

Electric Propulsion Systems of Autonomous Hydrogen Fuel Cell Buses

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Saša Milojević^{*1}, Slobodan Savić¹, Aleksandar Ašonja², Slavica Miladinović¹,
Blaža Stojanović¹

¹Faculty of Engineering, University of Kragujevac, Sestre Janjić 6, Kragujevac 34000, Serbia

²Faculty of Economics and Engineering Management, University Business Academy, Cvečarska 2, Novi Sad 21000, Serbia

Abstract:

The decarbonization of public transport represents a major challenge in achieving sustainable urban mobility. This paper presents a comprehensive analysis of electric propulsion systems in autonomous hydrogen fuel cell buses. The study evaluates technological characteristics, operational efficiency, regulatory frameworks, and economic feasibility. A comparative analysis with battery electric buses and compressed natural gas buses is also provided. Special attention is given to integrating autonomous driving technologies and the necessary infrastructure adaptations. The results indicate that hydrogen buses are particularly suitable for high-demand and long-distance routes, while regulatory, infrastructural, and economic challenges remain key barriers.

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1. INTRODUCTION

Urban transport systems significantly contribute to greenhouse gas emissions. The transition toward zero-emission technologies has accelerated the development of alternative propulsion systems [1].

Hydrogen fuel cell electric buses (FCEBs) represent an advanced solution that combines electric propulsion with a high-energy-density fuel [2,3]. Unlike conventional diesel and compressed natural gas (CNG) buses, FCEBs produce only water vapor as a byproduct [4]. Studies show that hydrogen buses are particularly effective in applications where battery-electric buses (BEBs) face limitations, especially regarding range and charging time [5]. Also, a fuel cell can be used to supply power to onboard devices and equipment, such as the operation of the air conditioning system, etc. [6].

The available literature primarily examines the advantages and comparative performance of battery-electric and fuel cell propulsion systems in passenger cars, trucks, and buses, considering factors such as emissions associated with electricity

generation, end-of-life recyclability, available installation space, and related aspects [7].

Regarding the regulatory framework, for example, the European Union promotes zero-emission transport through CO₂ emission standards, the Renewable Energy Directive (RED), and Green Deal policies. This includes logistical support, electrification of freight transport, investment in supporting infrastructure, creation of zero-emission priority corridors, fleet management, and other measures aimed at improving operational efficiency. However, challenges remain in harmonizing regulations governing hydrogen production and use.

The use of autonomous buses in public transport is regulated through evolving legal frameworks [8]: UNECE Regulation No. 157 – defines Automated Lane Keeping Systems (Level 3), EU Regulation 2019/2144 – mandates advanced safety systems, Vienna Convention on Road Traffic – permits the use of automated systems under human supervision.

Currently, fully autonomous buses (Levels 4–5) are primarily limited to pilot projects, controlled

*CONTACT: Saša Milojević, e-mail: sasa.milojevic@kg.ac.rs

urban environments, and dedicated transport corridors [9]. Key regulatory challenges include liability issues, cybersecurity, and data protection.

The main objective of this research is to analyze electric propulsion systems of autonomous hydrogen buses and evaluate their applicability in urban transport systems.

2. ELECTRIC BUS PROPULSION SYSTEMS

Electric propulsion in public transport comprises three main technologies [10]:

- **Battery Electric Buses:** Powered by onboard batteries; require dedicated charging infrastructure and limited range, particularly on longer routes;
- **Hydrogen FCEBs:** Generate electricity using hydrogen fuel cells, offer extended range and rapid refueling, and are suitable for high-demand and intensive routes.
- **Hybrid Systems:** Combine battery systems with alternative fuels, as a transitional solution toward full electrification.

2.1 Concept of a Hybrid Fuel Cell–Battery Propulsion System for Long-Distance Buses

As an example of a hydrogen fuel cell bus propulsion system, Fig. 1 presents a proposed concept of an electric propulsion system for an intercity bus or long-distance buses, which offers more space for the installation of hydrogen storage tanks (35-70 MPa), fuel cells, electric batteries, electric motors, and other components.

