhead for front-end structural support that links the steering system to the chassis, a rear drive arm as the suspension, and a rear wheel system that provides rear suspension housing.

It also consists of a load-balanced power of powertrain compartment, which serves as a self-contained unit housing the hydrogen fuel cell, smart controller, and the drivetrain, a Steering Structure, which is a dedicated module for fine adjustment of steering, a front brake & wheel assembly as has fast releasing lock for adjusting the functions of the braking and wheeling system and a rear wheel system which detachable without the associated wheel to facilitates faster changes. The urban HFCEV is configured as a single-seat vehicle with an overall length of approximately 2.70 m, a width of 1.00 m, a height of 1.10 m, and a wheelbase of 1.80 m.

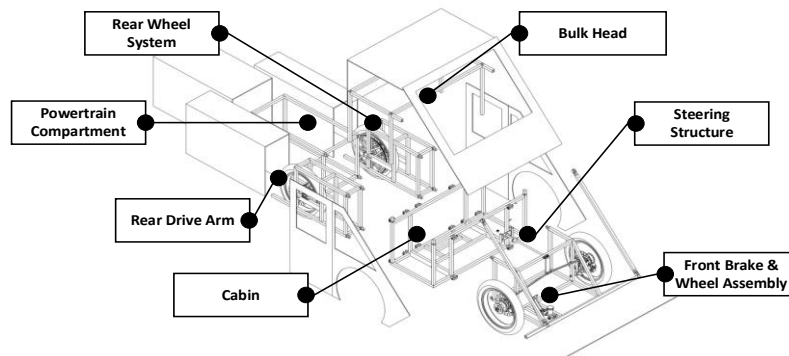


Fig. 2. Modular chassis of the HFCEV.

The chassis of the HFCEV is constructed using an aluminum alloy. Aluminum is light, has high tensile strength, is economically viable, and is environmentally recyclable. Modular hinges with extra release locking mechanisms make chassis assembly and disassembly easier. The chassis is easier to transport for maintenance and other tasks. The chassis structural finite element analysis (FEA) of the HFCEV was performed to assess its durability and stiffness under specific stress and loading

conditions. The analysis confirmed that modular joints and locks enable stiffness to be designed for quick assembly and disassembly. HFCEV flexibility for other scaling to design and urban commercial applications. The FEA predictions were confirmed after the field achieved 100 km.

3.2. Hydrogen fuel cell and drivetrain integration

A Proton Exchange Membrane Fuel Cell (PEMFC) converts hydrogen to electricity, producing only water vapor as a byproduct. Fuel cells are emission-free, unlike internal combustion engines, which emit pollutants. The Drivetrain consists of three main elements: the hydrogen fuel cell system, an Independent Motor, and a Gear Ratio System. The rear Powertrain Compartment houses the PEMFC components, a DC-DC converter, and a high-pressure hydrogen storage tank. Each rear DC motor is used for propulsion and is driven by a high-voltage DC Motor driver. The Gear ratio system allows fixed drive stages to be shifted to achieve overall ratios of 1:23, 1:13, and 1:10 for this study.

3.3. Hydrogen fuel cell system

A fuel cell system comprises a lithium-ion battery pack, a fuel cell stack, and a hydrogen storage tank. The storage tank is engineered to safely and effectively store fuel under high pressure. The fuel cell stack can achieve 60%-70% efficiency and generate electrical energy through the chemical reaction of hydrogen and oxygen. The battery pack captures excess energy, supports energy management and control, and ensures smooth energy delivery under varying load conditions. The stack's voltage and current were recorded using a custom data-acquisition system to calculate power consumption at any given time. The power management system was designed so that the fuel cell could meet the average load demand, while the battery could supply short transients and provide regenerative back-EMF to the motor.

