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STUDY OF ENERGY CONSUMPTION BY TROLLEYBUSES MOVING UNDER REGULATED TRAFFIC CONDITIONS

At the current stage of development of electric transport, the task of studying the energy efficiency of such vehicles is still relevant. Various models of electricity consumption developed and proposed by scientists still do not reflect the actual energy consumption of vehicles. A particular problem in such studies is the need to take into account the amount of electricity recovered by the engine. The analysis of the literature shows a variety of approaches to modeling electricity consumption that take into account the actual operating conditions of vehicles. In this paper, we have studied the consumption of electric energy by trolleybuses moving along established routes in Vinnytsia. Based on the results of the studies, the total amount of energy consumed, the amount of energy consumed by the traction electric drive, the total amount of recovered energy, and the amount of recovered energy returned to the contact network were determined.

The data obtained were processed and it was determined that the difference between the amount of electric energy recovered by the vehicle traction motor and the total amount of recovered electric energy sent to the contact network is 6...14 %, while the amount of electric energy recovered by the vehicle traction motor ranges from 7 to 27 % of the electric energy consumed by the electric drive. The research results obtained indicate significant losses of part of the electrical energy recovered by the engine, as well as a significant variation in the amount of recovered energy, depending on the route. Further research should be aimed at improving mathematical models of electric energy consumption, taking into account the specific operating conditions of vehicles.

Keywords: consumption of electrical energy, trolleybus, energy recovery, specific energy consumption, traffic routes

INTRODUCTION

The recently adopted Law of Ukraine “On Certain Issues of the Use of Vehicles Equipped with Electric Engines and Amendments to Certain Laws of Ukraine on Overcoming Fuel Dependence and Development of Electric Charging and Electric Vehicle Infrastructure” [1] provides for the use of electric buses instead of buses with spark-ignition internal combustion engines for passenger transportation in Ukrainian cities.

The increase in the number of wheeled public transport vehicles on electric traction that carry out passenger transportation in Ukrainian cities will require an increase in the capacity of power supply systems of transport enterprises and cities in general.

Therefore, the task of studying the energy consumption of such vehicles that move in accordance with regulated traffic conditions becomes relevant.

Given the fact that a small number of electric buses are currently in operation in Ukraine, and their design is almost similar to that of trolleybuses, trolleybuses can be used as an object of study/

ANALYSIS OF LITERATURE DATA AND FORMULATION OF THE PROBLEM

In [2], a new model of MTECM energy consumption by an electric bus was developed using a multivariate linear regression method. Thus, based on the proposed model, it is possible to calculate the energy consumption for any route planned for the establishment of electric bus operation. Thus, in accordance with the obtained consumption, it is possible to make a correct determination and selection of parameters that significantly affect investment costs, such as route, vehicle length, engine power, and battery capacity.

In order to study the correlation between the type of route an electric bus travels and the amount of energy it consumes to run it, studies were conducted on three different routes [3].

Article [4] provides an overview of the Advanced Vehicle Simulator (ADVISOR), which provides a relatively easy-to-use analysis package for vehicle modeling. It is primarily used to quantify the fuel economy, performance, and emissions of vehicles that use alternative technologies, including fuel cells, batteries, electric motors, and internal combustion engines in hybrid (i.e., multiple power source) configurations.

The research, the results of which are presented in [5], is aimed at developing a model for estimating energy consumption on the road for planning, operating, and evaluating the life cycle of an electric bus fleet.

The results show that: the average absolute percentage error of the proposed model is 12.108%; the accuracy of the model estimation with a probability of 99.7814% meets the requirements of EB fleet planning.

In [6], the authors present a two-stage electric vehicle routing problem (2sEVRP), which includes an improved assessment of energy consumption by considering detailed topography and speed profiles.

In [7], based on real data, the authors propose models that make it possible to predict the consumption of electric energy by vehicles on specific routes.

It is also worth noting [8], which proposes a new approach to forecasting changes in energy demand with a wide range of uncertain factors. The identification of factors was carried out to determine the range of changes in operating conditions. A computationally efficient surrogate model is generated on the basis of a previously developed numerical simulation model.

Based on the data of electric bus trips in China and Norway, the authors of [9] proposed a model of energy consumption taking into account the auxiliary systems of electric buses, such as heating, ventilation, air conditioning, and other vehicle systems.

The analysis of current areas of research on electricity consumption indicates the need to adapt mathematical models to specific operating conditions. Paper [10] demonstrates that operating conditions have a great impact on the consumption of electricity by vehicles, and this issue is especially acute for buses that transport passengers on established routes in cities.

In Ukraine, a number of studies have also been carried out, mainly related to the development of a mathematical model of the energy capacity of a traction battery [11] and the optimization of its parameters [12]. Studies have been carried out on the energy consumption of vehicles with an electric motor [13], as well as on the assessment of energy consumption by an electric bus and the parameters of the traction battery in operation. However, the issue of energy use by vehicles with an electric traction system has not been sufficiently studied, since this issue is not relevant for the subway, tram, and trolleybus, since they are powered by separate traction substations.

PURPOSE AND OBJECTIVES OF THE STUDY

The purpose of the research is to determine the consumption of electric energy by trolleybuses that move along established routes in Vinnytsia. The study was conducted on trolleybuses due to the fact that electric buses are currently not used in Ukrainian cities. On the other hand, the technical characteristics of electric buses and trolleybuses are almost identical, which makes it possible to extend the results to both types of transport (Table 1).