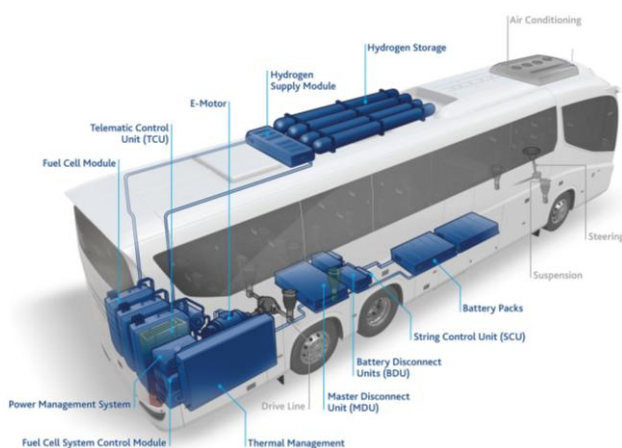


Fig. 1. Fuel cell propulsion system for a long-distance coach bus

The proposed propulsion concept for the coach is designed to deliver power and acceleration characteristics comparable to those of current Euro VI diesel buses. The expected driving range without

refueling the hydrogen tank exceeds 600 km, with refueling times of 15–20 minutes, enabling operational performance comparable to that of conventional long-distance buses. The hybrid propulsion system intelligently integrates electricity generated from both battery and fuel cell technologies, combining the benefits of high energy density and flexible energy management. This approach is particularly well-suited for long-distance bus transportation and has broad applicability, including freight transport and other heavy commercial-vehicle applications. By replacing diesel engines with a zero-emission powertrain, the system can significantly reduce CO₂ and other pollutant emissions, contributing to environmental sustainability and supporting the transition to cleaner public transport solutions.

Fig. 2 shows the schematic diagram of the fuel cell electric bus system, including the main components and energy flow paths [11].

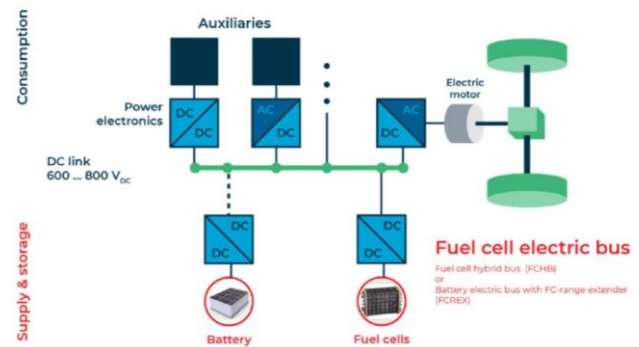


Fig. 2. Concept of an extended-range electric bus with DC/DC converter (voltage regulation)

The FCEB is based on a hybrid propulsion system that integrates a hydrogen fuel cell system with battery storage. The fuel cell serves as the primary energy source, continuously generating electricity through the electrochemical conversion of hydrogen and oxygen, while the battery system supports peak power demands and enhances overall system efficiency. The electric motor is powered by this combined energy supply, with water being the only by-product of the conversion process, making the system eco-friendly.

Hydrogen consumption depends on vehicle configuration and operating conditions, typically ranging from approximately 8-16 kg/100 km for standard-solo buses and 12-24 kg/100 km for articulated buses. The achievable driving range is influenced by hydrogen storage capacity; therefore, it is important to distinguish between installed and usable storage volumes and to consider potential

adjustments to storage systems to meet operational requirements.

In practical applications, the system can support long daily operating distances; however, efficient operation requires advanced IT support. This includes real-time prediction and monitoring of vehicle range, as well as tracking the state of charge (SOC) of both energy storage systems, namely, the battery and hydrogen tanks. Furthermore, refueling planning and scheduling depend on the availability of hydrogen infrastructure and can be optimized through appropriate modeling approaches. Continuous monitoring and evaluation of vehicle performance data, including extended diagnostic and log data, are also essential for ensuring reliability and optimizing system operation.

