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TRACTION CAPACITY OF RECHARGEABLE LFP BATTERIES FOR TROLLEYBUS

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Abstract. The article deals with the actual problem of reducing air pollution by internal combustion engines of public transport in urban and suburban traffic through the use of battery trolleybuses for passenger transportation. A method is proposed for calculating the capacity of batteries for the autonomous movement of trolleybuses, which can be used to calculate the required capacity of trolleybus batteries for use on city bus routes partially passing under the trolleybus overhead contact wires. The calculation of the required capacity of the lithium iron phosphate (LFP) battery for the operation of the battery trolleybus on the real bus route of the Chisinau municipality has been carried out.

Keywords: *Calculations of the energy consumed by a trolleybus, calculation of the capacity of storage LFP batteries, choose the optimal power of storage batteries*

Rezumat. Articolul este dedicat problemelor actuale a reducerii poluării aerului de către motoarele cu ardere internă ale transportului public în traficul urban și suburban prin utilizarea troleibuzelor cu baterii pentru transportul de persoane. Se propune o metodă de calcul a capacității bateriilor pentru deplasarea autonomă a troleibuzelor, care poate fi utilizată pentru a calcula capacitatea necesară a bateriilor de troleibuz pentru utilizare pe rutele autobuzelor urbane care trec parțial pe sub firele de contact aeriene ale troleibuzului. S-a efectuat calculul capacității necesare a bateriei litiu fier fosfat (LFP) pentru funcționarea troleibuzului cu baterii pe ruta reală de autobuz a municipiului Chișinău.

Cuvinte cheie: *Calcule ale energiei consumate de un troleibuz, calculul capacitatii acumulatorilor LFP, alegerea puterii optime a acumulatorilor.*

Abbreviations

Bl	service life of lithium-iron-phosphate battery (LFP), years.
Ccell	nominal capacity of LFP cells, Wh.
Cdc	charge/discharge cycles of LFP battery.
Cstored	electrical energy stored in the battery, kWh
Cstored, *one section*	- electrical energy stored in one battery section, kWh.
DoD	depth of discharge of LFP battery, %.
EFK	number of discharge/charge cycles of LFP battery.

f	rolling resistance coefficient.
fc	coefficient of rolling resistance at low speed (fc = 0.015… 0.025).
G	weight of the vehicle, N.
G_B	weight of the bus Ikarus 260.0, N.
G_F	weight fuel, kg.
G_T	weight of the trolleybus RTEC 62321, N.
kf	the coefficient of increasing the consumption of useful energy of the trolleybus for rolling additional mass.
L_A	autonomous run of trolleybus (long autonomous mileage), km
L_R	full length of bus route, km.
$Ndpy$	number of days of operation of a trolleybus, year.
η_{TOTB}	coefficient of efficiency of a bus engine.
η_{TOTT}	coefficient of efficiency of a trolleybus with a battery.
P_{fB}	the power expended by the bus to overcome rolling resistance on a flat road surface, kW.
P_{fT}	the power expended by a trolleybus to overcome rolling resistance on a flat road surface, kW.
P_f	the power expended to overcome rolling resistance on a flat road surface, kW
Q_{TEF}	the thermal energy of the diesel fuel, kJ.
Qy	specific heat of combustion for diesel fuel, kJ/kg.
$Unom$	rated output voltage of one battery section,V DC.
v	speed of the vehicle within the city, m/s.
W_{CET}	the total energy consumption of a trolleybus, kWh.
W_{CETA}	the total energy consumption of a bus, kWh.
W_{EEF}	the electric equivalent of diesel fuel energy, kWh.
W_{UWB}	useful work produced by the bus engine, kWh.
α	angle of the road, angular degrees.
Υ_{Fl}	specific gravity of one liter of summer diesel fuel, kg/dm^3.

1. Introduction

The problem of air pollution in cities from internal combustion engines of vehicles has stimulated the search for alternative sources of energy for transport. Urban public transport buses, taxis and trolleybuses are equally good at transporting passengers. However, trolleybuses have an important advantage - they do not pollute the atmosphere. Research has shown that trolleybuses significantly help to reduce emissions of nitrogen oxides, non-methane volatile organic compounds and particulate matter, while increasing sulphur dioxide emissions on the served lines. They also generate lower specific emissions of carbon dioxide compared to diesel buses [1]. At the same time, trolleybuses have a drawback - they depend on power supply devices, that is, for their operation, it is necessary to build traction networks and substations. With the invention of batteries with a high energy capacity per unit weight, trolleybuses were able to move autonomously using the energy stored in the batteries.