Table 1 - Comparison of technical characteristics of trolleybuses and electric buses

Name of the indicator	Vehicle model	
	Trolleybus T 70110	Electric bus Electron E191
Manufacturer	Subsidiary of Automobile Assembly Plant No. 1 of Public Joint Stock Company Automobile Company Bogdan Motors	Ukrainian-German joint venture Electrontrans
Overall length by body elements, mm	11960	12100
Overall width, mm	2550	2500
Overall height, mm	3800	3280
Wheelbase, mm	5860	5900
Front/rear axle track, mm	2160/1890	2160/1890
Passenger capacity, persons	105	100
Empty weight, kg	11800	12880
Technically permissible maximum weight, kg	18940	19000
Front axle	VOITH TURBO IFS 75-225	ZF, RL 82EC
Rear axle (drive)	ZF AV-132/80	ZF, AVE 130
Gear ratio of the final drive	9.82	22.63
Wheel tires	275/ 70R 22.5	275/ 70R 22.5
Tire pressure, kgf/cm^2	8.0	8.0
Traction motor	ЕД-139АУ2	AVE130-350VAC (2 шт)

Name of the indicator	Vehicle model	
	Trolleybus T 70110	Electric bus Electron E191
IGBT	Cegelec CDC 050P	ENI-FT/ZF/AVE
Static converter 600/27 B, 3p 400 B	Cegelec SMTK 7.0Z	550/28 B ENI-BAT_24DC_6_U
Brake resistor block	R9PO4B125, 300 кВт	None
Compressor drive motor	Siemens 1LA7113-4AA10-Z	S POL2-2 B3
Hydraulic pump drive motor	Siemens 1LA7106-4AA16	SLg100L-4B
Battery pack for powering low-voltage circuits	6CT-190, 12B, 190 Ah (2 pcs.)	6CT-190, 12B, 190 Ah (2 pcs.)
Traction battery pack	None	based on LiFeYPO4 cells Winston Battery WB-LYP 400AHA, (4 battery packs connected in series)
Front axle suspension	Independent, pneumatic with two-lever guide devices, two elastic elements, two telescopic hydraulic shock absorbers and a body position adjuster	
Rear axle suspension	Dependent, pneumatic with a rod guide, four elastic elements, four telescopic hydraulic shock absorbers and two body position adjusters	
Steering	Steering mechanism - integrated with hydraulic power steering. Steering column - adjustable in angle and height	
Service brake system	Pneumatic, dual-circuit with ABS system, brake mechanisms of all wheels - disc brakes, with automatic adjustment of the gap between the brake pads and the disc	
Parking brake system	One of the circuits of the working brake system	
Spare brake system	Mechanical drive brake mechanisms of the drive axle wheels from the spring energy accumulators of the rear axle with pneumatic control	
Auxiliary brake system	Electrodynamic braking as a function of the traction motor	

RESEARCH RESULT

The study of electricity consumption was conducted on trolleybuses T70110, which are operated on the routes of the Vinnytsia City Amalgamated Territorial Community. Figure 1 shows a diagram of the trolleybus routes of this community. The length of the routes of Vinnytsia city amalgamated territorial community is 165.44 km, the length of the contact network is 90.5 km.

