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E-MOBILITY DEVELOPMENT STRATEGY IN PUBLIC URBAN TRANSPORT-INTRODUCTION OF ARTICULATED ELECTRIC BUSES

Keywords

The articulated electric bus
E-mobility development strategy
Public transport
Energy efficiency
Ecological benefits
Economic feasibility

Abstract:

Electric buses have a steady trend of increasing usage in many cities in Europe and the world. In the previous period, electric buses with a standard length of 12m were the most represented, while articulated buses of 18m had a lower representation due to poorer technical and operational performance (lower passenger capacity, limited autonomy of movement, long charging time at the depot or terminus...) compared to conventional articulated buses. With the development of new generations of electrical energy storage systems (batteries, supercapacitors) and fast charging systems using high-power chargers, articulated electric buses have become increasingly competitive with conventional buses. In the coming period, one of the E-mobility development strategies related to public urban transport is the introduction of articulated electric buses instead of conventionally driven buses, primarily on central city lines as well as on the lines of the BRT system.
The paper will present the results of the trial operation of the Higer UC 18 articulated electric bus on city line No. 31 (Studentski trg-Konjarnik) in Belgrade, which was carried out in October 2022, from the aspect of energy efficiency and environmental advantages. Through a case study of the replacement of articulated buses with diesel engines currently operating on line no. 31 with articulated electric buses, an analysis of the economic feasibility of introducing articulated electric buses into operation will be carried out.

1. INTRODUCTION

The transport sector has a significant place in meeting the needs of society in the transport of goods and passengers, but at the same time, it is also a source of emissions of harmful gases and carbon dioxide as a result of the burning of fossil fuels. The use of fossil fuels is directly proportional to the industrial and economic development of a country, region, or city [1]. The emission of carbon dioxide (CO2) originating from the transport sector in 2020 amounted to 24% [2], as a result of the combustion process, primarily of oil derivatives (diesel fuel, gasoline), which has a share of 57% of the total oil consumption at the global level [3]. In the European Union, heavy-duty vehicles, such as trucks, coaches, and buses, are responsible for about 6% of total greenhouse gas emissions [4]. The bus subsystem of public urban transport as part of the transport system in cities is one of the most important segments of urban mobility in cities. Diesel-powered buses are still the most prevalent in public transport systems. They emit gases (CO, CxHy, NOx, PM...) that are harmful to human health and carbon dioxide that causes the greenhouse effect [5]. Many cities around the world are replacing their existing fleets of conventionally fueled city buses with electric buses to reduce the negative effects of pollutant emissions on the environment and public health. The application of buses for public city transport with zero emissions, which includes electric buses in the European Union, should additionally reduce the level of emissions of harmful gases from traffic in cities and contribute to the strategy of using vehicles with zero emissions in cities, which is planned after 2050 [6, 7]. The Clean Vehicle Directive 2019/1161 entered into force in August 2021 and is binding on EU member states. It defines representation in the procurement of M3 class buses with low and zero emissions for the period until December 31, 2025, and from January 1, 2026, to December 31, 2030 [8]. An important goal of using electric buses is to increase energy efficiency in the passenger transport sector. Electric buses have better energy performance compared to conventional technologies [9,10,11].

2. PRESENTATION OF PREVIOUS PRACTICE IN THE APPLICATION OF ARTICULATED BUSES ON ELECTRIC DRIVE IN THE WORLD

Currently, almost all world bus manufacturers have electrically powered buses of different lengths in their product range: midi (8-9 m), standard (11-13 m), articulated (18-19 m), and double-articulated (24-27 m), which have become part of the standard offer on the bus market [12]. Electric buses fall into the category of zero-emission vehicles now available on the market and are gaining an increasing share of purchases from cities and public transport companies. At the beginning of 2022, 9,354 electrically powered buses were registered in Europe, of which only 2% were buses over 18 m in length [13]. The rapid development of battery technologies and supercapacitors for the storage of electrical energy, the system for fast charging of vehicles that have been present in the last 5-6 years have influenced that, in addition to the electric buses of standard length, which have the largest representation, electric buses with a length of 18 m (articulated) and 24m (two articulated), which make them adequate competition for buses of the same type with conventional drive. Depending on the concept of the articulated electric bus, the most common electrical energy storage systems are batteries: LTO (lithium titanate) with a capacity of 125-170 kWh, LFP (lithium iron phosphate) with a capacity of 480-700 kWh, as well as supercapacitors with a capacity of more than 100 kWh.