3.4. Independent motor and gear ratio system

The vehicle's powertrain consists of an electric system with two 300 W rear-wheel motors. The motors are designed to provide direct torque without any losses from mechanical transmission systems. For direct gear ratios, custom designs were developed to optimize energy consumption and torque distribution. The tested gear ratios were:

- 1:23 Low Gear - Suitable for acceleration and slope climbing with low current consumption of 10 A.
- 1:13 High Gear - Best for cruising straight lines. Allows the vehicle to maintain 24 km/h with a low current draw (18 A).

A multitude of tests were performed to investigate the vehicle's drivetrain performance. The conclusion was that the 1:13 high gear was the best trade-off between energy efficiency, velocity, and power loss. While testing, vehicle speed, motor current, and stack voltage were recorded simultaneously. For each gear ratio, several repetitions of an urban-like driving section with standard driving behaviour (acceleration, steady cruising, and braking) were performed.

3.5. Computational fluid dynamics (CFD) analysis for aerodynamics

CFD (Computational Fluid Dynamics) analysis was performed to evaluate how the modular joints and gaps between panels affect airflow distribution and the resulting aerodynamic resistance. The analysis was performed in Ansys Fluent 2023, where boundary conditions were applied to simulate urban driving conditions. The conditions were set to 25 km/h and an air density of 1.225 kg/m³. The k-ε turbulence model was utilized to determine the drag coefficient (Cd) and to assess flow separation and vortex formation. The computational domain was established as a virtual wind tunnel, 12 times the vehicle's length in the longitudinal direction and at least 6 times the vehicle's frontal area in the transverse direction.

3.6. Energy efficiency testing

An evaluation of power consumption under various driving conditions and gear ratios was conducted using a series of energy-efficiency tests. Other analyses performed simultaneously included hydrogen fuel cell load performance, drivetrain power consumption, and power and voltage fluctuations across speed changes, including terminal voltage fluctuations. Additional tests were performed to analyse power consumption across different gear ratios and to assess the current drawn from the hydrogen fuel cell (Fig. 3).

The study has developed a fully modular HFCEV chassis that facilitates easier assembly, transport, and maintenance access. Hydrogen fuel cell systems directly coupled to hub motors with higher gear ratios demonstrated impressive energy efficiency and powertrain optimization. The CFD analysis confirmed that the aerodynamic efficiency improvements in structural modularity do not adversely affect performance at low urban speeds (below 30 km/h).

For each test configuration, the vehicle was driven over repeated laps of a controlled route, totaling 100 km, with flat sections and moderate gradients. The fuel cell system's power consumption was recorded, and vehicle-level energy efficiency was compared across gear ratios. Testing verified that enhanced vehicle efficiency is achieved through an advanced control strategy for power distribution and active steering of the vehicle's electric motors.

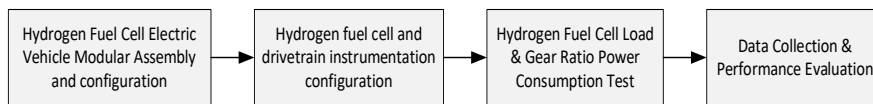


Fig. 3. Hydrogen power consumption test on the HFCEV.

4. Results and Discussion

This research confirms the urban design HFCEV, with a modular disassembly chassis, across operational performance, energy use, and practical benefits. The findings correspond to four elements: chassis modularity, powertrain efficiency, and aerodynamics. A different perspective provides a way to consider a broad range of practical and simulated evaluations of the vehicle. The findings particularly show that a chassis of modular, rapid disassembly can accommodate structural and logistical needs while housing an efficient hydrogen fuel-cell powertrain.

4.1. Performance of modular chassis

The modular chassis showed notable increases in transportability, maintenance optimization, and adaptability to structures. The tests were centred on assessing disassembly duration, reassembly simplicity, and the system's endurance to define operational strain constraints.

The vehicle, shown in Fig. 4, was successfully modularized into seven sections within six hours, enhancing transport and logistics. The modular components are strategically arranged to be stored in oversized baggage, reducing transportation costs compared to traditional hydrogen vehicles. Furthermore, operational constraints and research frameworks requiring rapid deployment attest to the need for streamlined reassembly processes, initially projected to meet the six-hour full assembly target.