2.2 Techno-Economic Analysis (TCO Model)

To evaluate the economic feasibility of hydrogen buses, a Total Cost of Ownership (TCO) model is introduced, Eq.(1):

$$TCO = C_{vehicle} + C_{fuel} + C_m + C_i. \quad (1)$$

where are:

- $C_{vehicle}$ - Acquisition cost;
- C_{fuel} - Hydrogen cost per km;
- C_m - Maintenance-service and repair costs;
- C_i - Fueling infrastructure investment.

Hydrogen buses have a higher initial cost (approximately 2-3 times that of diesel-powered buses) but lower emissions costs (zero-emission benefit).

FCEBs provide longer range and faster refueling, Fig. 3.

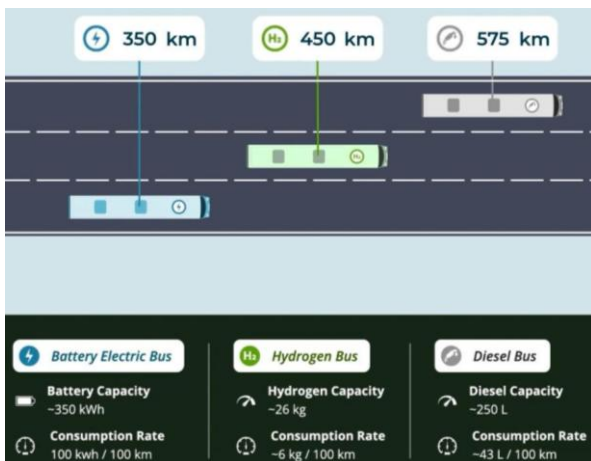


Fig. 3. Bus range comparison: BEB vs H₂ and diesel

Existing studies confirm that CNG buses reduce emissions by approximately 20–25% compared to diesel buses. However, they are not zero-emission systems and therefore represent only an

intermediate step toward sustainable transport [1,12].

BEBs achieve high energy efficiency (up to 85%) but are limited by battery capacity and charging time, Table 1 [13].

Table 1. Comparison of Energy Efficiency for Various Propulsion Systems

Propulsion System	Efficiency (%)	Notes
Diesel	30-35	High emissions
CNG	35-40	Transitional
BEB	75-85	Very efficient
FCEB	45-55	Medium efficiency

FCEBs efficiency can be expressed as Eq. (2):

$$\eta_{FCEB} = \eta_{fuel\ cell} \cdot \eta_{inverter} \cdot \eta_{motor} \approx 0.5 \quad (2)$$

Typical values for efficiency are:

- $\eta_{fuel\ cell}$ – Fuel cell: 50-60%;
- η_{motor} – Electric motor: 90-95%.

The Sankey diagram of the fuel cell bus operation is shown in Fig. 3 [13].

The input value for the lower heating value (LHV) of hydrogen is used in the calculation of bus efficiency and in the development of the Sankey diagram, Fig. 4. Generally, LHV is applied in most engineering calculations (particularly for internal combustion engines and fuel cells), as in real operating conditions, the heat contained in water vapor is typically not utilized.