LFP batteries are only suitable for charging with lower powers, meaning these buses must be charged overnight at the depot [14]. LTO batteries and supercapacitors accept high charging powers and are used for fast charging at the terminals. Fast 400-600 kW power chargers are used to charge vehicles with LTO batteries or supercapacitors. LFP batteries used in electric articulated buses are charged in depots (night charging) using chargers with a power of up to 150 kW. The reduction of the empty vehicle weight allowed the capacity of the number of passengers that can be transported to be 140-145 passengers, which is about 10% less compared to the diesel-powered articulated bus. The possibilities of using articulated electric buses in Europe were realized for the first time in May 2013 in Geneva (Switzerland) with the "TOSA" project, when the company TPG Geneva started operating 11 fully electric buses manufactured by "Hess", line no. 7 (Airport - Hospital via CFF main station). Considering that these are articulated vehicles that use supercapacitors to store electrical energy, recharging is done via pantographs at the terminals but also at some stations along the route [33]. The power of the chargers at the terminals is 200 kW, which allows a charging time of 3-4 minutes. Chargers with a power of 400 kW were installed along the route at a total of 12 stops. The charging time is about 15 seconds during the regular wait for the vehicle at the station. The average consumption is 2.6 kWh/km [15]. The Chinese bus manufacturer "BYD" presented an 18m-long articulated electric bus at the Houston (USA) fair in October 2014, which used an LFP battery with a capacity of 480 kWh as a storage system. The charging time with the 80 kW plug-in charger was about 5 hours. The transport capacity of the vehicle was 120 passengers [16]. As part of the Zeus project, in Barcelona on the H16 line, exploitation began in April 2016 with two Solaris Urbino 18 articulated buses. The battery capacity was 125 kWh. Using a mobile pantograph mounted on the roof of the vehicle, fast charging was performed with 400 kW chargers installed at the terminus as well as with a 50 kW slow charger installed in the depot. The number of seats in the vehicle was 135 passengers [17]. An example of good practice in the application of a large number of articulated electric buses is the city of Eindhoven (Netherlands), wherein 2016 the first 43 electric articulated buses manufactured by VDL were put into operation, which had the concept of "convenient-fast charging" in the depot and central terminus, using a movable pantograph on the roof of the vehicle [13]. The successful application of electrically powered articulated buses was realized in 2018 in Amsterdam on line No. 316 (Amsterdam-Volendam-Edam) with 10 articulated buses operated by the manufacturer VDL. The average electricity consumption was 1.4 kWh/km, while the average charging time was 12 minutes with a 450 kW charger [18]. The capacity of the LTO battery is 170 kWh. In March 2019, the first 13 articulated electric buses were put into operation in Osnabruck (Germany) on Metrobus line M1. In 2020-2022.year, 49 more articulated electric buses operating on lines M2, M3, and M4 were acquired. A total of 62 articulated electric buses manufactured by VDL provide 60% of the transport work on the network of lines in Osnabruck [19]. The bus subsystem in Mexico City is one of the largest in the world, with approximately 22,300 buses in operation. In 2021, 10 articulated electric buses manufactured by "Yutong" [13] were put into operation on BRT line No. 3, so at the beginning of 2023. year there will be 60 articulated electric buses in operation [20]. Since December 2019, the city of Nantes (France) has put into regular operation 22 fully electric buses of the manufacturer "Hess" with a length of 24.5 m, which operate on the BRT line "Busway". Average electricity consumption is in the range of 1.7-2.5 kWh/km. The charging time is 4.5 minutes and is enabled via a fast charger with a power of 600 kW [21]. LTO battery capacity 130 kWh. Positive experiences in the exploitation of bi-articulated buses in Nantes on the BRT line were the inspiration that some cities in Europe and the world (Barcelona, Amsterdam, Athens, Prague, Istanbul, Bogota, plan to introduce articulated electric buses 18-24.5 m on BRT lines, by participating in the EC funded project EBRT-2030 [22].

3. TRIAL OPERATION OF THE ARTICULATED ELECTRIC BUS IN BELGRADE

Testing of the articulated bus Higer 18 UC Electric bus in the conditions of exploitation in JKP GSP "Belgrade", which was carried out in the period 29.9.-5.10.2022. represents a joint project of GSP "Belgrade" and Consortium CHARIOT Motors a.d. , 10 Tsar Osloboditel Blvd., 1000 Sofia, Bulgaria PIB BG202659250, I DAT Holding d.o.o. Belgrade [23]. The trial test of the Higer 18 UC Electric bus is important for assessing the possibility and justification of using this bus concept for public city transport in Belgrade. The acquisition of new electric-powered buses and their significant presence in the PT system represents the policy of developing E-mobility in Belgrade, which together with the trolleybus and tram subsystem of public urban transport and the affirmation of non-motorized movement (cycling, pedestrian zones) should contribute to improving the quality of the environment in Belgrade [24].

3.1. Aim, space, methodology, and period of the trial test

The trial operation aims to assess the technical-operational performance of the Higer 18m UC electric bus (electricity consumption, charging time, vehicle-dynamic characteristics, and ergonomic characteristics...). Considering that at the terminal SRC Milan Gale Muskatirovic, there is a charger for fast charging used by E-buses operating on the EKO2 line, for the test with the articulated Higer 18 UC Electric bus, an extended line No.31-test was established (SRC Milan Gale Muškatirović-Konjarnik) to more realistically compare the technical performance with diesel-powered buses operating on the existing route 31 (Studentski trg-Konjarnik).

Line No. 31, the central city line, from the point of view of environmental requirements (emissions, noise) is very suitable for replacement with E-buses. It is the only line with diesel buses that currently runs along the central corridor: The Slavia-Kralja Milana-Trg Republike. The average length of the line is 7.3 km. There are 15 stops on line 31 in direction "A" and 16 stops in direction "B". Line No. 31-test has an average length of 9.2 km. The number of stations in direction "A" is 20, and in direction "B" is 21. The spatial position of the routes of lines No. 31 and 31-test is shown in Figure 1.

Figure 1. Routes of line No. 31-test and line No. 31

Line No. 31-test is characterized by the presence of longitudinal ups and downs on certain sections of the route. They are especially pronounced on the section along Franska Street, Oslobodjenja Boulevard, and Ustanička Street. Figure 2 shows the geometric characteristics of the route of line No. 31-test.