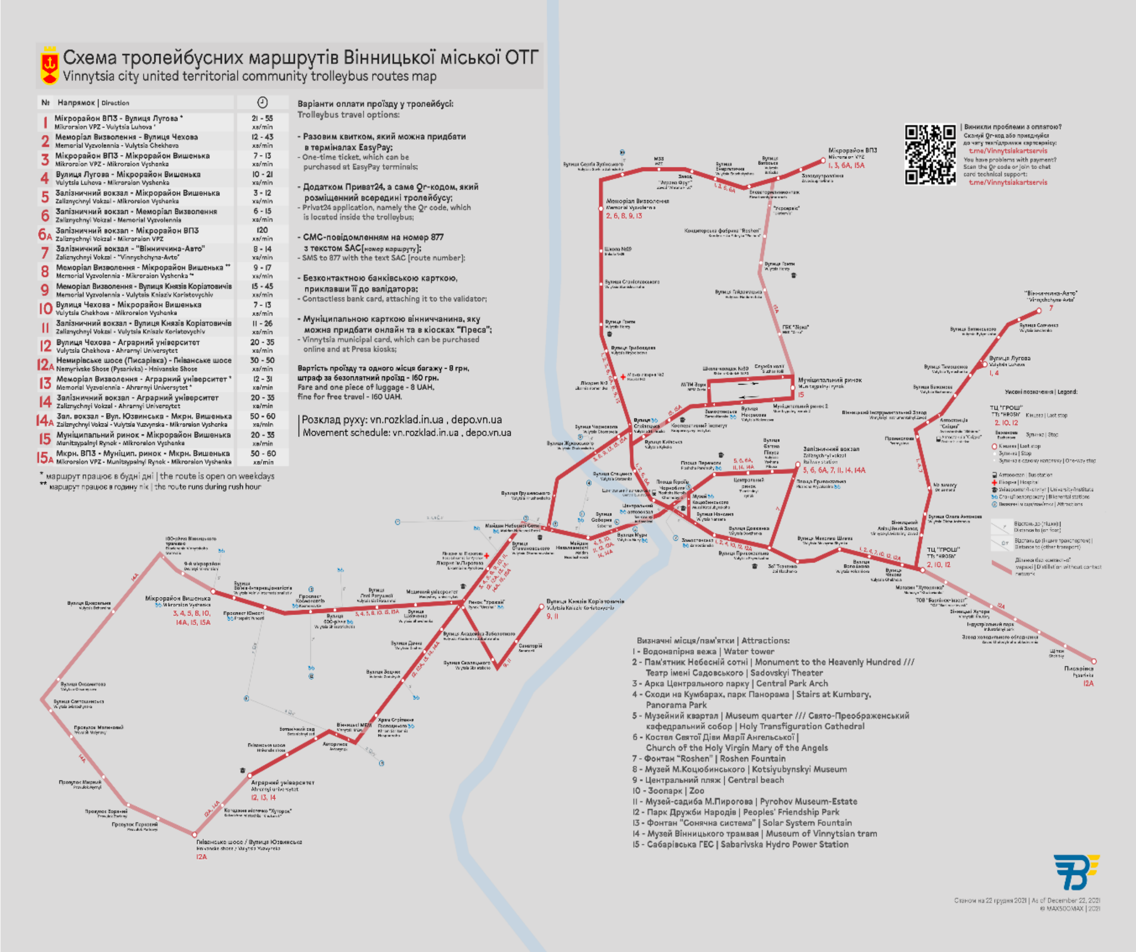

Figure 1 – Scheme of trolleybus routes of Vinnytsia city amalgamated territorial community [according to https://transphoto.org/articles/1236/]

During the research, we organized monitoring of electricity meters installed on T70110 trolleybuses. As a result, the following information was obtained

- the amount of energy consumed: total - since the beginning of the trolleybus operation and daily - for the last day of operation on the route;

- the amount of energy consumed by the traction drive is the amount of energy that was used to create the kinetic energy of the trolleybus (this energy does not include energy consumed for its own needs, namely: power supply of the compressor, hydraulic booster, air conditioner, external lighting, heating and interior lighting). The share of recovered energy generated during trolleybus braking is excluded from this energy;

- the amount of recovered energy is the amount of energy produced by the traction motor during regenerative braking of the trolleybus;

- the amount of energy consumed in total and for the last day is the amount of energy consumed from the contact network during passenger transportation, respectively, from the beginning of operation and for the last day;

- the total amount of recovered energy is the amount of energy that was returned to the overhead line during trolleybus braking;

- total trolleybus mileage and for the last day.

It is worth noting that not all of the recovered energy can be returned to the contact network, due to the characteristics of the contact network itself.

That is, if the voltage of the contact network reaches its maximum value, the recovered energy is sent to the braking resistors and converted into heat.

Tables 2 and 3 summarize the results of the observations.

Table 2 – Electricity consumption by Bogdan T70110 trolleybuses during their operation

Trolleybus number	Mileage. km	Energy consumed by the traction drive. kWh	Amount of recovered energy. kWh	Total amount of consumed energy. kWh	Total amount of recovered energy. kWh
3	375714.24	474516.73	93477.64	645007.34	78651.63
4	442414.51	531923.77	115543.43	727179.93	97528.24
4	441649.54	531078.59	115328.11	726135.93	97326.57
9	510751.44	586138.44	102710.64	781663.67	85266.44
11	441821.61	514884.80	104873.89	692838.83	91063.27
15	428055.09	514706.48	86763.95	707023.65	74410.58
16	483418.33	598761.80	138366.95	810720.29	116585.96
16	482475.34	597678.98	138150.28	809465.93	116377.09
17	407141.38	502849.98	82233.18	691844.40	68458.63
21	432074.01	501351.39	79974.12	362493.69	6134.39
22	481616.78	540970.90	122693.80	773530.56	105218.99
23	481769.18	543179.16	107896.20	753945.79	93115.87
27	416730.88	478682.90	96423.78	683102.97	85303.75
28	494240.03	594514.77	102236.44	766941.75	87245.98
28	493307.79	593492.11	102114.91	765801.53	87128.13
29	443339.96	518757.32	127492.33	739575.84	107923.46
30	423002.77	499332.62	102769.71	706851.97	88579.84
34	409786.89	500515.31	85895.20	672528.42	74259.16
34	408593.00	499201.18	85704.42	670979.15	74075.38
35	446936.53	495941.93	108044.46	741473.34	92191.76
39	411264.94	436537.88	72370.17	598042.38	60814.19
40	384886.99	431390.24	95124.43	626138.30	81288.25
40	384056.30	430529.67	94955.08	625097.34	81122.93
13	417591.61	472744.69	119989.36	680396.99	102017.29
37	450377.56	490666.14	117367.81	697848.85	100659.93
7	361802.16	403797.96	83555.11	573231.87	71289.81
5	404123.37	469742.28	83236.03	649735.13	69715.81
19	494793.48	555764.05	100050.91	747778.29	87860.41
25	408404.79	505372.47	104592.73	699849.11	85955.11
31	422818.97	514084.82	106560.90	727201.82	91158.88
38	464329.57	543190.44	88612.51	740536.90	76208.19
2	442814.51	533659.19	94014.52	999999.00	74339.09
32	425617.68	511023.90	107924.92	700794.87	90346.39
6	207811.60	310405.84	33869.42	425496.74	28369.28
26	474681.86	539671.07	105304.74	755980.09	91211.21
36	408973.78	479563.58	73737.62	698352.84	60519.09
14	460439.42	521290.10	115134.70	720887.14	98893.04

In order to estimate the amount of electricity consumed and recovered, the energy consumption figures are converted to specific kWh per 1 kilometer of travel. The results of the calculations are shown in Table 3.