The energy content of batteries has increased significantly due to the successful commercialization of lithium-ion batteries (LIB) in the 1990s. The LIB energy density has been increasing at a rate of less than 3% over the past 25 years [2]. Practically, the energy densities of 240−250 Wh kg−1 and 550-600 Wh L−1 have been achieved for power batteries.

Such battery trolleybuses, when moving on contact networks, use current both for movement and for charging batteries. This made it possible to lengthen urban transport routes to the suburbs without spending on the development of a contact network and to replace buses on these routes. For autonomous movement on long routes, it is necessary to install batteries of appropriate energy capacity on trolleybuses to cover energy costs for movement.

The determination of energy consumption for the autonomous movement of a trolleybus has been considered in numerous articles. Sinhuber, Rohlfs & Sauer (2012) [3] and Rogge, Wollny & Sauer (2015) [4] used a simulation model to determine the energy consumption on the route and to calculate the required battery capacity. Rogge et al. (2015) discussed the trade-off between passenger traffic, battery capacity and the relationship between charging power and battery capacity when electrifying the existing bus network. Battery capacity is investigated by Gao et al. (2017) [5] Researchers have concluded that operational requirements and charging concept have a significant impact on battery size and design. Safonau (2012) [6], believes that when calculating the energy consumed by traction vehicles, the following methods can be used:

- on the curves of currents I (t), obtained as a result of traction calculations;
- analytical, based on the assessment of the components of the energy balance;
- empirical, based on the analysis of experimental data obtained under basic conditions.

At the same time, Safonau (2012) [6], believes that these methods do not take into account random factors (intervals between trolleybuses, interference with passing vehicles, passenger compartment occupancy, road conditions, meteorological factors, etc.), but deterministic factors (acceleration, inclines, resistance to movement, etc.) are taken into account by averaged values. Calculations by these methods can be taken as approximate with errors of up to 30%, and as a method with a greater degree of accuracy, the thrust calculation should be used, since in it the main factors are taken into account in a more rigorous mathematical model. Safonau (2012) [6], concludes that the most accurate determination of energy consumption is possible only on the basis of statistical probabilistic methods, which requires a number of experimental studies [6].

However, the fuel consumption of the bus is the best indicator of the energy consumption for the transportation of passengers. Therefore, it is of practical interest to determine the energy consumption for the transportation of passengers on the route according to the fuel consumption of the bus, as well as to calculate the required battery capacity of battery trolleybuses - this is the purpose of this work. The proposed method for calculating the power of the trolleybus battery when replacing buses on city routes is illustrated with a specific example.

2. Use of battery-powered trolleybuses in the mun. Chisinau

In the municipality of Chisinau since June 2017 on the route number 30, from the center of Chisinau to the International Airport of the Moldovan capital. started using hybrid battery trolleybuses instead of Ikarus 260 buses These trolleybuses model RTEC 62321 were purchased in Belarus and assembled in Chisinau [7].

The production of these trolleybuses, including battery ones, was organized by the Moldavian production holding “Informbusiness”, which produces power and low-voltage electrical equipment for trams and trolleybuses in cooperation with the Belarusian plant “Belkomunmash”. Trolleybuses assembled in Moldova on the basis of the electronics of the "Informbusiness" holding and Belarusian bodies and chassis for BKM-321 cars were named

RTEC model after the name of the municipal transport company of the capital of Moldova - "Regia Transport Electric Chișinău". The low-floor urban RTEC 62321 has a microprocessor control system, and a braking energy recovery mode is provided. The battery trolleybus is equipped with two lithium-iron-phosphate battery sections, 2x80 LiFePO4 (LFP) cells each. LFP cells have a nominal voltage of 3.2 V, a nominal capacity of 40 Ah [9], that is, *Ccell* = 128 Wh. Therefore, one section is capable of storing a charge of electrical energy:

$$\begin{aligned} &Cstored\text{, one section} = Ccell \cdot Ncell \\ &Cstored\text{, one section} = 128 \cdot 160 \\ &Cstored\text{, one section} = 20\,480\ Wh = 20.5\ kWh \end{aligned} \tag{1}$$

The section output voltage is *Unom* = 512 V DC. Section weight - 300 kg. The holding “Informbusiness” informs that the batteries installed on RTEC 62321 trolleybuses provide the total number of discharge/charge cycles *EFK* = 20 000 (by Depth of Discharge *DoD* = 51% see figure 1) These indicators are in good agreement with the data of PowerTech Systems [8]. The expected service life is 6 -7 years at 10 charge cycles per day. The “Informbusiness” holding claims that the RTEC 62321 battery trolleybus can travel up to 50 km without being connected to a power source.