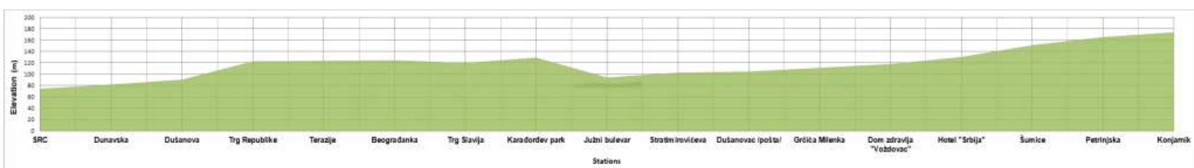

Figure 2. Geometric characteristics of the route of line No. 31-test

During the test on line No. 31-test, the vehicle was evenly loaded with a load (sandbags) with a total mass of about 4500 kg, which simulates an average load of 66 passengers (Figure 3). During the test, there were 3-4 members of the expert committee in the vehicle who were present throughout the test [23].

Figure 3. Loading the E-bus with sandbags

The bus stopped at all the stations along the route, which simulated the real number of acceleration cycles, driving and braking constants, and stopping at the station. The results of measuring the electricity consumption of Higer 18m UC electric, expressed in kWh/km, were performed for each half-turn of operation (Direction "A", directionn "B") in different periods of the day (peak load, intermediate load, with and without using the system for cooling the passenger compartment (Air-Condition).

Electricity consumption was measured:

• By reading SOC (State of charge) values, mileage status, and time from the dashboard of the E-bus at the beginning and end of each trip, based on which the approximate value of the consumed electricity from the supercapacitor was calculated for each trip.

• Acquisition of data related to the current values: supercapacitor SOC charge level, voltage, current, vehicle speed, accelerator, and brake pedal positions, via S-CAN and V-CAN E-bus network. (Figures 4 and 5).

Figure 4. Laptop computer for data acquisition

Figure 5. Connectors for S-CAN and V-CAN E-bus network

Considering that data acquisition: SOC, current strength, voltage via V-CAN and S-CAN E-bus network is performed at an extremely short time interval of 0.1 s, the processing of the downloaded data achieves a higher precision of the results compared to the first method. The differences in the obtained results of electricity consumption expressed in kWh/km are up to 5%, which makes the first method simpler with sufficient accuracy for processing a larger measurement sample than the methodology where the results of electricity consumption are obtained by processing data downloaded via S-CAN and V-CAN E-bus network. The test with the Higher 18m UC electric articulated bus was carried out in the period September 29-October 5, 2022. years. In the same period, the operation of the Solaris Urbino 18 buses operating on the existing line No. 31 was analyzed from the aspect of diesel fuel consumption. (Table 1).

Table 1. Test execution plan

Examination day	Line	Line description	Factor of weight	Vehicle to be compared
1,2,3,4,5,6	Line 31-test: (SRC M.G. Muskatirovic-Konjarnik) Line 31 (Studentski trg-Konjarnik)	Radial, urban, with distinct ascents	High	Higer 18 UC E-bus Solaris Urbino 18 (Euro 5)

3.2. Technical characteristics of the bus Higer 18 UC Electric bus

The low-floor bus Higer 18 UC Electric bus (Figure 6) is intended for the transportation of passengers on city lines. The vehicle meets all requirements regarding homologation for the EU market according to WVTA (Whole Vehicle Type Approval). The technical characteristics of the electric bus Higer (Chariot) 18m UC Electric bus are shown in Table 2.

Table 2. Technical characteristics

Higer 18 UC Electric bus
Dimensions: (L, W, H): 18.090 x 2.550 x 3300 mm
Curb weight: 19,100 kg
Number of seats: 44+1
Number of standing places: 95
Number of doors: 4
Maximum speed: 70 km/h
Drive electric motor:
Dana TZ488XSPE352WH-E,
permanent magnet, central position
Max. power of the driving electric motor: 350 kW
Max. torque: 3700 Nm
Controller and management: Higher control system
Supercapacitor: AOWEI
Capacity: 108 kWh
Charging time: 3-10 min

Figure 6. Higer 18 UC Electric bus

The basic characteristics of fast chargers installed at the line terminal are shown in Table 3

Table 3. Technical characteristics of the charger

Input Voltage	3x380 V (AC)
Max. Power	400 /600 kW
Max. Output current	500/800 A (DC)
Max. Output Voltage	750 V (DC)
Charging efficiency	97%
Height of the pylon	4.5-4.6 m

The chargers are connected to the AC distribution network, via substations located near the chargers. The high power of the charger guarantees an average charging time of 3-10 minutes for the 108 kWh supercapacitor built into the E-bus Higer.

4. RESULTS OF THE RESEARCH

From the point of view of the test run of the Higer 18m UC electric bus, the following especially were examined:

- driving cycle characteristics
- travel time and achieved transport speeds
- electricity consumption, expressed in kWh/km
- charging time at SRC M.G Muskatirovic terminus

• energy efficiency compared to diesel-powered buses
• environmental advantages compared to diesel-powered buses.

4.1. Characteristics of the driving cycle on line No. 31-test

Considering that the route of the line is located in the central city area, passing through corridors (Dusanova, Francuska, Kralja Milana, Slavija Square, Oslobodjenja Boulevard, Ustanicka) with high traffic intensity, a large number of traffic lighted intersections, one of the characteristics of the driving cycle is relatively low transport speeds. Based on the results of measuring travel time by direction for each half-turn, it follows that the average transport time in direction "A" (SRC-Konjarnik) is 00:39:15 while in direction "B" (Konjarnik -SRC) 00:39:33, i.e. transport speeds of 14.1 km/h and 13.8 km/h were obtained. Figure 7 shows the achieved transport speeds by achieved turn and directions.