Table 3 – Specific electricity consumption by Bogdan T70110 trolleybuses during their operation

Trolleybus number	Specific energy consumed by the traction drive. kWh/km	Specific amount of recovered energy. kWh/km	Total specific energy consumption. kWh/km	Total specific amount of recovered energy. kWh/km	% of recovered energy	% of the total amount of recovered energy	The difference
2	1.21	0.21	2.26	0.17	18	7	10
3	1.07	0.21	1.46	0.18	20	12	8
4	1.20	0.26	1.64	0.22	22	13	8
4	1.20	0.26	1.64	0.22	22	13	8
5	1.06	0.19	1.47	0.16	18	11	7
6	0.70	0.08	0.96	0.06	11	7	4
7	0.91	0.19	1.29	0.16	21	12	8
9	1.32	0.23	1.77	0.19	18	11	7
11	1.16	0.24	1.56	0.21	20	13	7
13	1.07	0.27	1.54	0.23	25	15	10
14	1.18	0.26	1.63	0.22	22	14	8
15	1.16	0.20	1.60	0.17	17	11	6
16	1.35	0.31	1.83	0.26	23	14	9
16	1.35	0.31	1.83	0.26	23	14	9
17	1.14	0.19	1.56	0.15	16	10	6
19	1.26	0.23	1.69	0.20	18	12	6
21	1.13	0.18	0.82	0.01	16	2	14
22	1.22	0.28	1.75	0.24	23	14	9
23	1.23	0.24	1.70	0.21	20	12	8
25	1.14	0.24	1.58	0.19	21	12	8
26	1.22	0.24	1.71	0.21	20	12	7
27	1.08	0.22	1.54	0.19	20	12	8
28	1.34	0.23	1.73	0.20	17	11	6
28	1.34	0.23	1.73	0.20	17	11	6
29	1.17	0.29	1.67	0.24	25	15	10
30	1.13	0.23	1.60	0.20	21	13	8
31	1.16	0.24	1.64	0.21	21	13	8
32	1.15	0.24	1.58	0.20	21	13	8
34	1.13	0.19	1.52	0.17	17	11	6
34	1.13	0.19	1.52	0.17	17	11	6
35	1.12	0.24	1.67	0.21	22	12	9
36	1.08	0.17	1.58	0.14	15	9	7
37	1.11	0.27	1.58	0.23	24	14	9
38	1.23	0.20	1.67	0.17	16	10	6
39	0.99	0.16	1.35	0.14	17	10	6
40	0.97	0.21	1.41	0.18	22	13	9

Based on the obtained data on specific electricity consumption, taking into account the amount of recovered energy, we have built graphs:

- the total amount of consumed and recovered electric energy (Fig. 2);
- the difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus (Fig. 3);

– the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus (Fig. 4);

– Pareto diagram of the difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus (Fig. 5).

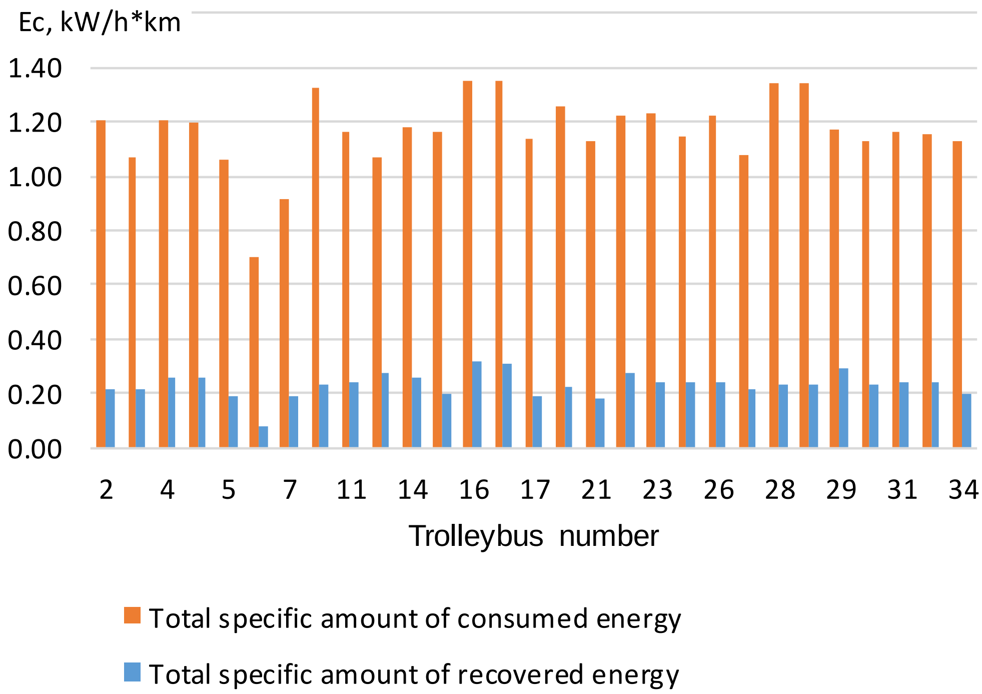

Figure 2 – The total amount of electricity consumed and recovered is reduced to specific indicators