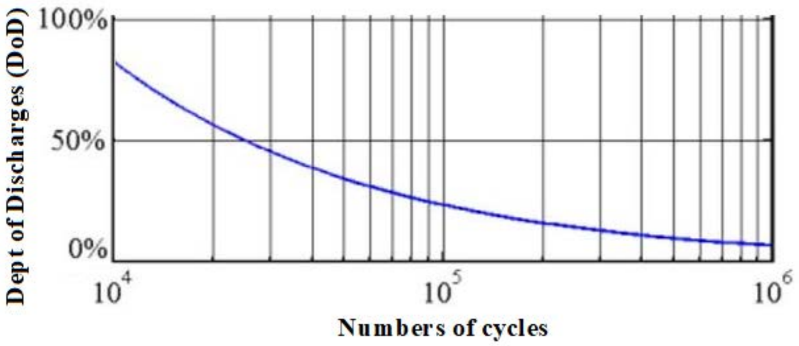

Figure 1. Life Cycle chart of new LiFePO4 cell generation [8].

After the appearance of route Nr. 30 in Chisinau, several more new trolleybus lines to the suburbs of the capital were launched to the airport (see Table 1).

The Directorate of Electric Transport of Chisinau municipality noted the positive effect of using the RTEC 62321 battery trolleybuses; they are three times more economical on municipal routes than diesel buses. Therefore, it is of practical interest to investigate bus routes in Chisinau, which partially coincide with the routes of trolley buses, for the use of battery trolley buses.

Analyzing the routes given in table 1 should be noted:

- all routes, with the exception of Nr. 30, are new and during their development the length of the autonomous run was chosen equal on average to 50% of the total length of the route;
- the routes are served by trolleybuses with an autonomous running reserve of 50 km, at the same time this cruising range is used by less than 47% (see Table 1);
- battery trolleybuses replaced minibuses on commuter routes and reduced air pollution from minibus diesels.

Table 1

Routes served by battery trolleybuses in mun. Chisinau

Route	Round trip route length, km	Autonomous mileage, km	Autonomous mileage from the entire route, %	Power reserve utilization, %
Nr. 30 - to airport	28.9	15.0	51.9	30.0
Nr. 31 - to Singhera	36.5	23.2	63.6	46.4
Nr. 32 - to Stauceni	24.0	11.2	46.6	22.4
Nr. 34 - to Trusheni	31.6	17.1	54.1	34.2
Nr. 35 - to Durlesti (circular route)	19.3	10.4	53.7	20.8
Nr. 36 - to Ialoveni	28.4	14.4	50.7	28.8
Nr. 37 - to Bubuieci	21.7	9.2	42.5	18.4

Based on data on routes served by RTEC 62321 battery trolleybuses in mun. In Chisinau, we can conclude that the autonomous running range declared by the "Informbusiness" holding is more than twice the autonomous mileage on the routes.

Determination of the required capacity of trolleybus batteries when replacing buses on city routes is the goal of this work. The proposed method for calculating the power of the trolleybus battery is illustrated with a specific example.

3. Methodology for calculating the energy consumed by trolleybuses on bus routes

The thermal energy of the diesel fuel, Q_{TEF}, in joules, can be expressed in W_{EEF} kilowatts. The useful work produced by the bus engine and spent for the transport of passengers by the W_{UWB} can be determined through the efficiency coefficient η_{TOTB} of the engine, transmission and other systems of the bus.

This energy will be spent by a trolleybus of equal weight to perform for useful work. The total energy consumption W_{CET} of a trolleybus can be determined through the efficiency coefficient η_{TOTT} of the battery, electric motor, transmission and other trolleybus systems.

When driving outside the contact network, the trolleybus covers the full energy consumption W_{CET} with the energy stored in the battery.

The application of the methodology is demonstrated by solving a specific problem: calculating the required battery capacity for the RTEC 62321 trolleybus when replacing the Ikarus 260 bus on bus route Nr. 23 (see Figure 2).