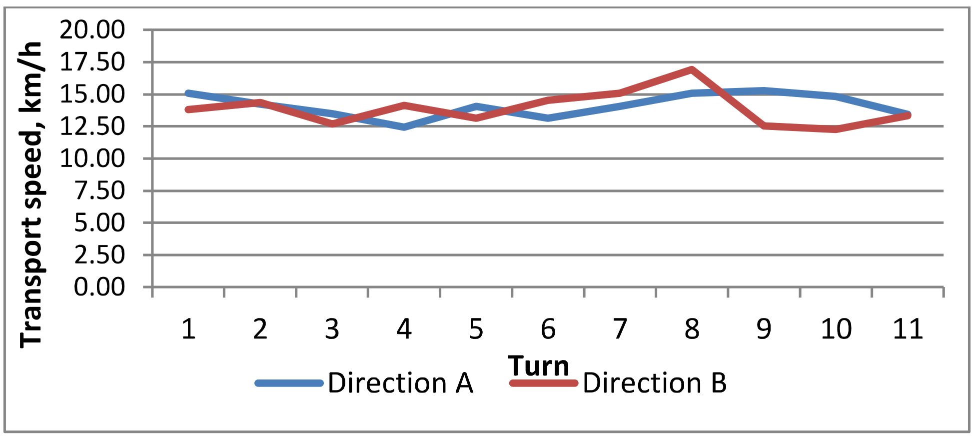

Figure 7. Achieved transport speeds

An example of a drive cycle recorded on October 3, 2022, in direction "B" (Konjarnik-SRC M.G Muskatirovic) in the period from 11:58 to 12:42 is shown in Figure 8.

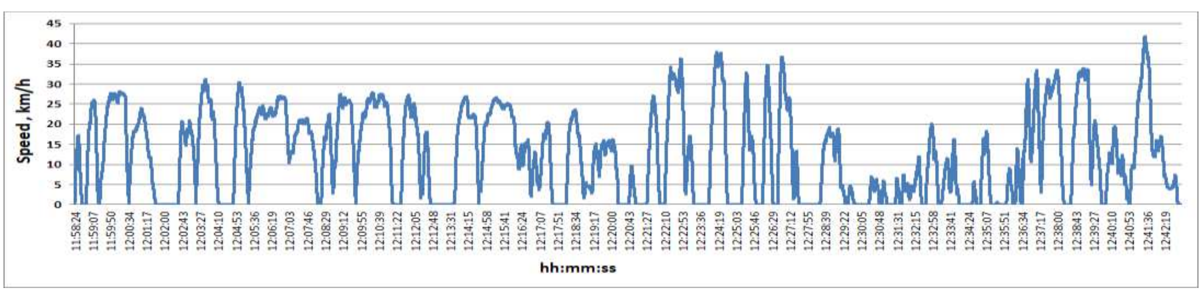

Figure 8. Driving cycle on line no. 31-test Konjarnik-SRC M.G. Muskatirovic

Based on the shown driving cycle, the transport speed was 12.5 km/h. On the largest part of the route, the maximum speeds achieved are up to 30 km/h [23].

4.2. Electricity consumption of Higer 18 UC on line no. 31-test

Electricity consumption represents one of the most significant operational indicators of E-bus operation on the route, which allows for comparison of energy efficiency with buses that use other types of propulsion energy (diesel, CNG), calculation of costs for consumed electricity, assessment of real autonomy of movement with one charging, etc. Table 4 shows the results of the measured electricity consumption of the E-bus Higer 18 UC in the operating mode when the air conditioner was not used.

Table 4. Measured values of electricity consumption

Direction "A" number of measurements (ride)	Consumption kWh/km	Direction "B" number of measurements (ride)	Consumption kWh/km	Consumption Average (A+B)/2 kWh/km
1	2.114	2	0.678	1.396
5	2.103	4	0.727	1.415
7	2.280	8	0.870	1.575
9	2.245	10	0.814	1.529
13	2.435	14	0.660	1.547
15	1.923	16	0.828	1.375
17	2.241	18	0.690	1.465
19	2.352	20	0.791	1.572
	2.192		**0.752**	**1.472**

In the direction "A" the average electricity consumption is 2.192 kWh/km with a standard deviation of ±0.160 kWh/km. The average measured electricity consumption in direction "B" is 0.752 kWh/km with a standard deviation of ±0.08 kWh/km. If we look at the average electricity consumption for both directions for line No. 31-test, it amounts to 1.472 kWh/km with a standard deviation of ±0.081 kWh/km. It is observed that there is a significant difference in the consumption of electricity observed by directions as a consequence of the different geometric configurations of the line's route. In the direction "A", sections of the route with climbs dominate, where a higher engaged power of the propulsion system is required to overcome the resistance of the E-bus movement, compared to the direction "B", where sections with longitudinal drops dominate, where the utilization of regenerative braking is significantly higher vehicles when the drive system works in generator mode and realizes the return (recovery) of electrical energy to the supercapacitor. The test drives were carried out during two characteristic periods of vehicle operation in public city transport, the off-peak period and the afternoon rush hour. Considering that the vehicle was loaded with a constant mass, the influence of the duration of the drive, which in direction "A" was from 35 to 45 minutes and in direction "B" from 33-45 minutes, did not significantly affect the consumption of electricity E- bus. This is explained by the fact that when the E-bus stops due to traffic congestion, at a traffic light, or a station..., the engaged power is minimal and amounts to only 0.7 to 1.4 kW, which is necessary for the operation of light signaling, displays, and dashboard.