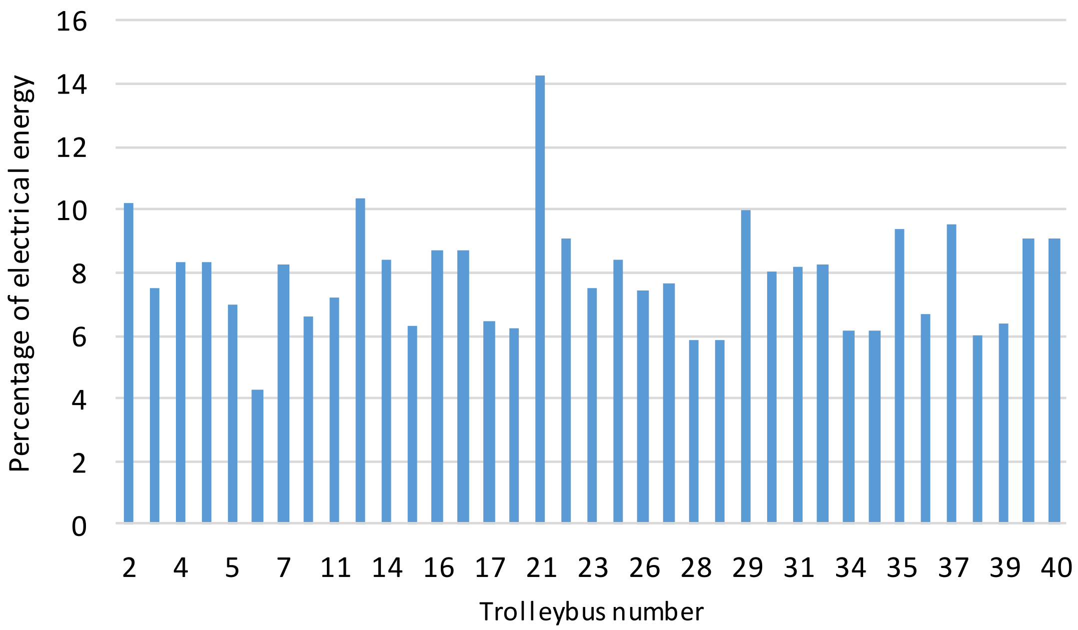

Figure 3 – The difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

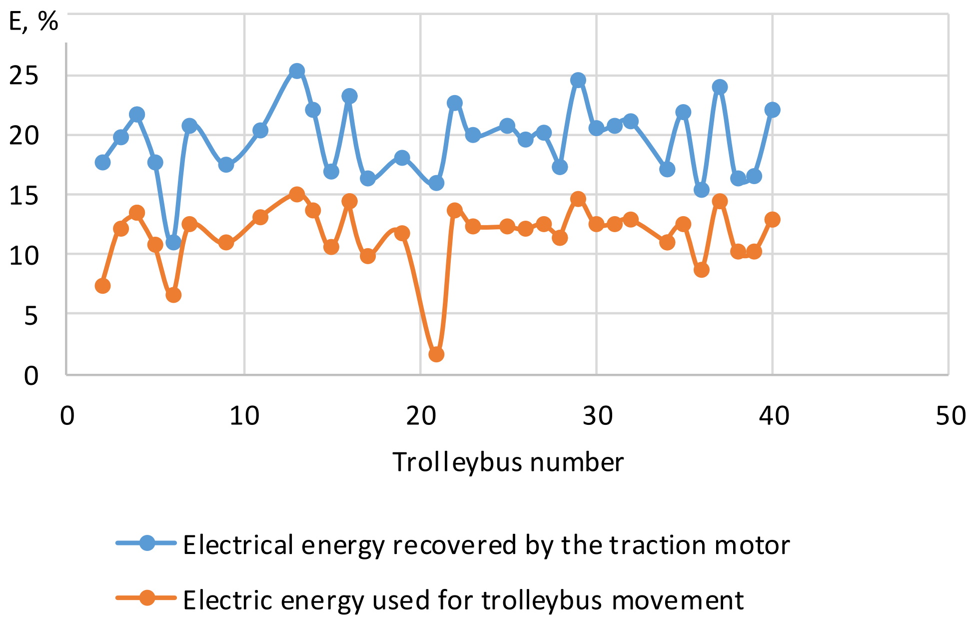

Figure 4 – Graphs of the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

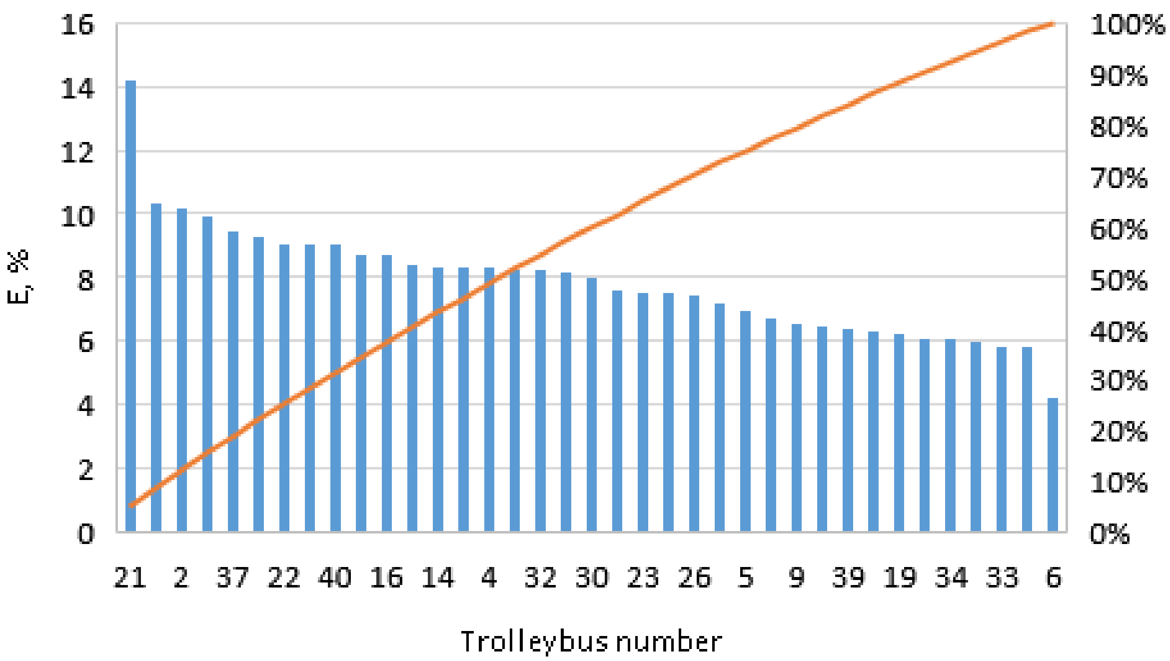

Figure 5 – Pareto diagram of the difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

DISCUSSION OF THE RESULTS OF THE STUDY

As a result of the studies, it was found that when a trolleybus is moving along the established routes in Vinnytsia, the amount of electricity recovered by the traction motor of the vehicle ranges from 15 to 25 % of the electricity consumed by the electric drive.

The total amount of recovered electric energy that is sent to the contact network, i.e., actually spent on trolleybus movement, ranges from 2 to 15%.

Thus, the difference between the amount of electrical energy recovered by the traction motor of the vehicle and the total amount of recovered electrical energy sent to the contact network is 6...14 %.

The Pareto diagram shows that only 20 % of the rolling stock provides the maximum use of recovered energy, while the amount of electricity that is reused ranges from 9 to 14 %.

The study also obtained data on electricity consumption by trolleybuses during one day (Table 4).

Table 4 – Electricity consumption by Bogdan T70110 trolleybuses per day