Fig. 4. The urban concept electric vehicle shows the ease of assembly and maintenance.

A Finite Element Analysis (FEA) simulation was conducted to evaluate the modular chassis's structural integrity. The outcomes showed that, under dynamic loads, the modular joints were self-sustaining, capable structures, and stress concentration did not exceed allowed limits. Furthermore, the vehicle met all international competition inspection requirements, further corroborating the engineering strength of the modular design.

Endurance tests showed a distance of 100 km driven across various conditions. In Fig. 5, the urban concept electric vehicle durability test shows that the chassis stayed within the operational load limits and therefore remains reliable for extensive use. Furthermore, the modular connections, with no sign of gapping, reached the expected structural durability and strength/endurance under little transverse force. It shows a fully modular chassis design, and outsourcing structural strength is a pragmatic alternative to the traditional monocoque chassis.



Fig. 5. The urban concept electric vehicle durability test.

4.2. Powertrain efficiency analysis

A primary objective of this research was to assess the energy consumption and performance of the hydrogen fuel cell system with an integrated motor drive and custom-designed gear ratios. The Drivetrain was tested with gear-ratio steps, measuring speed, current consumption, and power efficiency over a cumulative distance of 100 km across different terrain conditions. Table 1 illustrates power consumption as a function of gear performance and ratios.

Table 1. Power consumption and gear ratio performance.

Gear ratio	Achieved speed (km/h)	Current draw (A)	Performance Findings
1:23 (Low Gear)	14	10	Optimal for acceleration and inclines
1:13 (High Gear)	24	18	Best for straight-line cruising efficiency
1:10 (Tested Gear)	N/A	>30	Inefficient, excessive power draw

The 1:23 low gear ratio was advantageous for urban stop-and-go driving. High torque was achievable at a low current of 10 A for starts, acceleration, and hill climbing. High gear 1:13 was the most power-efficient for constant-state driving at an 18 A draw and 24 km/h. It was also the most efficient steady-state driving. The 1:10 ratio was tested and found inefficient and impractical at the current demand of over 30 A. The tested and proven best ratios for minimizing unnecessary fuel consumption and distance within the operational range are 1:23 and 1:13.

Using data from Table 1 on power consumption and gear ratio, and considering the recorded speed and current over time, it is possible to observe distinct dynamic features associated with the varied gear ratios. A notable example is the low-gear 1:23, which reached 14 km/h faster and exhibited lower current peaks. It indicates good performance in both hill climbing and launching. However, during the cruise phase, the vehicle operated near the lower-power end of the PEMFC. At high gear 1:13, the speed increase was more gradual, and the current stabilized at 18 A at 24 km/h, which was highly efficient on long, flat stretches of road. In contrast, the 1:10 gear ratio required a high, sustained current, with only a limited increase in speed, indicating that the hub motors were operating outside the optimal efficiency zone.

When the hydrogen consumption data are normalised by distance, the 1:13 ratio shows the lowest g H₂/km for flat-route cruising, while 1:23 minimises consumption on routes with frequent acceleration and mild gradients. These trends are consistent with gear-ratio optimisation studies for multi-gear electric powertrains, which find that an intermediate ratio is typically optimal for steady cruising and a shorter ratio is beneficial for urban drive cycles with frequent stops [17, 18].

4.3. Hydrogen fuel cell performance and load response

The performance of the hydrogen fuel cell system was assessed at different loading levels, focusing on how the system managed power changes over time. The fuel cell produced a constant voltage, indicating that the generated energy was stable and would not fluctuate. The acceleration command of 1:23 produced moderate

speed, and with a consistent increase in cruising speed (1:13 gear ratio, 24 km/hr), fuel usage was deemed acceptable. The vehicle is typically considered energy-efficient for extended journeys.