An example of data acquisition from the S-CAN network is the display of the measured current values of the electric current and voltage of the supercapacitor for ride no. 17, which was realized on October 3 in the period from 11:13:50 to 11:45:01 in the direction of "A" (Figure 9) [23].

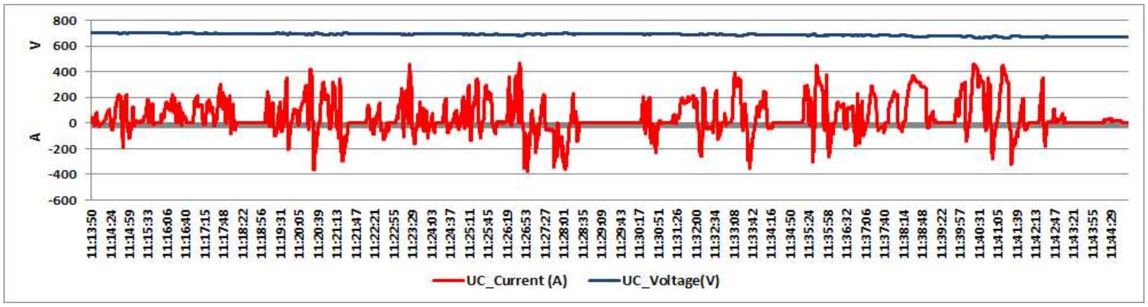

Figure 9. Current values of the supercapacitor, current and voltage for line No. 31-test, direction "A" Konjarnik-SRC M.G Muskatirovic, October 3, 2022, 11:13-11:45

The maximum measured value of the current in the drive mode is 468 A, while the maximum recovery current is -369 A. By processing the data taken from the S-CAN network of Higer 18 UC Electric bus, October 3, 2022, for direction "A" 11:13-11:45 and direction "B" 11:50-12:30 the results are obtained which are shown in Tables 5 and 6 [23].

Table 5. Energy balance of Higer 18 UC Electric bus, Direction "A", 11:13-11:45

Ep, kWh	24.567
Er, kWh	-7.372
λ_r , %	30.0
ΔE, kWh	17.195
L_a, km	7.94
E_{ebus}, kWh/km	**2.166**

Table 6. Energy balance of Higer 18 UC Electric bus, Direction "B", 11:58-12:42

Ep , kWh	14.997
Er, kWh	-8.787
λ_r , %	58.5
ΔE, kWh	6.210
L_b , km	9.25
E_{ebus}, kWh/km	**0.671**

E_p-taken electrical energy from the supercapacitor
E_r- returned electrical energy to the supercapacitor
λ_r – recovery efficiency

$L_{a,b}$ – length of line, Direction "A" and "B"
ΔE- the difference between the taken and returned electrical energy to the supercapacitor
E_{ebus} – electricity consumption of E-bus

Tables 5 and 6 show the level of recovery electricity generated in the braking and deceleration phases. In Direction "B" the recovery efficiency is 58.5%, while in Direction "A" it is 30.0%. The higher level of achieved recuperation in direction "B" is the result of the configuration of the route, i.e. the presence of slopes as well as greater intensity and frequency of braking.

4.3. Summary of electricity consumption Higer 18 UC on line no. 31-test

Based on the analysis of the average electricity consumption of the Higer 18 UC Electric bus on line No. 31-test in operating modes without using the Air conditioning system (AC) and heating vehicle systems (HV), with the use of the AC system and with the use of the heating vehicle system are given in Table 7 [23].

Table 7. Electricity consumption of Higer 18 UC Electric bus with and without using an AC and HV system

	E_{ebus} kWh/km	$\eta_{ch.}$ %	**E_{ebus}' kWh/km**
AC-off, HV-off	1.472	97	1.517
AC-on	1.810	97	1.865
HV-on	2.422	97	2.496

$\eta_{ch.}$ – charger efficiency, %
E_{ebus}' – consumption of E-bus included electrical losses in the charging phase

The significant impact of the operation of the cooling system and especially the heating system of the passenger compartment of the E-bus on the increase in electricity consumption of the Higer 18 UC Electric bus is evident. The heating system increases consumption by 64.5%, while the passenger compartment cooling system increases consumption by 22.9%. When analyzing the electricity consumption of the E-bus, the electrical losses that occur in the fast charger during charging should also be taken into account. Modern chargers have a charging efficiency of around 97%.

4.4. Analysis of the autonomy of movement of the Higer 18 UC on line no. 31-test

Based on the measured values of electricity consumption of the Higer 18 UC Electric bus in characteristic operating modes (with/without air conditioning system) and based on static and dynamic elements of line No. 31-test, it is possible to estimate the real autonomy of the E-bus operation with one charge of the supercapacitor, expressed through the number of turns on the line and the number of kilometers traveled, as shown in Table 8 [23].

Table 8. Expected E-bus autonomy

	E_{ebus} kWh/km	$2L_s$ Km	ΔE kWh	E_{uc} kWh	Number of realized turns	Mileage km
AC-off., HV-off	1.472	18.4	27.08	108	3.5	64.4
AC-on	1.810	18.4	33.30	108	3.0	55.2
HV-on	2.422	18.4	44.56	108	2	36.8

L_s – the average length of line No. 31-test, km

E_{uc} – electrical capacity of the supercapacitor, kWh

4.5. Analysis of the charging time of the Higer 18 UC electric bus

Charging of the E-bus during operation on line No. 31-test was carried out at the terminus of SRC Milan Gale Muškatirović, on the existing fast charger with a power of 400 kW. A view of the charging phase of the Higer 18 UC Electric bus is presented in Figure 10.