Trolleybus number	Mileage. km	Energy consumed by the traction drive. kWh	Amount of recovered energy. kWh	Total amount of consumed energy. kWh	Total amount of recovered energy. kWh
3	132.95	131.89	20.84	149.73	19.41
4	88.33	97.54	21.59	121.02	20.73
11	58.83	67.45	13.74	80.34	12.94
15	61.92	55.25	8.29	65.38	8.04
16	59.08	71.98	14.21	82.37	13.56
16	58.74	74.34	16.22	85.60	15.45
21	103.35	115.73	9.61	69.90	1.24
22	63.36	51.07	6.88	69.15	7.17
27	95.25	106.78	22.90	129.95	22.34
28	83.52	80.29	10.10	90.99	9.78
29	61.74	63.79	12.52	76.42	11.86
30	103.59	114.21	20.48	139.02	20.26
34	61.84	56.68	5.26	66.39	5.19
34	62.02	57.55	4.97	67.29	5.04
35	59.51	60.67	11.74	199.66	5.32
39	125.06	152.73	15.02	171.86	14.04
40	124.70	131.08	26.22	156.62	25.73
40	47.48	49.56	10.31	63.31	10.21
13	49.67	59.12	16.04	71.09	15.08
37	63.39	62.70	11.41	74.83	11.23
5	62.73	67.39	7.73	76.13	7.44
19	108.69	116.96	17.11	136.05	17.55
25	135.78	138.56	9.19	161.56	8.86
2	65.76	81.06	13.02	92.68	11.55
32	61.66	66.24	10.87	75.93	10.24
6	67.15	84.88	10.42	96.53	9.75
26	109.94	107.42	16.24	133.21	16.46
36	100.15	130.97	21.07	149.03	19.96
14	125.15	127.97	24.03	145.14	23.42

Table 4 does not include trolleybuses that did not perform transportation work on the route.

According to the obtained daily electricity consumption, similar calculations of specific and percentage indicators were made. The results of the calculations are shown in Table 5 and Figures 6, 7, 8, 9.

Table 5 - Electricity consumption by Bogdan T70110 trolleybuses based on daily runs

