Energy efficiency analysis of a Fuel Cell Bus model using real scenarios generated by data collection

H. Cărăușan[1,2], B. O. Varga[1,2], D. Moldovanu[1,2], G. Prunean[1,2], T. Oargă[1,2]

[1]Technical University of Cluj-Napoca, Department of Automotive Engineering and Transports, B-dul.Muncii 103-105, Cluj-Napoca, ROMANIA
[2]EMARC – Electric Mobility Applied Research Center, Muncii Bvd. 103-105, Room C205-a

gabriel.prunean@auto.utcluj.ro

Abstract. Modernizing public transportation is crucial given the ongoing call for sustainable mobility. Growing concerns about climate change and the increasingly stringent emissions standards have compelled public transport operators to embrace alternative propulsion vehicles on a broader scale. For the past years, Battery Electric Busses (BEBs) have been the vehicle of choice for public transportation. However, an emerging contender in this sector is arising, the Fuel Cell Electric Bus (FCEB). This paper aims to evaluate the way in which one such vehicle would perform in terms of energy efficiency, while being exploited following an urban scenario generated from collected data.

1. Introduction

The current paradigm has the transport industry at a turning point, in regard to one of the most pressing issues humanity has to deal with. Climate change issues accumulated at an alarming rate during the past decades, causing a major shift in the developmental areas in all sectors. One of the main indicators of this tendency is the alarming rate of growth of the carbon footprint. Unfortunately, society has neglected energy efficiency in favor of rapid development and increased consumption [1]. This has put society on a precarious path that will have critical long-term environmental repercussions for our evolution.

The construction of broad public transportation together with the imposition of traffic limitations is one of the most practical solutions to this issue, in which the transport sector has been one of the main contributors. Several innovative and sustainable transportation options are being proposed as workable substitutes for personal transportation vehicles in order to encourage the adoption of public transportation as a primary transportation solution.

Sustainability in the transportation industry has undoubtedly become a major issue across Europe in light of the current environmental challenges. The European Union has taken a number of actions to solve this problem, such as imposing stronger emission limits and continually updating the fleets of public transportation vehicles [2]. BEBs and FCEBs are two of the most popular solutions for environmentally friendly public transportation in Europe. The way in which these solutions manage and store the energy necessary for propulsion, is where they diverge the most from one another [3-4].

For both storing and delivering the electrical energy needed for propulsion, BEBs generally rely on battery packs with adequate capacity. Although using batteries offers a series of benefits for the the environment, their degradation over time cannot be ignored. This in turn, equates into larger operating costs and more tedious maintenance operations.

On the other side of the spectrum, hydrogen is used by FCEBs in addition to smaller battery packs, as an energy buffer. Fuel cells use hydrogen as a source of energy to produce the necessary electricity for propulsion. By managing energy delivery and storage using hydrogen, this dual-energy strategy lessens the burden on the battery, thus reducing the rate at which they degrade over time, while reducing the total operational costs [3-5].

As a result of Europe's dedication to sustainability in the transportation industry, both BEBs and FCEBs have been adopted, with the latter providing a special benefit in reducing battery-related problems (e.g. in cold regions) and enhancing the long-term viability of sustainable bus transportation. These cutting-edge strategies are essential first steps in tackling the pressing environmental issues.

Given that hydrogen is one of the most effective energy carriers on the market right now, it plays a very important role in this context. It can be obtained in several ways and used in conjunction with fuel cells to store the energy needed to run long-distance electric motors. Right now, the two most common processes for producing hydrogen are steam reformation of natural gas and electrolysis, with the latter being the more ecologically favorable option [6].

There are many different types of fuel cells available, and each has pros and cons of its own. The most popular type of fuel cell is the proton exchange membrane (PEM) fuel cell, which uses an exchange membrane as a solid electrolyte. PEM fuel cells may generate up to 100 kilowatts of power at an efficiency of 40–60% and work within a restricted temperature range of 80–100 °C. In the mobility industry, they are widely used because of their compact size, low weight, and fast startup time. However, PEM fuel cells are susceptible to temperature changes, salt concentration of the water, moisture, and dehydration. Phosphoric acid (PAFC), alkaline (AFC), solid oxide (SOFC) and molten carbonate (MCFC) fuel cell technologies are among the others; but, because of their longer startup times and greater production and operating costs, they are less commonly used in mobility applications [7-9].