Figure 10. Charging phase of Higer 18 UC electric bus

The presentation of the required charging time expressed in minutes (mm: ss) required to charge the supercapacitor from the SOC value at the moment of arrival at the terminus to 99/100% SOC is shown in Table 9 [23].

Table 9. Charging time of the Higer 18 UC Electric bus at the terminal SRC

number of measurements (runs)	SOC_d %	SOC_k %	ΔSOC %	Time required for charging mm:ss
1-2	74	99/100	26	8:30
3-4	71.1	99/100	28.9	8:10
5-6	73.6	99/100	26.4	8:16
7-8	71.4	99/100	28.6	8:04
9-10-11-12	35.4	99/100	64.6	12:15
13-14	64.2	99/100	35.8	8:45
15-16	74.1	99/100	25.9	8:01
17-18	68.1	99/100	31.9	8:40
19-20	68.4	99/100	31.6	8:48

SOC_d – at the beginning of charging, %
SOC_k – at the end of charging, %

Charging of the E-bus was performed after each completed turnaround on line No. 31-test, except in the case of realization of runs numbered 9, 10, 11, and 12 when two turnarounds were completed on the line. The charging time depends on the degree of discharge, i.e. the current value of the voltage of the supercapacitor and the value of the current from the charger. The initial charging current is about 500 A and it decreases during the charging phase depending on the supercapacitor voltage reached. The average charging time was 8:24 minutes. The measured charging time after two revolutions was 12:15 minutes. Given that the average E-bus charging time is less than 10 minutes per completed turn, in practice it would not have an impact on the implementation of the planned timetable, where the planned waiting times at the terminus are 5 minutes per half turn. It should be noted that the Higer 18 UC Electric bus can also be charged with a 600 kW fast charger, with an initial charging current of 800 A. In that case, the required charging time would be significantly shorter compared to a 400 kW charger and would amount to about 5 minutes for one full turn.

4.6. The energy efficiency of Higer 18 UC Electric bus

One of the most significant advantages of using electric buses is their greater energy efficiency compared to buses that use conventional fuels (diesel, KPG). The electric motor in the E-bus has a higher degree of a useful effect than the IC motor and the possibility of operating in generator mode during the braking phase of the E-bus. Table 10 presents the consumption of diesel fuel for Solaris Urbino 18 articulated buses (Euro 5) that operated on the existing route No. 31 (Studentski trg-Konjarnik) in the period 26.9.-30.9.2022. year [23].

Table 10. Diesel fuel consumption for Solaris Urbino 18 buses on line no. 31

Garage	26.9.2022			27.9.2022			28.9.2022			29.9.2022			30.9.2022		
number	Km	L	L/100km	Km	L	L/100km	Km	L	L/100km	Km	L	L/100km	Km	L	L/100km
3116	265	177	66.8												
3112	197	135	68.5										180	100	55.6
3197	262	166	63.4	262	172	65.6				262	170	64.9			
3136				290	190	65.5	258	169	65.5						
3195				186	118	63.4	180	110	61.1	186	125	67.2			
3106							236	164	69.5						
3103										203	140	69.0			

In the mentioned period, the outside temperatures were between 13 ℃ and 23 ℃, so the vehicle's air conditioning system was not used, which in that case would have an impact on diesel fuel consumption. The average consumption of diesel fuel for Solaris Urbino 18 buses in the observed period was 65.07 L/100km. If the consumption of diesel fuel expressed in L/100km is shown in kWh/km to compare the energy balance with the electricity consumption of the E-bus, the results shown in Table 11 are obtained.

Table 11. Comparative view of energy efficiency on line No.31-test and line No.31

Drive Type	Average consumption kWh/km
Higer 18 UC Electric bus	1.472
Solaris Urbino 18 (Euro 5)	6.507

Based on the average energy consumption for city articulated buses, it follows that the Higer 18 UC Electric articulated bus has more than 4 times the energy efficiency of the Solaris Urbino 18 articulated bus.

4.7. Analysis of the environmental performance

From an environmental point of view, electrically powered buses are classified as zero-emission vehicles. This practically means that during operation, the vehicle's propulsion system does not emit harmful products such as CO (carbon monoxide), CxHy (hydrocarbons), NOx (nitrogen oxides), PM10 (suspended microparticles), there are no local emissions of CO2 (carbon dioxide), but it is indirectly present at the level of the wider environment, i.e. state level, given that 70% of electricity production in the Republic of Serbia comes from thermal power plants. The environmental advantages of using the Higer 18 UC Electric bus compared to Solaris Urbino 18 diesel buses (Euro 5) in the example of line No. 31 and line No. 31 test are shown in Table 12. The emission results obtained are shown on an annual basis for one vehicle. assuming that the vehicle exceeds 70,000 km [23].