Trolleybus number	Specific energy consumed by the traction drive. kWh/km	Specific amount of recovered energy. kWh/km	Total specific energy consumption. kWh/km	Total specific amount of recovered energy. kWh/km	% of recovered energy	% of the total amount of recovered energy	The difference
2	1.23	0.20	1.41	0.18	16	12	4
3	2.01	0.32	2.28	0.30	16	13	3
4	1.48	0.33	1.84	0.32	22	17	5
5	1.02	0.12	1.16	0.11	11	10	2
6	1.29	0.16	1.47	0.15	12	10	2
11	1.03	0.21	1.22	0.20	20	16	4
13	0.90	0.24	1.08	0.23	27	21	6
14	1.95	0.37	2.21	0.36	19	16	3
15	0.84	0.13	0.99	0.12	15	12	3
16	1.09	0.22	1.25	0.21	20	16	3
17	1.13	0.25	1.30	0.23	22	18	4
18	0.88	0.08	1.02	0.08	9	7	1
19	1.78	0.26	2.07	0.27	15	13	2
21	1.76	0.15	1.06	0.02	8	2	7
22	0.78	0.10	1.05	0.11	13	10	3
25	2.11	0.14	2.46	0.13	7	5	1
26	1.63	0.25	2.03	0.25	15	12	3
27	1.62	0.35	1.98	0.34	21	17	4
28	1.22	0.15	1.38	0.15	13	11	2
29	0.97	0.19	1.16	0.18	20	16	4
30	1.74	0.31	2.11	0.31	18	15	3
32	1.01	0.17	1.15	0.16	16	13	3
34	0.86	0.08	1.01	0.08	9	8	1
35	0.92	0.18	3.04	0.08	19	3	17
36	1.99	0.32	2.27	0.30	16	13	3
37	0.95	0.17	1.14	0.17	18	15	3
38	1.99	0.40	2.38	0.39	20	16	4
39	2.32	0.23	2.61	0.21	10	8	2
40	0.75	0.16	0.96	0.16	21	16	5

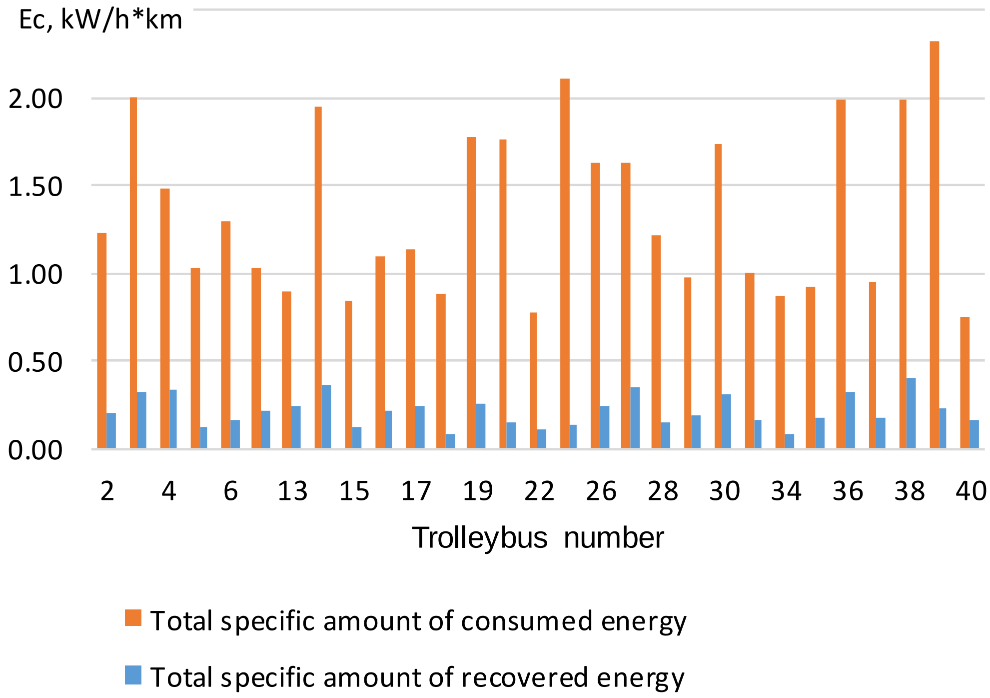

Figure 6 – The total amount of electricity consumed and recovered is reduced to specific indicators