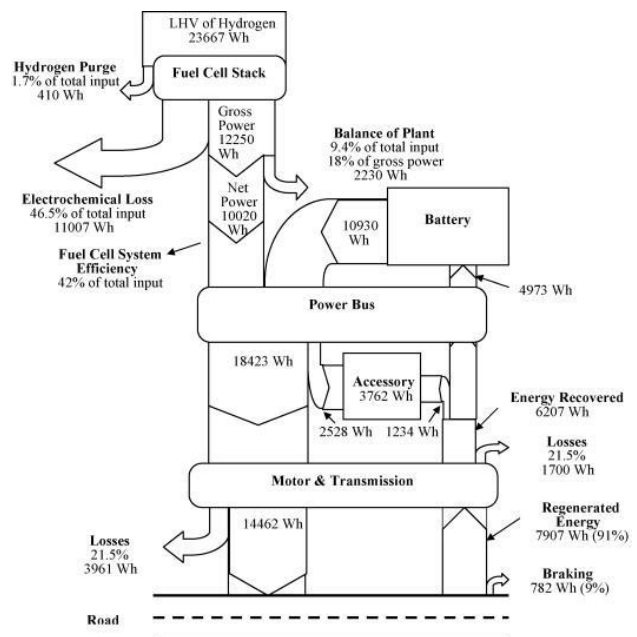


Fig. 4. Sankey Diagram of Energy Flow in a Hydrogen Fuel Cell Bus

The hydrogen propulsion system can be modeled using the energy balance Eq. (3):

$$P_{total} = P_{fuel\ cell} + P_{battery} \quad (3)$$

where are:

- $P_{fuel\ cell}$ – Fuel cell output power, (kW);
- $P_{battery}$ – Auxiliary battery power, (kW).

The research methodology is based on a multi-layered analytical approach that includes system modeling, efficiency analysis, and total cost of ownership modeling, as described above. The evaluation criteria include energy efficiency, emissions, operational costs, and infrastructure complexity.

3. AUTONOMOUS DRIVING IN HYDROGEN BUSES

Autonomous vehicle systems rely on advanced sensing and control technologies, including LiDAR, radar, and camera-based perception systems, supported by artificial intelligence (AI) decision-making algorithms and real-time control units. LiDAR (Light Detection and Ranging) is a sensing technology that uses laser light to measure distances and create precise 3D maps of the environment. As illustrated in Fig. 5, these components are integrated into the overall vehicle architecture, enabling continuous environmental monitoring and adaptive control of the propulsion system [14].

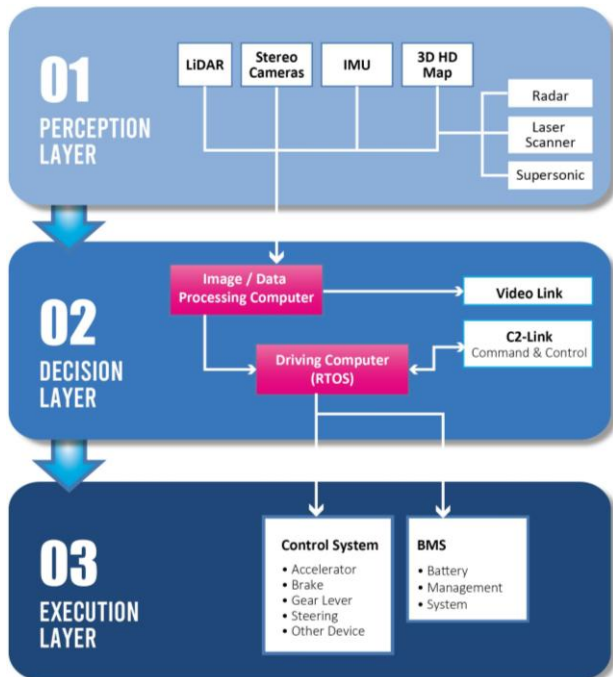


Fig. 5. Layered Architecture of Perception, Decision-Making, and Execution in Autonomous Vehicle Systems

The Fig. 5 illustrates the layered architecture of an autonomous vehicle.

The perception layer integrates data from multiple sensors, such as LiDAR, cameras, GPS, and IMU, to detect, classify, and track surrounding objects, performing localization, detection, and tracking through multi-level data fusion.

The decision layer processes this information to predict the environment, plan optimal paths, and avoid obstacles. It typically involves multiple computing units, with one processing raw sensor data and another generating control commands.

Finally, the execution layer implements these commands by controlling mechanical systems, including steering, acceleration, braking, and shifting, through a real-time operating system, enabling the vehicle to respond accurately to dynamic conditions.