Table 12. Comparative view of the ecological performance of articulated buses Higer 18 UC Electric bus and Solaris Urbino 18 (Euro 5)

Pollutant	Higer 18 UC Electric bus kg/per year	Solaris Urbino 18 (Euro 5) kg/per year
CO (carbon monoxide)	0.0	252.63
CxHy (carbon-hydrogen),	0.0	77.49
NOx (nitrogen-oxides),	0.0	336.84
PM_{10} (micro-particles)	0.0	3.36
CO_2 (carbon dioxide)	88340	143724

When comparing the CO2 emission, it is higher by about 62.6% for the Solaris Urbino 18 diesel-powered bus (Euro 5). The monetary value of generated emissions as an impact on human health and removal of the consequences of air pollution can be expressed according to Directive EC/33/2009 [25].

4.8. The level of emitted noise

The Higer 18 UC Electric bus is characterized by extremely quiet operation, especially at low speeds, where the drive system of the E-bus is the dominant source of noise. At low speeds, the E-bus is equipped with a system for emitting a characteristic sound that should warn passers-by (elderly people, people with impaired hearing...), especially in the area of pedestrian crossings and stops where the vehicle is in the immediate vicinity. The E-bus has a lower noise level compared to diesel buses by at least 11% [11].

5. CASE STUDY

The economic effects of the application of the Higer 18 UC Electric bus can be shown through a "case study" of the analysis of the total costs of exploitation in the entire life cycle (LCC), which would refer to line No. 31, is, to the replacement of existing articulated diesel buses with articulated electric buses drive. On line no. 31 (Studentski trg-Konjarnik), there are currently 17 articulated buses in operation according to plan. An overview of static and dynamic work elements is presented in Table 22.

Table 13. The existing number of buses in operation and indicators of operation on line 31

Line	Number of buses in operation (Nr)	f (bus/h)	i (min)	Type	Cmax (places/h)	Lsr (km)	To (min)	Vo (km/h)	Zmax (passengeres/h)	Kik
31	17	13.2	4.53	18m	2119	7.36	77	11.47	1280	0.60

With the introduction of electric-powered buses on line 31, the same or approximately the same level of passenger transportation service must be maintained in terms of providing the necessary capacity, arrival intervals, and utilization coefficient of the offered capacity, as in the case when diesel-powered buses are operating. The introduction of electric buses would mean extending the route of the existing line no. 31, to the SRC M.G. Muskatirovic terminal, where the existing chargers are. In this sense, the proposal for dimensioning the required number of E-buses on the new line EKO 31 is given in Table 23.

Table 14. Proposed number of articulated E-buses in operation and performance indicators on line EKO 31 (SRC M.G. Muskatirovic-Konjarnik)

Line	Number of E-buses in operation (Nr)	f (bus/h)	i (min)	Type	Cmax (places/h)	Lsr (km)	To (min)	Vo (km/h)	Zmax (passengeres/h)	Kik
EKO 31	19	12.6	4.73	18m	1764	9.2	90	12.2	1280	0.72

The case study was done under the assumption that vehicles and equipment are purchased through a loan with a repayment period of 7 years. The warranty period is 2 years for vehicles, 5 years for chargers, and 10 years for supercapacitors. It would be necessary to install two fast chargers of 400 kW each at the Konjarnik terminus. The prices of energy products (diesel fuel and electricity) are taken according to the valid market prices as of October 24, 2022. as well as the average Euro exchange rate of 117.5 din/€ and the discount rate. The total costs of operating a bus in its lifetime represent the sum of individual costs and can be represented as:

$$T_{uk} = T_{inv} + T_{iop} + T_{ios} + T_{ood} + T_{oen} + T_{oek} + T_{oot} \qquad (1)$$

T_{uk} – total costs in the lifetime of a vehicle or group of vehicles, €,
T_{inv} – investment costs of vehicle acquisition, €,
T_{iop} – investment costs of purchasing equipment (chargers), €,
T_{ood} – vehicle maintenance operating costs, excluding labor costs, €,
T_{oen} – operating costs of driving energy, €,
T_{oek} – operational costs of environmental pollution from vehicle use, €
T_{oot} – operating costs, other costs: registration, mandatory insurance, comprehensive insurance, annuities, €.

Table 15. Overview of input elements costs in the lifetime

Input elements	Unit	E-bus 18 UC	Diesel bus 18m (Euro 6)
Number of vehicles to be purchased	[комада]	19	17
Annual mileage	[km]	70000	70000
The lifetime of the vehicle	[year]	16	16
Discount rate	[%]	2.5	2.5
Interest rate	[%]	2.5	2.5
Loan repayment period	[year]	7	7
Electricity consumption	[kWh/100km]	151.7	
The price of electricity	[€/kWh]	0.095	
Diesel fuel consumption	[L/100km]		65.07
The price of diesel fuel	[€/L]		1.70
Ad-Blue consumption	[L/100km]		3.0
Ad-Blue price	[€/L]		0.22
E-bus maintenance costs	[€/km]	0.0567	
Supercapacitor service costs	[€/E-bus)	10000	
Diesel bus maintenance costs	[€/km]		0.1380

Table 16. Overview of investment costs for the purchase of articulated buses

Investments	Unit price [€]	Number of units	Total [€]
E-bus with a supercapacitor, capacity of 108 kWh	750,000.00	19	14,250,000.00
Diesel articulated bus, Euro 6	335,000.00	17	5,610,000.00
Charger for fast charging power 400 kW	220,000.00	2	440,000.00
Charger for slow charging power 50 kW (for depot)	40,000.00	3	120,000.00

