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EVALUATION OF THE INDICES OF ENERGY RECUPERATION PART BY THE TROLLEYBUSES IN URBAN CONDITIONS

An investigation of a power consumption by the electric buses, trolleybuses is especially actual nowadays, in the time when an economous using of energy resources is necessary. Finding the power consumption during the tests or separate researches gives only a general image about the indices, but in real conditions of exploitation of the electric drive vehicles, when there is a row of external factors, such as movement conditions, driver's qualification, movement intensity etc., a value of power consumption can vary a lot, an indice of quantity of the recuperated electric power by a vehicle is especially sensitive to different factors. Buying the new modern movable units by the Urkainian trolleybus parks gives a possibility to make the volume researches of power consumption not only by separate trolleybuses, but also on separate routes and to determine this indice for a trolleybus park in general.

The analysis of literary sources shows that there is no determination of the fate of the recovered energy during the movement of the vehicle along the established route. Modern trolleybuses are equipped with direct current meters, which provide information on the amount of recovered energy during the vehicle's operation on the route. This fact was the basis of the conducted research.

In the given research work there is shown that a meaning of an electrical energy recuperation part by the vehicles with an electric traction unit that are powered from a contact system, are distributed by a normal law. It was established that the parameters of the normal distribution law are individual for each city of Ukraine, as they are significantly affected by traffic conditions. There were determined the confiding bounderies for further evaluation of applying this function in the trolleybuses operating systems.

Keywords: electric power, power consumption, recuperated energy, distribution law, trolleybus.

INTRODUCTION

An exploitation of urban public transport is constantly linked with the risks of losses, that is why a majority of countries introduces a system of dotations with a purpose to properly organize the passenger transportation. The problems concerning an economical expediency of applying the trolleybuses and/or electric buses have appeared in almost all the countries [1…4]. Undoubtedly that for an effective using of electric public transport it is necessary to upgrade (to renew) the movable units and to make an investigation concerning an increasing of exploitation effectiveness of trolleybuses and electric buses. So far as the power consumption makes a considerable part of a transportations value, these investigations are aimed exactly at the determination of the power consumption by the trolleybuses that are exploited in Ukraine, namely in cities Mariupol and Kryvyi Rih.

Realisation of the programs « UUPTP – Ukrainian urban public transport project» [5] and «UPTF – Ukrainian public transport framework» [6] in Ukraine, that are financed by the European Investment Bank and the European Bank for Reconstruction and Development, assured a possibility of renovation of the movable units for the enterprises of urban electric transport.

Whithin the frames of these programs, the enterprises of urban electric transport started to get the modern movable units that have modern operating systems of a tractive drive with a fucntion of energy recuperation while breaking. Such movable units, as a rule, are equipped with the direct current meters that allows to make the investigations aimed at a study of power consumption by the movable units at passenger transportation with a purpose to minimize the expenses of such works.

LITERATURE DATA AND FORMULATION OF THE PROBLEM

The main part of the investigations that were made in Ukraine and all over the world, where the vehicles with electric traction unit were a research object, concerned a scientific reasoning of separate parameters of such vehicles and their systems. Thus, an evaluation of exploitation cost of the vehicles with different types of power units is stated in the research works [7…11]. An expediency of using the energy storages in the electric networks of urban type is observed in a work [12…20], and optimization of parameters of the energy storages – in the works [21…26].

In the research works [27…30] there is given an argument of the main parameters choice of the bus with a power supply from a tractive accumulator battery.

The problems of consumption of energy sources for passenger traffic were examined in last years on the base of statistic infirmation concerning an energy consumption according to the indices of the alternating current meters that are mounted on the traction substantions and register all the consumptions for conversion of alternating current energy into direct current and its transportation from a traction substation to a collector of a trolleybus or a tramcar.

Besides, a majority of traction substations in Ukrainian cities feeds at the same time the tram and trolleybus transport that makes difficult an objective evaluation of energy distribution between these types of electric transport.

The main methodological approach to the evaluation of the volumes of consumed energy with a purpose to plan their consumptions for a planned time period is stated in the work [31].

An appearance of the first industrial prototypes of the measuring equipments to keep records of consumed electrical energy contributed to a beginning of works concerning an evaluation of energy consumption by a concrete tramcar or trolleybus for both passenger transportation and during their preparation for proper use.

The main methodological approaches to evaluation, control and management of energy consumption, in the presence of direct current meters on the movable units, were stated in the works [32, 33].

It is worse to notice that in all before mentioned works there was not examined such an important factor as a recuperated energy part during vehicle movement on a route, because the measuring equipment mounted on the vehicles, did not have such a function.

A problem of investigation of the energy recuperation systems, namely an effectiveness of its usage, is actively examined and reported in the research works [34…37].

The last samples of modern buses that were bought by the enterpises of urban electric transport, have got the direct current meters that give information about the number of recuperated energy during the vehicle operating on a route. It allows to make a research with a purpose to find its part in general energy consumption during a movement of a vehicle on a route. It is worse noticing that such investigations were made and cleared in the works [38…41].

PURPOSE AND OBJECTIVES OF THE STUDY

The aim of given research is a determination of a law of distribution of the values of recuperated energy part in general power consumption by trolleybuses during the passenger transportation on different routes.

RESEARCH RESULT

The reasoning of recuperated energy part that is created by the trolleybuses during the passenger transportation needs a determination of a law of its distribution, that, on its turn, needs a monitoring of the power consumption by a trolleybus and of the number of recuperated energy for different movement conditions. With this purpose there were given some offers to the organisation of statistic monitorings on the enterprises of urban electric transport that received new trolleybuses (a research object) with the direct current meters that have got a function of registration of consumed and recuperated energy number for 24 hours during an operating on a route.