Considering the technologies used in FCEBs, as well as the use of hydrogen in propulsion systems, the outlook offers a remarkable energy efficiency perspective, as well as a very viable option to reduce emissions. Because of their alteration in the powertrain, FCEBs are able to go farther than traditional BEBs.

This paper aims to explore sustainable transport solutions and offer an insight into the behavior of a FCEB within a set of scenarios collected from real BEBs used for public transport in the city of Cluj-Napoca. Alongside the refinement process of the model, the extensive simulations carried out using driving cycles generated by real bus and driver data, will be able to offer an energetic estimation with regards to potential hydrogen consumption of such busses in a populated urban framework.

2. Material and Method

The objective of this study is to evaluate the behavioral patterns exhibited by a FCEB when deployed in a public transportation role, inside a densely populated urban setting. The primary metrics under analysis will encompass hydrogen consumption, in addition to other relevant elements such as distance traversed and vehicle velocity. The primary outcome of this study will encompass the energy management patterns and the energy efficiency of the vehicle. The investigation was conducted using AVL Cruise M, a software developed by AVL List GmbH.

To conduct the analysis, an AVL Cruise M simulation was employed to model a vehicle manufactured by Solaris. Solaris has successfully designed and manufactured a flexible public transportation system, available in several construction configurations. The selected construction solution is the Urbino 12, a bus model that is offered in both completely electric and fuel cell iterations. The focus of this study will be on the vehicle's range and hydrogen consumption, which were determined through the simulation of test cycles. Prior to the commencement of the modeling phase, it is imperative to establish and delineate the many structural and functional attributes of the vehicle under consideration. The data is located within Table 1.

Table 1. Main characteristics of the Solaris Urbino 12 Fuel Cell bus [10]

Model	
Urbino 12 Fuel Cell	
Kerb mass	11032 Kg
Maximum authorized mass	19000 Kg
Length	12000 mm
Width	2550 mm
Frontal area	1.97 m^2
Friction coefficient	0.8
Battery power	100 kW
Motor	2 x ZF AVE 130
Motor power	2 x 150 kW
Fuel cell	Ballard HD 60
Range	350 Km
Tank capacity	28 – 37.5 kg H_2

The modeling technique involved a sequence of parametrization procedures. The FCEB exhibits a modular design, wherein each functional component is represented by a separate module. To ensure the acquisition of accurate findings, all elements were simulated according to the specifications provided by the manufacturer. The electric model consists of several key components, including a battery pack, a set of 2 ZF AVE 130 hub-mounted electric motors, a consumer module, and a control functions subsystem. In addition to the aforementioned components, the Urbino 12 Fuel Cell model is outfitted with a Ballard HD60 fuel cell.

The battery pack was designed and arranged based on the output power, voltage, and current specifications, with the aim of achieving a high level of precision. The tractive system comprises two electric motors that are designed based on the actual machinery employed by Solaris and produced by ZF. According to ZF [11] , every motor exhibits a maximum power output of 250 kW, operates at a nominal voltage of 650V, and can sustain a maximum current of 340A. The control functions subsystem encompasses algorithms employed for the regulation of individual motors, with the computational functions responsible for determining the range and performance characteristics of the vehicle. The functions utilized for the implementation of the test cycle are likewise encompassed inside this subsystem. The fuel cell model incorporates the Ballard HD60 fuel cell, together with a specialized mechanism responsible for regulating the energy transfer between the battery and the fuel cell [12]. The model can be observed in Figure 1.

Figure 1. Urbino 12 Fuel Cell model

The outcomes derived from the simulations were produced from authentic data gathered from the operational electric buses within the municipality of Cluj-Napoca. The data obtained from the buses encompasses several factors, including the GPS coordinates of the bus, the velocity of the vehicle, the date and time of the data collection, and additional metrics such as brake lining usage and the total amount of energy charged and discharged.