Table 17. Overview of operating costs on an annual level

Annual exploitation costs	Unit price [€]	No. of units	Total [€]
Maintenance costs of E-bus UC 18	3,969.00	19	75,411.00
Supercapacitor service costs after 10 years, for E-bus UC	10,000.00	19	190,000.00
Diesel bus maintenance costs	9,660.00	17	164,220.00
Maintenance costs for fast chargers after 5 years	350.00	2	700.00
Electricity costs for driving the E-bus UC	10,088.05	19	191,672.95
Diesel fuel costs for driving diesel buses and "Ad-Blue"	77,895.30	17	1,324,220.10
Air pollution costs from E-buses UC (CO2 - WtW)	3,092.44	19	58,756.33
Air pollution costs from diesel buses (CO2-WtW, CO, CxHy, NOx, PM)	5,325.48	17	90,533.16
Loan repayment - Annuity for E-bus UC, chargers			2,332,507.31
Loan repayment - Annuity for diesel buses (Euro 6)			883,549.36
Casco-for E-buses UC 18	5,250.00	19	99,750.00
Casco for diesel buses	2,310.00	17	39,270.00

Based on the case study done, which refers to the substitution of existing diesel-powered articulated buses with articulated electric buses, it follows that the total costs in a lifetime of 16 years are 22.28 million € for electric-powered buses or 31.39 million € for diesel-powered buses. The difference is 9.10 million Euros in favor of electric buses.

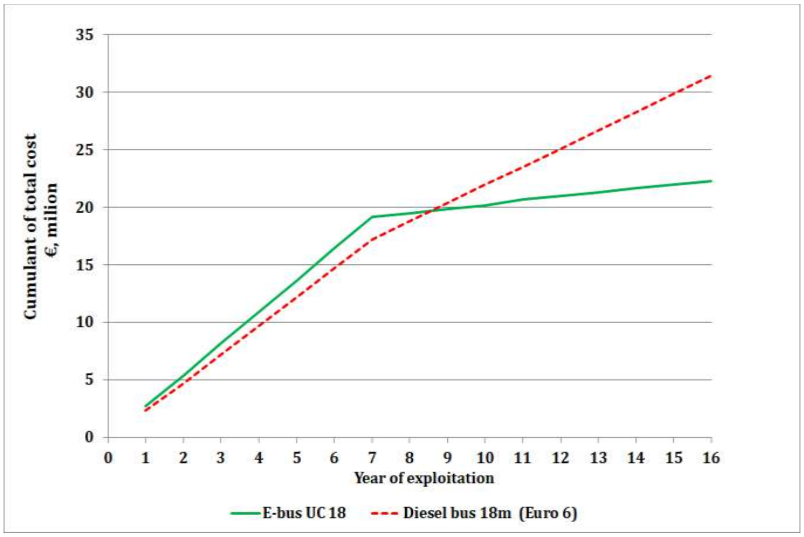

Figure 11. Cumulative costs over the lifetime of the buses

If the criterion related to the investment payback time is analyzed, it follows that the total costs are equalized after 8.5 years of exploitation. After that period, we have direct benefits (savings) which are the consequences of the exploitation of electric buses. Using the minimum net present value criteria (min T_{nsv}).

$$T_{nsv} = \sum_{t=0}^{n_{zv}} \frac{T_{uk}}{(1+d_{sk})^t} , \qquad (2)$$

T_{nsv} – the net present value of total costs over the lifetime of the vehicle, €,
T_{uk} – total costs in the lifetime of a vehicle or group of vehicles, €,
d_{sk} – discount rate, %,
n_{zv} – a lifetime of the vehicle (years).

The net present value of the total lifetime costs of electric-powered articulated buses is 19.70 million Euros, while for diesel-powered buses that amount is 26.15 million Euros. And according to this criterion, the difference in total costs is 6.45 million Euros in favor of electric buses.

6. CONCLUSION

The use of articulated electric buses will have a further upward trend in many cities of Europe and the world as an effective way of decarbonizing the public transport system due to the substitution of existing diesel buses with electric ones, as well as a great potential for use on BRT system lines.

The test operation of the articulated bus Higer 18 UC Electric bus presented all the specifics of the use of an articulated bus with electric drive compared to buses that use diesel fuel, on the representative city line No. 31-test (SRC M. G Muskatirovic-Konjarnik). From the point of view of requirements in real exploitation: traction-speed characteristics, braking dynamics, stability, controllability, vehicle capacity, electricity consumption, charging time, the autonomy of movement, and environmental and ergonomic requirements, the vehicle met all criteria.

The test proved that the articulated bus Higer 18 UC Electric bus has more than 4 times higher energy efficiency compared to the bus Solaris Urbino 18 (Euro 5) in approximately the same operating conditions that are present on the line No. 31 (Studentski trg-Konjarnik) and line No. 31-test (SRC M.G. Muskatirovic-Konjarnik). The environmental effects of using electric buses instead of diesel buses are reflected in the reduction of air pollution and noise levels as a result of the withdrawal of articulated diesel buses from the existing line No. 31 and the introduction of electric buses. This practically means that with the introduction of electric articulated buses, the effect of reducing the emission of harmful gases would be lower by: 4294.2 kg (CO-carbon monoxide), 1317.3 kg (CxHy-carbon hydrogens), 5725.6 kg (NOx-nitrogen oxides), 57.12 kg (PM10 – suspended microparticles) as well as a smaller emission of 941.5 tons (CO2 – carbon dioxide). The economic evaluation on the example of a case study of the complete substitution of diesel buses with electric ones on line No. 31 proved the profitability of the project from the point of view of comparing the total costs in the lifetime, the net present value, and the investment return time.

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