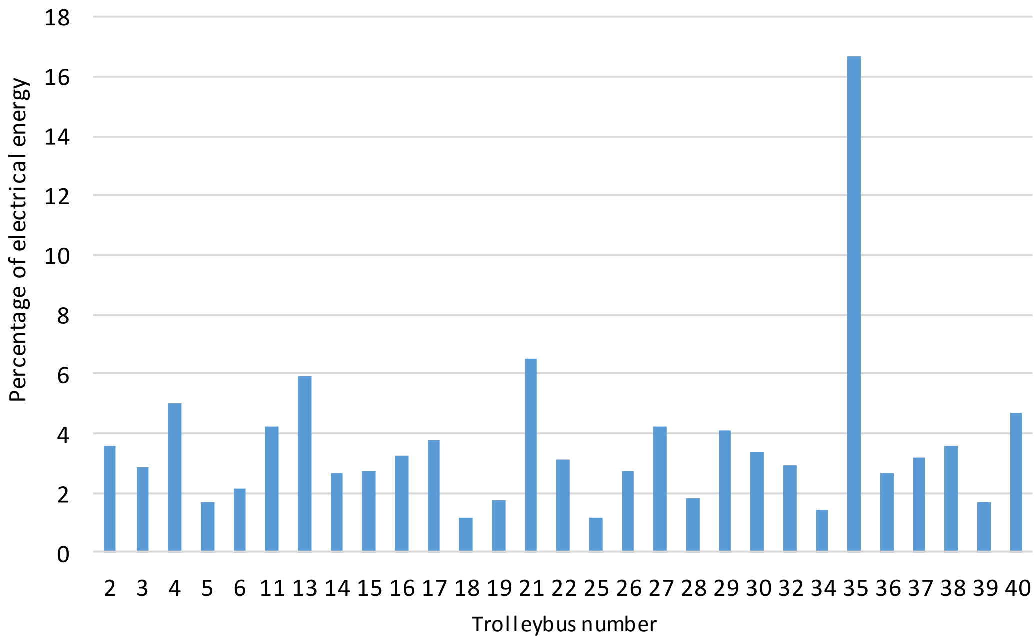

Figure 7 – The difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

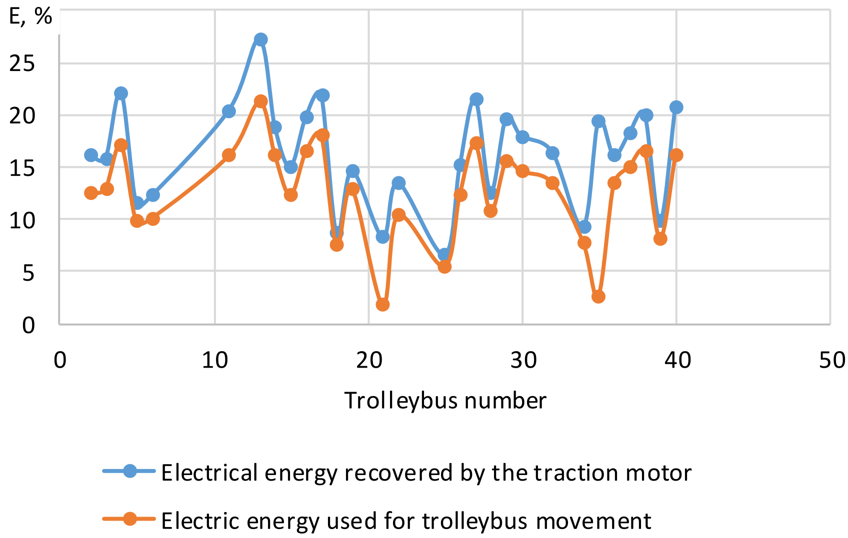

Figure 8 – Graphs of the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

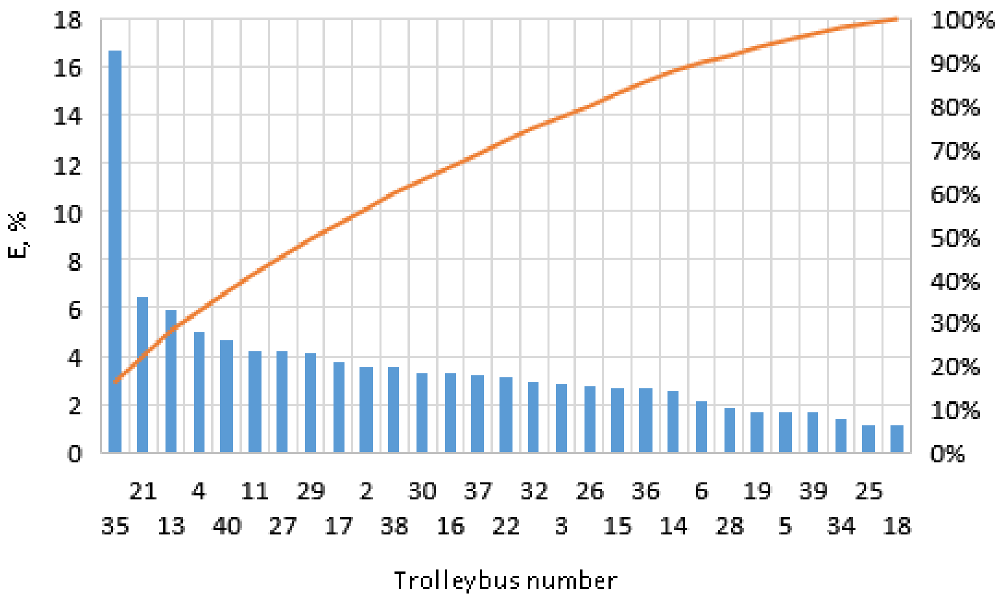

Figure 9 – Pareto diagram of the difference between the amount of electric energy recovered by the traction motor and the amount of electric energy consumed for further movement of the trolleybus

SUMMARY

As a result of the calculations on the daily values of electric energy consumption, it was found that during the movement of the trolleybus on the established routes in Vinnytsia

- the amount of electric energy recovered by the traction motor of the vehicle ranges from 7 to 27 % of the electric energy consumed by the electric drive;
- the total amount of recovered electric energy sent to the contact network, i.e. actually spent on trolleybus movement, ranges from 2 to 21 %;
- the difference between the amount of electric energy recovered by the traction motor of the vehicle and the total amount of recovered electric energy sent to the contact network is 1...16 %.

After comparing the data on electricity consumption collected from the beginning of trolleybus operation and during the day, it was found that the difference in electricity consumption is (see also Figure 10):

- specific energy consumed by the traction drive is up to 19 %;
- specific amount of recovered energy up to 5 %;
- total specific energy consumption of 3 %.

- total specific energy recovered up to 5 %.

Thus, the results of the studies indicate a discrepancy between the indicators obtained from the beginning of trolleybus operation and those obtained from the daily mileage data of up to 20 %. Such a deviation can be considered acceptable, given the stochastic nature of the processes caused by the influence of a significant number of external factors [15], such as the duration of heating systems in winter and air conditioning in summer.

DECLARATION OF COMPETING INTEREST

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

DATA AVAILABILITY

Data will be made available on request.

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