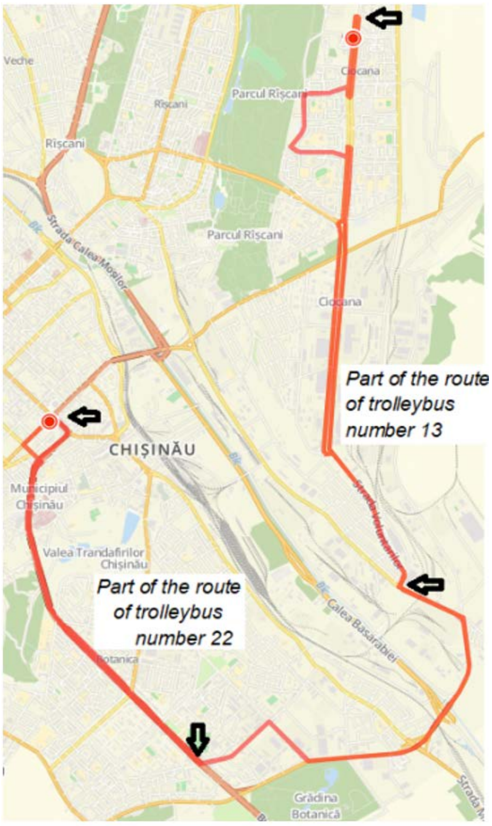

Figure 2. Diagram of connecting public transport lines of bus number 23 and trolleybus numbers 22 and 13 in Chisinau (source: own development based on OpenStreetMap [10]).

4. Approximate calculation of the energy consumed by the trolleybus on the bus route

Bus route Nr. 23 str. Izmail - bvd. Mircea cel Batrîn passes under the contact wires of the trolleybus route Nr. 13 – 5.75 km, and under the contact wires of the trolleybus route Nr. 22 – 6.0 km, that is 11.75 km from the length of the route L_R = 19.45 km, and in the autonomous total mileage L_A = 7.70 km (1.95 + 5.75) (see Figure 1).

Table 2

Technical characteristics of rolling stock

Bus Ikarus 260.01 release 1980 [8]	**Trolleybus RTEC 62321 (AKSM-32100M) release of 2017**
High floor city bus, single link, three door	Low-floor, city trolleybus single-link, three-door
Diesel engine - RABA-MAN D2156HM6U, Power - 250 HP at 2200 rpm	Asynchronous traction motor Power - 180 kW
Maximum speed - 66 km/h	Maximum speed - 70 km/h
Gross mass of the bus – 16 000 kg The mass of the equipped bus – 9 000 kg	The total mass of the trolleybus – 18 000 kg Weight of the equipped trolleybus - 11 100 kg
Total capacity: 102 - 107 passengers	Total capacity: 115 passengers

A bus of the Ikarus 260 type on the bus route Nr. 23 in Chisinau, when performing the transportation of passengers, consumes fuel: 7.6 L of diesel fuel [11].

Let's calculate the energy of the combustion heat of diesel fuel used by a bus of the Ikarus 250 type for a run of L_R = 19.45 km of route Nr. 23 and find the equivalent of this energy in kilowatt hours of battery charge required for a trolleybus with the same weight and number of passengers carried.

According to the current GOST [12], for summer diesel fuel at a temperature of 20^{O}C, the specific gravity must be within γ_F = 860 kg/m^3, which means that the specific gravity of one liter will be γ_{Fl} =0.86 kg/dm^3, and, accordingly, the weight is 7.6 L fuel: G_F =6.54 kg. Specific heat of combustion for diesel fuel is in the range of Qy = 43 000 kJ/kg [13]. Therefore, therefore for G_F = 6.54 kg the thermal energy of the fuel Q_{TEF}:

$$\begin{gathered} Q_{TEF} = G_F \cdot Qy \\ Q_{TEF} = 6.54 \cdot 43\,000 \\ Q_{TEF} = 281\,220 \text{ kJ} \end{gathered} \tag{2}$$

Let's convert the thermal energy of the fuel in joules Q_{TEF} into the electric equivalent of fuel energy Q_{TEF} in watt-hours based on the ratio 1 Wh = 3 600 J, the conversion factor will be equal to kp = 1 Wh / 3 600 kJ = 0.28 Wh/kJ.