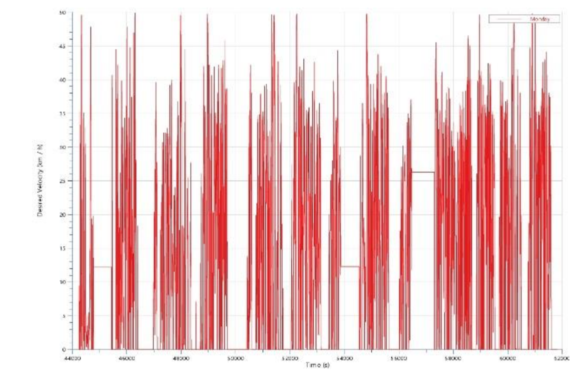
Figure 2. CANedge2 device used for bus data collection

The data for the simulation was gathered utilizing a CANedge 2 device, which had the capability to collect data through the OBD (On Board Diagnostics) connector of the bus. This was achieved by employing an adaptor provided by the maker of the equipment. The device and adapter are seen in Figure 2.

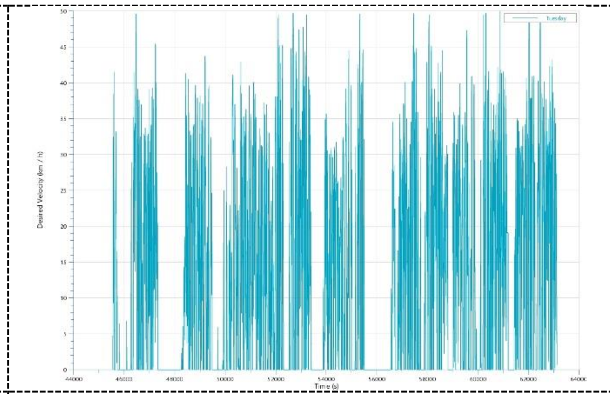
The data collection process may involve two methods: on-site collection using a memory card or utilizing an API (Application Programming Interface) implementation to capture a larger volume of data. The acquired data was subsequently analyzed using Microsoft Excel and put into AVL Cruise M.

The sequences employed in the simulations were gathered consistently on a single bus throughout the course of an entire work week. Therefore, the utilization of decisive data pertaining to the driving profile, vehicle velocity, and vehicle position could enable the recreation of the bus's behavior in real-world scenarios.

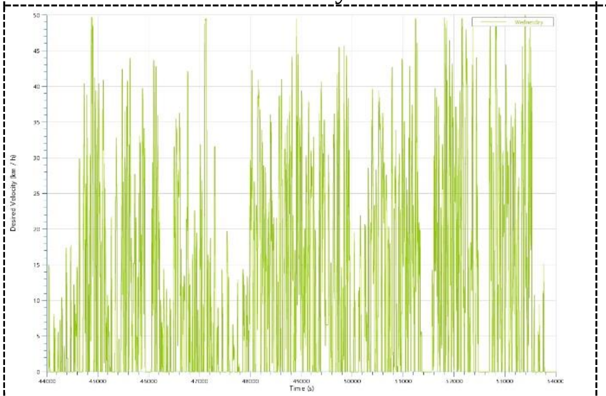
Five driving cycles were generated, one for each workday of the week, using data on time and vehicle speed collected from Line 47 in the Municipality of Cluj-Napoca. The main difference observed between the driving cycles, is the usage rate of the bus. On Monday, the bus is used at its maximum capacity, having only a few breaks for charging and driver changes. As the week progresses, the usage rate of the bus decreases, as it is replaced by other buses covering the same route. The generated driving cycles can be seen in Figure 3.