Figure 6 presents a representative power performance curve for the fuel stack at the 1:23 and 1:13 gear ratios. Under low-gear acceleration, stack current ramps up smoothly while voltage remains within a narrow band, indicating good load-following behaviour with limited voltage sag. During high-gear cruising, the current settles to an intermediate level, and voltage is nearly constant, confirming that the PEMFC operates in a relatively stable region. The 1:10 ratio produces significantly higher currents at comparable vehicle speeds, leading to larger voltage drops and higher ohmic and activation losses, which explains its poorer efficiency.

The independent motor system results confirmed that the dual motor system operates in synergy with the hydrogen fuel cell, validating the design prototype for hydrogen-powered vehicles for use in urban environments. The system efficiency, calculated as the ratio of mechanical power at the wheels to fuel cell electrical power, was highest at 1:13 during steady cruising and at 1:23 during low-speed acceleration. This study concluded that, in practical situations, fuel cell stability under load has a more pronounced impact on energy expenditure, hydrogen loss, and the car's travel distance. The observations are consistent with the latest reviews on PEMFC, which emphasize that to ensure longevity and hydrogen efficiency, the fuel cell must operate within the load window and avoid frequent start-stop operation [6, 7].

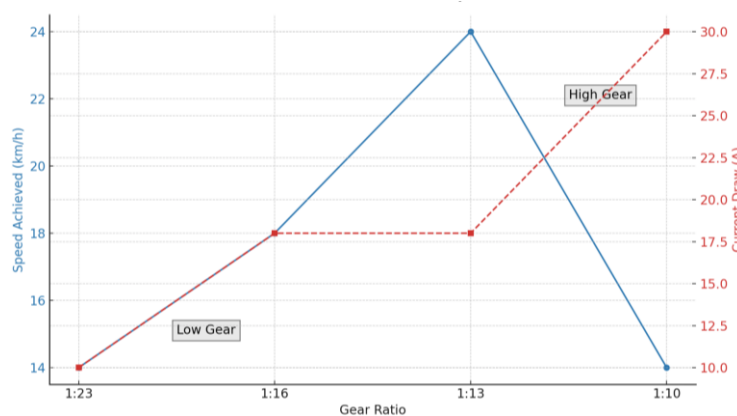


Fig. 6. Hydrogen fuel cell stack power performance drawn for the 1:23 and 1:13 gear ratios.

4.4. Computational fluid dynamics (CFD) analysis for aerodynamic

The aerodynamic drag coefficient (C_d) of 0.7 is worse than that of monocoque structures, but at lower speeds (approximately 25 km/h) it is still acceptable. The main flow separation and vortex formations around the modules suggest that the form drag due to the module construction was small. In the urban concept category of vehicles, the speed limit is 25 km/h; therefore, overall energy consumption is the most important metric, with the efficiency of the powertrain drive system more important than aerodynamic drag. In terms of energy efficiency, city driving is not

affected negatively by the vehicle's drag coefficient of 0.7, even though that figure makes the vehicle highly inefficient at higher speeds.

Figure 7 displays pressure contours for the baseline modular configuration, showing a high-pressure stagnation area at the front and low-pressure wake areas at the rear joints and around the wheel housings. The addition of simple joint fairings reduced the size of these separated-flow regions and lowered Cd by 4-5% without compromising joint modularity.

Given that rolling resistance and drivetrain losses require more energy than aerodynamic drag at 25 km/h, Cd's effect on energy consumption is limited for its intended urban purpose. Analyses of light-commercial vehicles demonstrate Cd's effect on drag. Drag is only relevant at higher speeds for light commercial vehicles with Cd values of 0.5-0.7. However, for high-speed highway applications, further refinement of the body shape and of modular joint sealing is needed to compete with low-drag monocoque designs.

Seamless modular connections and fairings, which reduce vortex and shear-layer separation, have been added to reduce drag. These changes have improved modular stiffness while maintaining flexibility and demonstrate the potential of small-scale changes to improve the aerodynamic performance of modular vehicle designs substantially. Thus, the CFD results indicate that the aerodynamic sacrifices made by a modular, rapidly disassemblable chassis can be partially mitigated, and, for low-speed urban applications, drivetrain and fuel-cell efficiency remain the main factors in energy consumption.