The electric equivalent of diesel fuel energy W_{EEF} will be equal to:

$$\begin{gathered} W_{EEF} = Q_{TEF} \cdot kp \\ W_{EEF} = 281\,220 \cdot 0.28 = 78\,742.60 \text{ Wh} \\ W_{EEF} \approx 78.74 \text{ kWh} \end{gathered} \tag{3}$$

To determine the amount of energy used to perform the useful work of the bus W_{UWB}, we use the efficiency of the engine, gearbox and other systems of the bus η_{TOTB} = 0.26 [14]:

$$\begin{aligned} &W_{UWB} = W_{EEF} \cdot \eta_{TOTB} \\ &W_{UWB} = 78.74 \cdot 0.26 \\ &W_{UWB} = 20.47 \text{ kWh} \end{aligned} \tag{4}$$

The bus has a gross weight of 16 tons: G_B = 2 841 N, and the RTEC 62321 trolleybus has a gross weight of 18 tons: G_T= 3 196 N, that is, 2 tons more. The consumption of useful energy will be larger, in proportion to the power expended on rolling the additional mass. Let us determine the power P_f spent on overcoming the rolling resistance on a flat road surface (we take the elevation angle of the road $\alpha = 0^o$), at a speed of 60 km/h within the city limits, that is, v = 16.67 m/s according to the "Eq. (5)" [15]:

$$\begin{gathered} P_f = (G \cdot f \cdot v \cdot \cos(\alpha))\, /1000 \\ \text{where: } f = fc\,(1 + v^2/1500) \\ f = 0.025\,(1 + 16.672^2/1500) = 0.030 \end{gathered} \tag{5}$$

For the bus: $P_{fB} = (2\,840.97 \cdot 0.030 \cdot 16.67 \cdot 1) / 1000 = 1.420$ kW
For a trolleybus: $P_{fT} = (3\,196.10 \cdot 0.030 \cdot 16.67 \cdot 1) / 1000 = 1.598$ kW

The coefficient of increasing the consumption of useful energy of the trolleybus for rolling additional mass km will be equal to the ratio of the power spent to overcome the rolling forces of the trolleybus to the power to overcome the rolling forces of the bus:

$$\begin{gathered} kf = P_{fT} / P_{fB} \\ kf = 1.598 / 1.420 \\ kf = 1.13 \end{gathered} \tag{6}$$

For a run on bus route Nr. 23 with a length of L_R = 19.45 km, a battery trolleybus with an efficiency η_{TOTT} = 0.65 [14] and a useful weight 2 tons more than the bus will consume energy W_{CET} equal to:

$$\begin{gathered} W_{CET} = W_{UWB} / \eta_{TOTT} \cdot kf \\ W_{CET} = 20.47 / 0.65 \cdot 1.13 \\ W_{CET} = 35.59\ (\text{kWh}) \end{gathered} \tag{7}$$

At the same time, only on the section of the bus route between trolleybus routes Nr. 13 and Nr. 22 there will be a long autonomous mileage L_A = 5.75 km on battery energy with energy consumption in proportion to the energy consumption for the full length L_R:

$$\begin{gathered} W_{CETA} = W_{CET} \cdot L_A / L_R \\ W_{CETA} = 35.59 \cdot 5.75 / 19.45 \\ W_{CETA} = 10.52\ \text{kWh} \end{gathered} \tag{8}$$

RTEC 62321 trolleybuses are equipped with an LFP battery of 2 sections with a capacity of *Cstored* each, one section – 20.5 kWh, therefore, when operating a trolleybus with one section on route Nr. 23, the battery discharge with an autonomous run of the L_A = 5.75 km section will be *DoD*:

$$\begin{gathered} DoD = W_{CETA} / Cstored\text{, one section} \cdot 100\% \\ DoD = 10.52 / 20.5 \cdot 100\% \\ DoD = 51\% \end{gathered} \tag{9}$$

According to the data of PowerTech Systems [8], at a battery discharge rate of 1C and a depth of discharge *DoD* = 51%, the expected number of discharge/charge cycles is *EFK* = 20 000 cycles. If the trolleybus is operated for *Ndpy* = 340 days per year and charge/discharge cycles *Cdc* = 16 per day battery life per year will be *Bl*:

$$Bl = EFK / (Ndpy \cdot Cdc)$$
$$Bl = 20\,000 / (340 \cdot 16) \quad (10)$$
$$Bl = 3.67 \text{ years}$$

the LFP battery will last 3.67 years.

Then you can replace this section with a second one and get the same service life of the LFP battery as 7.3 years announced by holding “Informbusiness”.

The calculation showed that on bus route Nr. 23, an RTEC 62321 trolleybus with one LFP battery section can be used. Therefore, the cost of a trolleybus when installing one section will be 3 000 USD cheaper. In addition, the trolleybus's curb weight will be less by 300 kg.