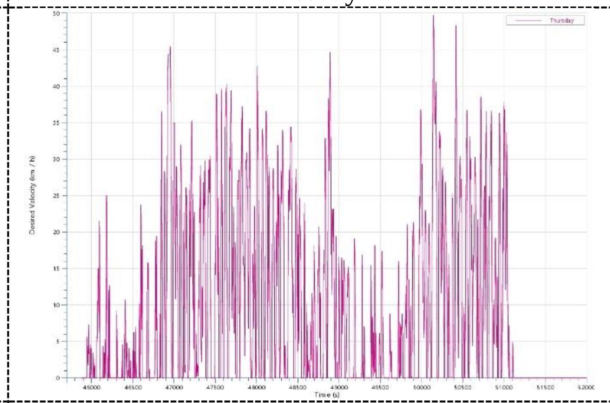
Monday



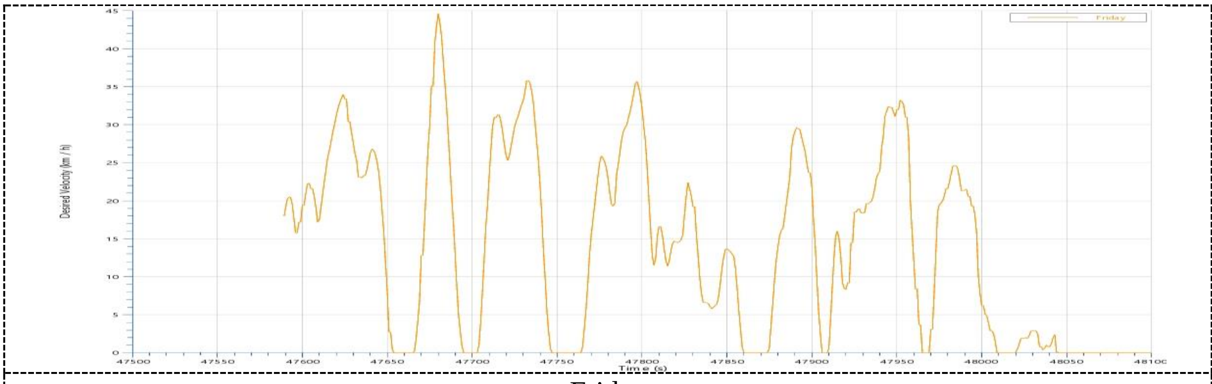
Tuesday



Wednesday



Thursday



Friday

Figure 3. Data generated driving cycles

3. Results and Discussions

The first analysed metric is the total distance travelled in each of the modelled cycles. The main indication of the difference between the travelled distances is the usage rate of the bus. During the first day, the bus is subjected to a series of charge-discharge cycles. As the week progresses, the usage rate of the bus reduces, thus causing the travelled distance to decrease. The total driven distance was calculated by the simulation software, as well as logged from the bus. The difference between the sources have been of less than 2%. The total travelled distance is depicted in Figure 4. The data can be seen in Table 2.

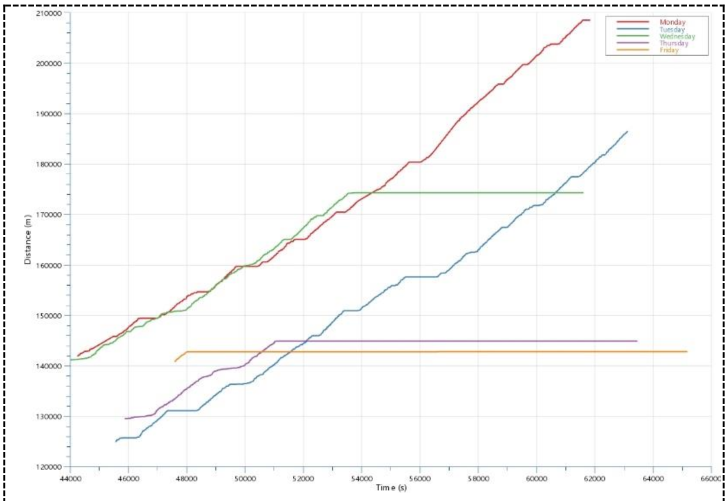


Figure 4. Total distance travelled

Table 2. Total travelled distance

	Simulation case				
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Distance travelled (km)	218.2	196	185.1	148.8	131.5
Average travelled distance (km)			175.9		
Total travelled distance (km)			879.6		

Following the data logging process and the mapping of the data, a steady decrease in distance travelled can be observed. The total travelled distance is of 879.6 km, with an average distance travelled of 175.9 km. On Monday and Tuesday, the evolution of this parameter is relatively steady throughout the day, while on the other days, most of the vehicle exploitation takes place in the first part of the day, the route being served by other electric busses with similar exploitation cycles.

The second metric analysed is the vehicle velocity, captured in the generation process of the driving cycles. The variations observed are due to the driver inputs, as well as being limited by the surrounding traffic conditions. The prime hours were the most noTable time periods in the generation of the drive cycles. The data on average vehicle velocity can be observed in Table 3.