Modern autonomous vehicles rely heavily on advanced sensing technologies to operate without a driver. Cameras, radar, LiDAR, and ultrasonic sensors provide real-time information about the vehicle's surroundings, enabling detection of obstacles, other vehicles, pedestrians, and lane markings. The data from these sensors is continuously processed to support navigation, speed regulation, and collision avoidance. By combining multiple sensor types, vehicles achieve high accuracy and reliability even in complex and dynamic environments. This integration allows autonomous systems to make informed decisions, optimize energy use, and maintain safe and efficient operation over extended distances.

In addition to improving safety and reducing human error, autonomous control directly impacts the vehicle's energy performance. By optimizing driving behavior such as acceleration, deceleration, and speed profiles, these systems contribute to more efficient energy utilization. This effect is reflected in the Sankey diagram (Fig. 4), where optimized energy flow results in reduced losses across key components, including the fuel cell system, power electronics, and electric drivetrain.

Furthermore, the integration of intelligent control strategies with the hybrid fuel cell battery system enables more effective energy management, particularly in terms of load balancing and regenerative braking. As a result, the overall system efficiency is improved, providing a closer alignment between the input energy of hydrogen (expressed through LHV) and the useful mechanical output.

3.1 Infrastructure for Autonomous Hydrogen Buses

Fig. 6 represents a conceptual illustration of a smart bus operating in urban traffic [15].



Fig. 6. Conceptual Representation of an Intelligent Bus in Traffic

The Fig. 6 illustrates a smart bus integrating artificial intelligence and camera-based technologies within a public transportation setting. Onboard cameras continuously monitor the environment, supporting functions such as passenger counting, providing a full 360-degree situational view, and tracking driver activity. The inclusion of 5G connectivity enables reliable, real-time data transmission, enhancing operational performance. Additionally, the system can detect pedestrians and obstacles, enhancing safety and situational awareness in urban traffic.

Fig. 7 illustrates the key components of an intelligent transportation system (ITS).

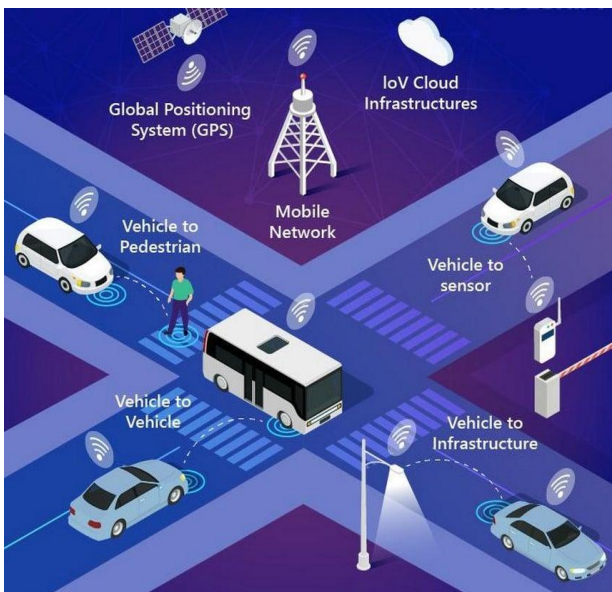


Fig. 7. Functional Overview of an Intelligent Transportation System

Fig. 7 primarily illustrates the interaction among a bus, the surrounding infrastructure, and a central control system. The infrastructure includes traffic lights, sensors, and other monitoring devices, while the control center manages data and coordinates operations. Key enabling technologies depicted in Fig. 7 include Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communication, which allow vehicles to exchange information with their environment and with other vehicles in real time. These capabilities support dynamic traffic optimization, route planning, and safe operation in complex urban scenarios. Fig. 7 highlights the critical role of infrastructure digitalization in enabling high levels of vehicle autonomy, particularly Level 4 autonomy, by ensuring continuous situational awareness and coordinated traffic management.