5. Conclusions

The proposed method makes it possible to calculate the power of a trolleybus battery required to serve a bus route, based on the technical characteristics of the bus running along this route and data on fuel consumption for passenger transportation.

The proposed method improves accuracy and facilitates feasibility studies for replacing buses on urban routes.

The application of the proposed method allows you to choose the optimal power of batteries for autonomous operation of trolleybuses and reduce the cost of purchasing trolleybuses.

The application of the methodology is shown on a specific example of replacing a bus with a battery trolleybus on the city route Nr. 23 in the municipality of Chisinau. The calculation shows that on the bus route Nr. 23, it is possible to use the RTEC 62321 trolleybus with just one LFP battery section. Consequently, the cost of a trolleybus when using one section instead of two regular ones will be cheaper by 3,000 US dollars, at the same time, the curb weight of the trolleybus will decrease by 300 kg.

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Conflict of interest. The author declares no conflicts of interest.

References

1. Połom, M.; Wiśniewski, P. Assessment of the Emission of Pollutants from Public Transport Based on the Example of Diesel Buses and Trolleybuses in Gdynia and Sopot. *International Journal of Environmental Research and Public Health* 2021, 18 (16), 8379. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC8394724/
2. Zhan, L.; Song, Z.; Shan, N.; Zhang, J.; Tang, J.; Zhan, H.; Zhou, Y.; Li, Z.; Zhan, C. Poly (tetrahydrobenzodithiophene): high discharge specific capacity as cathode material for lithium batteries. *Journal of Power Sources* 2009,193 (2), pp. 859-863.
3 Sinhuber, Ph.; Rohlfs, W.; Sauer, D.U. Study on power and energy demand for sizing the energy storage systems for electrified local public transport buses. In: *Vehicle Power and Propulsion Conference (VPPC)*, January 2012, IEEE.
4. Rogge, M.; Wollny, S.; Sauer, D.U. Fast Charging Battery Buses for the Electrification of Urban Public Transport—A Feasibility Study Focusing on Charging Infrastructure and Energy Storage Requirements. *Energies* 2015, 8(5), pp. 4587-4606.
5. Alsaidan, I. S.; Amin Khodaei, A.; Wenzhong Gao, W. A Comprehensive Battery Energy Storage Optimal Sizing Model for Microgrid Applications. In: *IEEE Transactions on Power Systems,* November2017.

6. Safonau, A. I. Justification of the traction characteristic and the problem of choice of the trolleybus electric motor and its auxiliary power sources. *Vestnik Belorussko-Possiiskogo Universiteta* 2012, 3 (36), pp. 72-81.
7. Another route was opened in Chisinau, on which autonomous trolleybuses operate. Available online: https://traffic.od.ua/news/worldtrans/1208751 (accessed on 22.05.2022).
8 . New high-performance lithium LiFePO4 cells, Posted on 04/07/2019 by content team. Available online: https://www.powertechsystems.eu/new-high-performance-lithium-lifepo4-cells/ (accessed on 22.12.2022).
9. White Paper on Active Current Balancing and Intelligent Voltage Balancing of Lithium Battery. Available online: e.huawei.com › EBG › PUBLIC › ru-RU ›(accessed on 23.12.2022).
10. Bus number 23. Route and stops (updated). Available online: https://moovitapp.com/index/en/public_transit-line-23-Chisinau-5624-1294131-24048918-1 (accessed on 20.12.2022).
11.Autobus. Podvijnoi sostav. Ikarus-260 Available online: https://gortransport.kharkov.ua/ps_models/18/ (accessed on 20.12.2022) [in Russian].
12. The specific gravity of diesel fuel (solar oil). Available online: http://autosquad.ru/udelnyij-ves-dizelnogo-topliva, (accessed on 22.12.2022).
13. Fuel combustion heat. Available online: http://temperatures.ru/pages/teplota_sgoraniya_topliva (accessed on 22.12.2022).
14 Carpetis, C. On the Global Enviromental Benefits by Using Electric Drive with Fuel Cells, Battery Storage or Hybrid Systems as Compared to Advanced Conventional Vehicle Systems with IC Engine Drive. Extended Summary DLR-IB-200044417400, STB-Bericht,2000, 22.
15. Safiullin, R.N. Explyatatia avtomobilei: ychebnic dlia vuzov. Izdatelstvo Urait, Moscwa, 2019, 204 p. [in Russian].

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