Table 3. Average vehicle velocity

	Simulation case				
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Average vehicle velocity (km/h)	13.6	12.5	12.8	13.2	13.7

The most important parameter resulted from the extensive simulations, is the hydrogen consumption of the bus. This metric is shown via the total mass of hydrogen consumed, as well as via the hydrogen mass flow. The manufacturer states that using the full 37.5 kg storing capacity of the bus, the maximum range would be of up to 350 km. The data gathered from the simulations shows that this range is quite difficult to obtain under real conditions. However, there are a few facts worth mentioning. The tests conducted by the manufacturer, do not take into account the ridership of the busses. In the developed model, the bus was conFigured to be at the maximum carrying capacity, in each of the cycle. Another aspect worth mentioning is the fact that each of the cycles take into account every single decrease in velocity, caused either by the driver's input, or by the external traffic conditions. The strain on the powertrain under these conditions is rather large. In each of the modelled cycle, the longer brakes taken in each scenario, represent a charging cycle of the electric bus. These sort of charging cycles would not be necessary in case of a fuel cell bus. However, the simulation model registers a hydrogen consumption during these passive times, impacting the overall results. The evolution of the consumed hydrogen mass can be seen in Figure 5 and the hydrogen mass flow can be observed in Figure 6, and the data can be observed in Table 4.

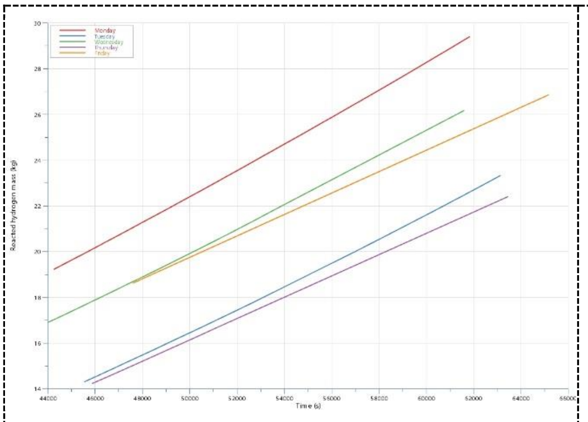


Figure 5. Consumed hydrogen mass

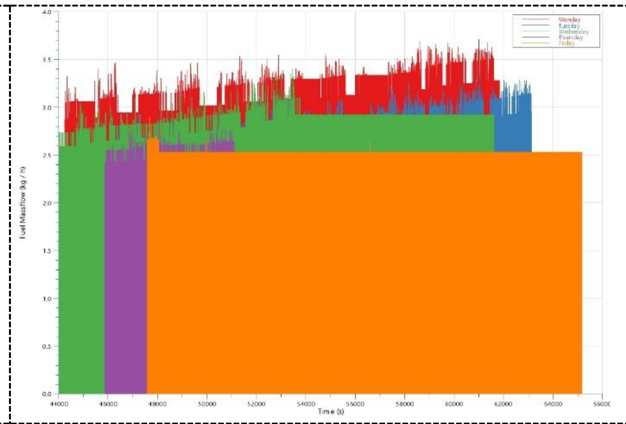


Figure 6. Hydrogen mass flow

Table 4. Hydrogen consumption

	Simulation case				
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Consumed hydrogen mass (kg)	29.4	23.3	26.1	22.3	26.8
Average consumed hydrogen mass (kg)			25.5		
Average hydrogen mass flow (kg/h)	2.08	1.84	1.89	1.67	1.68
Global hydrogen mass flow average (kg/h)			1.83		

4. Conclusions

In view of the aspects mentioned in this paper, as well as the data provided following the comparative analysis of the five driving cycles, the following can be concluded:

- Following the simulations, a series of comprehensive results were discovered. The final results are observable in Table 5.

Table 5. Data overview

	Simulation case				
	Monday	**Tuesday**	**Wednesday**	**Thursday**	**Friday**
Distance travelled (km)	218.2	196	185.1	148.8	131.5
Average vehicle velocity (km/h)	13.6	12.5	12.8	13.2	13.7
Consumed hydrogen mass (kg)	29.4	23.3	26.1	22.3	26.8
Average hydrogen mass flow (kg/h)	2.08	1.84	1.89	1.67	1.68
Average travelled distance (km)			175.9		
Average consumed hydrogen mass (kg)			25.5		
Global hydrogen mass flow average (kg/h)			1.83		
Total travelled distance (km)			879.6		