Fig. 7 illustrates an intelligent transport system that combines digital platforms with physical infrastructure to enhance urban mobility. Core elements include smart traffic lights and GPS-enabled vehicles that gather and analyze real-time data to predict traffic conditions, optimize routes, and dynamically adjust service levels. By utilizing AI for forecasting and planning, ITS improves travel efficiency, supports decision-making for transport planners, and helps maintain smooth and reliable operation of the overall transportation network.

Modern cities require transportation systems that seamlessly integrate multiple modes of travel, including buses, trains, bicycles, and pedestrian pathways, a concept known as multi-modal mobility. Intelligent transport planning facilitates the development of Mobility as a Service (MaaS), enabling users to plan, book, and pay for trips through a single digital platform. Effective urban mobility relies on careful system design, incorporating transit hubs, clear signage, and coordinated services. Examples from cities such as Helsinki and Singapore demonstrate how integrated transportation networks can simplify travel, reduce dependency on private vehicles, and improve overall urban quality of life. A well-designed transport system is essential for ensuring that residents can move around the city efficiently, safely, and conveniently [16].

Such integrated and intelligent mobility solutions also support sustainability goals by reducing traffic congestion, lowering emissions, and promoting the use of public and active transport modes.

4. STRATEGIES FOR EMISSION REDUCTION IN PUBLIC PASSENGER TRANSPORT

Reducing emissions in public passenger transport is a key element of achieving sustainable urban mobility. Modern strategies increasingly rely on FCEBs and autonomous vehicles, which provide zero-emission operation while enhancing safety and operational efficiency. New concepts, such as electric minibuses designed for flexible, on-demand service, enable scalable mobility solutions that complement traditional bus networks. By integrating these technologies into door-to-door transport services, cities can offer personalized, low-emission mobility, reduce reliance on private vehicles, and improve accessibility for all residents. Combined with intelligent transport planning and optimized operational strategies, these innovations support significant reductions in greenhouse gas emissions and contribute to cleaner, more efficient urban transportation systems.

Fig. 8 illustrates the environmental impact of personal versus public transportation. Personal vehicles are a major source of carbon dioxide (CO₂) emissions in households, with private cars often accounting for over half of total household emissions. In contrast, public transit provides a more sustainable mobility option, significantly reducing per-passenger emissions.

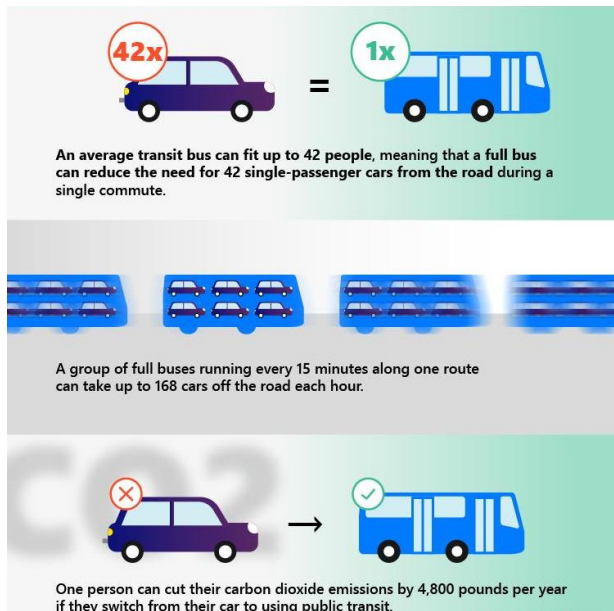


Fig. 8. Public transportation reduces CO₂ emissions

For example, a standard bus carrying up to 42 passengers can replace 42 single-occupancy vehicles on the road, while frequent bus service along a route can remove hundreds of cars each hour. This shift from private cars to public

transportation can reduce individual carbon emissions by thousands of pounds annually [17,18].