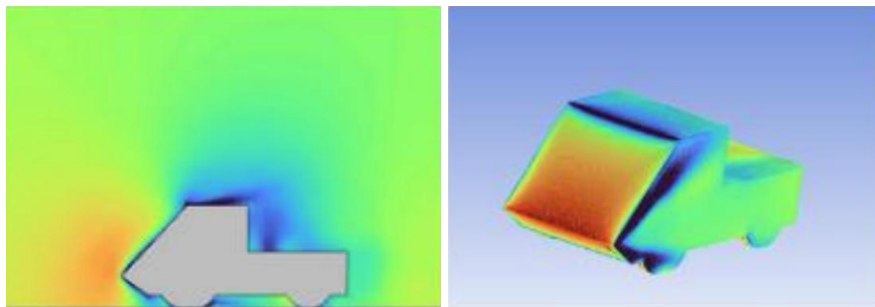


Fig. 7. Pressure contours for the actual urban concept car.

5. Conclusions

The study affirms both the practicality and the efficiency of the urban approach HFCEV coupled with a modular disassembly chassis. With assembly and disassembly times of under six and eight hours, respectively, the chassis is suitable for a wide range of research and competition activities. Modularizing the vehicle into seven modules while maintaining configurable structural integrity is a direct response to the logistical and proprietary challenges that typically constrain the deployment and evaluation of hydrogen-fuel application prototypes.

Each of the seven modular chassis is disassembled into seven detachable units. Compared to traditional monocoque chassis, these modular units offer significant improvements in transport logistics and cost efficiency while maintaining structural integrity. FEA and real-world durability tests of the modular connection's rigidity

and reliability demonstrated that it is sufficiently robust for long-term use. Further evaluations of the powertrain confirmed the vehicle's design and the ability to achieve higher acceleration at specific gear ratios, as well as improved fuel efficiency in urban driving and optimal energy savings.

The hydrogen fuel cell system demonstrated good load-following performance and maintained a constant power output across all driving conditions, proving effective for moderate acceleration and high-speed cruising. The measured hydrogen consumption from the current-drawn performance showed a 1:23 and a 1:13 gear ratio as a complementary pair, both operating with low current draw. The latter also helps keep energy consumption lower during steady urban cruising.

The modular chassis also showed limited impact on aerodynamics and energy consumption at urban speeds. CFD-based Cd values around 0.7 indicate that while modular joints produce additional drag, this impact can be less pronounced at lower speeds and can be offset by adding simple fairings. Reductions in airflow and improvements in vertical airborne stability were also implemented while preserving the modular design.

The evidence highlights hydrogen-fuel-cell modular vehicles as a solution for urban mobility but emphasises the need for enhanced trim configurations and improved vehicle aerodynamics. These vehicles require optimized configurations and aerodynamics. Overall, the novelty of this work lies in experimentally demonstrating a rapidly disassembled, modular chassis integrated with a dual-individual-motor PEMFC powertrain, including quantified assembly/durability performance, gear-ratio-dependent efficiency data, and CFD-based aerodynamic assessment.

Future work should focus on expanding shiftable gear-ratio adaptability, hybrid energy-recovery systems, modular joint aerodynamics, and other sustainable interventions to strengthen the vehicle's position relative to conventional automotive engineering. In particular, integrating regenerative braking, active energy management, and more advanced aerodynamic devices could further reduce hydrogen consumption and enhance the competitiveness of modular HFCEVs in real-world urban fleets.

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Abbreviations

BEV	Battery Electric Vehicle
Cd	Drag Coefficient
CFD	Computational Fluid Dynamics
FCV	Fuel Cell Vehicle
FEA	Finite Element Analysis
HFCEV	Hydrogen Fuel Cell Electric Vehicle
PEMFC	Proton Exchange Membrane Fuel Cell

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