- The results obtained are specific to the current model and do not represent the overall behaviour of vehicles due to the fact that the model was constructed using broadly available data, and has not yet been validated using an actual vehicle.
- The generated data offers a valuable insight into the everyday usage of a public transport vehicle. The simulation of a fuel cell vehicle within five of such scenarios, allowed to conclude the fact that, unlike a BEB, a FCEB does not require charging cycles throughout the day, being able to easily cope with the harsh requirements of the environment.
- Given the data resulted from the simulations, the use of one such FCEB can be adjusted to the point where with an optimal usage rate, it would successfully be able to cover two consecutive days of usage, only needing to be charged once, every two days.
- The obtained hydrogen consumption values are slightly larger than the ones declared by the manufacturer, in the light of a more demanding series of test cycles, as well as being carried out with the maximum carrying capacity. Given the current exploitation strategy that is in place for BEBs, the integration of such vehicles in the public transport fleet, would require an adjustment of the charging strategy for such vehicles, thus being to offer longer usage time for each individual bus, as well as fewer refuelling stops that can be carried out in non-critical time intervals.
- Given the average travelled distance of 175.9 km, and the average hydrogen mass consumption of 25.5 kg, the general estimate of range with a full tank of 37.5 kg, one FCEB would be able to cover around 258.6 km under the circumstances modelled throughout the simulations. Given the fact that the maximum declared range of one such vehicle is of 350 km, obtained in controlled settings, a FCEB would be more than capable of offering a viable alternative to the BEBs in use today.

Acknowledgements

This paper is supported by European Union's Horizon 2020 research and innovation programme under grant agreement No 101036871, project hOListic Green Airport (OLGA).

References

[1] Nevskaya, M.A.; Raikhlin, S.M.; Vinogradova, V.V.; Belyaev, V.V.; Khaikin, M.M. A Study of Factors Affecting National Energy Efficiency. Energies 2023, 16, 5170. https://doi.org/10.3390/en16135170

[2] Pietrzak, K.; Pietrzak, O. Environmental Effects of Electromobility in a Sustainable Urban Public Transport. Sustainability 2020, 12, 1052. https://doi.org/10.3390/su12031052

[3] Abu-Eisheh S., Kuckshinrichs W., Dwaikat A. (2020). "*Strategic Planning for Sustainable Transportation in Developing Countries: The Role of Vehicles*", Transportation Research Procedia, Volume 48, Pages 3019-3036, ISSN 2352-1465

[4] Skeete J. P., Wells P., Dong X., Heidrich O., Harper G. (2020). "*Beyond the EVent horizon: Battery waste, recycling, and sustainability in the United Kingdom electric vehicle transition*", Energy Research & Social Science, Volume 69.

[5] Fakhreddine, O.; Gharbia, Y.; Derakhshandeh, J.F.; Amer, A.M. Challenges and Solutions of Hydrogen Fuel Cells in Transportation Systems: A Review and Prospects. World Electr. Veh. J. 2023, 14, 156. https://doi.org/10.3390/wevj14060156

[6] Mo, T.; Li, Y.; Luo, Y. Advantages and Technological Progress of Hydrogen Fuel Cell Vehicles. World Electr. Veh. J. 2023, 14, 162. https://doi.org/10.3390/wevj14060162

[7] Mo, S., Du, L., Huang, Z. et al. Recent Advances on PEM Fuel Cells: From Key Materials to Membrane Electrode Assembly. Electrochem. Energy Rev. 6, 28 (2023). https://doi.org/10.1007/s41918-023-00190-w

[8] Efficiency of Fuel Cell: Calculation Formula & Equation (2021) https://www.linquip.com/blog/efficiency-of-fuel-cell/

[9] U.S. Department of Energy. (2016). *"Comparison of Fuel Cell Technologies"* . Energy Efficiency & Renewable Energy https://www.energy.gov/sites/default/files/2016/06/f32/fcto_fuel_cells_comparison_chart_apr2016.pdf

[10] Solaris Urbino 12 Catalogue https://www.solarisbus.com/public/assets/content/pojazdy/2021/2021/EN_Zeroemisyjne_1920_x_1080.pdf

[11] ZF Product Overview https://www.zf.com/products/media/en/pim/tu___axle___transmission_systems_for_buses___coaches/chassis_7/TU_Product_Overview_202206_DE_EN_LowRes_Opt_pdf.pdf

[12] Iclodean C., Cordoș N., Todoruț A. (2019). “*Analysis of the Electric Bus Autonomy Depending on the Atmospheric Conditions”*. Energies.