Although buses do produce some emissions, their fuel efficiency, measured in person-kilometers per liter, makes them far more environmentally friendly than private cars. For instance, a group of five individuals traveling the same distance in separate cars would collectively emit the equivalent of five units of fuel, whereas using a single bus for the same journey reduces this to roughly one liter. On a larger scale, public transportation systems can cut over 37 million metric tons of CO₂ annually and save approximately more than 4 billion liters of fuel, highlighting the substantial environmental benefits of integrating buses and other transit vehicles into daily urban mobility [19,20].

Autonomous buses are generally deployed in specific operational environments to enhance safety and simplify traffic management. These include dedicated corridors, such as those used in Bus Rapid Transit (BRT) systems, areas with mixed traffic supported by driver-assistance technologies, and geofenced urban zones where vehicle movement is restricted to predefined areas. Operating within these controlled settings helps reduce complexity, minimizes potential conflicts with other road users, and allows autonomous systems to function more reliably [21,22].

4.1 Proposed Concept of a Domestic Electric Minibus

Taking into account the previously discussed considerations, this research proposes a concept designed for a domestically produced electric minibus (eMiniBuS), Fig. 9.

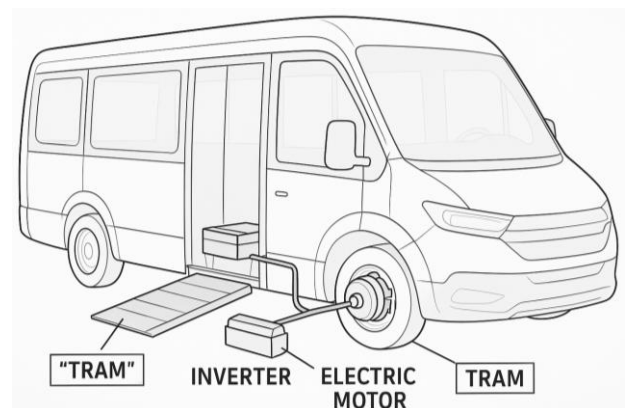


Fig. 9. eMiniBuS concept as proposition

The design is tailored for door-to-door passenger transport in densely populated urban areas, enabling efficient navigation of congested

city streets. The minibus propulsion system is designed to be flexible, capable of operating on electricity as well as alternative fuels such as methane or hydrogen. Additionally, the system can be adapted for autonomous driving, enabling integration into smart city infrastructures and enhancing both safety and operational efficiency.

Public transportation, including buses and electric minibuses, provides a safer and more sustainable travel option compared to private cars. Reducing the number of vehicles on the road lowers emissions, improves air quality, and encourages physical activity among passengers. Integrating flexible, door-to-door minibuses with traditional transit enhances accessibility, supports first- and last-mile connections, and contributes to healthier, more efficient urban mobility.

In countries such as the Republic of Serbia, where CNG infrastructure is already established but hydrogen networks are still underdeveloped, a potential transition strategy for public transport could involve shifting from CNG vehicles to BEBs for urban routes, and eventually adopting FCEBs for longer distances, though key challenges remain, including high investment costs, limited hydrogen production, and regulatory gaps.

5. CONCLUSION

The results confirm that integrating hydrogen propulsion and autonomous technologies significantly improves energy efficiency, operational performance, and environmental sustainability in public transport systems.

Hydrogen FCEBs offer a promising pathway toward sustainable public transportation, combining long operational range with rapid refueling, making them particularly well-suited for demanding intercity or long-route services where BEBs may face limitations.

Future development of hydrogen autonomous buses depends on reducing hydrogen production costs, expanding infrastructure, and establishing a harmonized regulatory framework.

In conclusion, hydrogen fuel cell autonomous buses represent a key technological pathway toward decarbonized and intelligent transport systems, particularly in applications where conventional electric solutions face operational limitations.

The proposed electric minibus concept contributes to sustainable urban mobility by reducing emissions, improving air quality, and supporting public health. Its flexible operation and

potential integration with autonomous technologies can enhance traffic safety and overall transport efficiency.

However, further progress depends on developing appropriate regulatory frameworks to ensure safe and reliable deployment.

Conflicts of Interest

The authors declare no conflict of interest.

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