The enterprises were offered to make a 10-days monitoring of the power consumption by the trolleybuses and to write down the monitoring results that should contain the next information:

- date of power consumption registration;
- route number where the power consumption monitoring was made;
- trolleybus run during the operating time on a route, km;
- consumed electrical energy during the trolleybus operating time on a route, kWt*h;
- number of recuperated energy, kWt*h .

According to the monitoring results there were received two samples whose general characteristics are shown in Table 1.

Table 1 – General characteristics of data samples

Ukrainian city	Number of routes	Number of participating trolleybuses	Sample dimension
Mariupol	7	8	71
Kryvyi Rih	3	11	107

A recuperated energy part in percents for a trolleybus working hours on a route during 24 hoours was calculated in such a way:

$$a_p = \frac{A_p}{A_c + A_p} \quad (1)$$

where A_p – recuperated energy number, kWh;

A_c – number of electrical energy consumed from a contact system, kWh.

The statistic indices of samples of the recuperation part values are shown in Table 2.

Table 2 – Statictic characteristics of samples of the recuperation part values

Ukrainian city	Sample dimension,	Minimal value, a_p^{min}, (%)	Maximum value, a_p^{max}, (%)	Average value, $\overline{x}$, (%)	Dispersion, σ^2	Standard deviation, σ
Mariupol	71	0,0281 (2,81)	0,1512 (15,2)	0,0635 (6,35)	0,0007	0,0262
Kryvyi Rih	107	0,0088 (0,88)	0,0971 (9,71)	0,0461 (4,61)	0,0002	0,0152

As though some factors influence a value of recuperation part, for example a speed of breaking start, a presence of electrical energy consumer during a recuperation breaking, a voltage value in an overhaed contact system, a driver's qualification, so it was taken into consideration like a working hypothesis that a distribution of the recuperation part values obeys a normal lawof distribution whose density is calculated in such a way:

$$f(x,\overline{x},\sigma)=\frac{1}{\sigma\sqrt{2\pi}}e^{\frac{(x-\overline{x})^2}{2\sigma^2}} \qquad (2)$$

where – $\overline{x}$ average value of recuperation part;

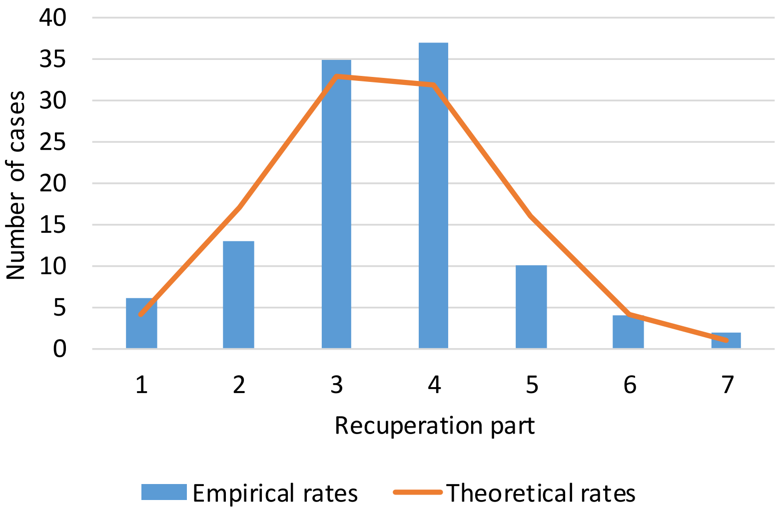
σ – standard deviation of recuperation part.

At figure 1 there is shown a distribution of empirical and theoretical rates of recuperation part.

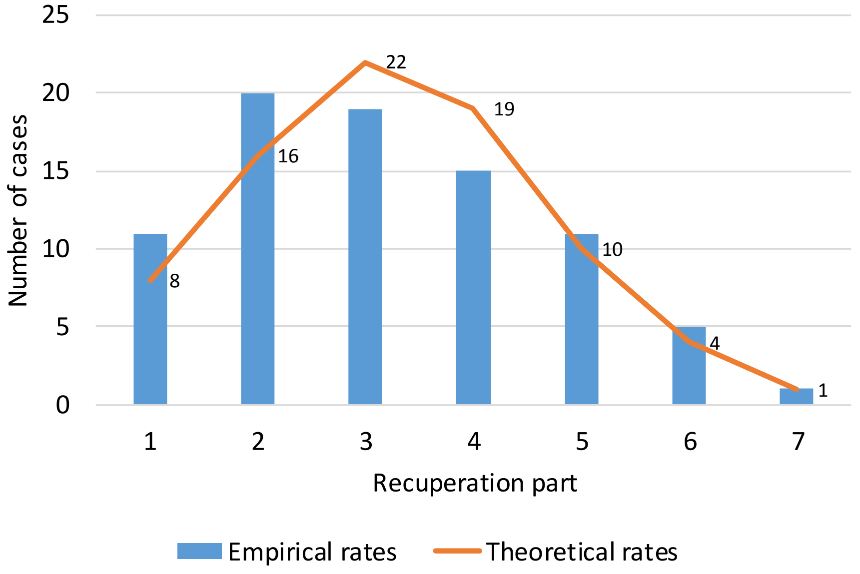
An evaluation of divergence between the empirical and theoretical distributions of recuperation part was made by a criterion χ^2 (2), that was calculated by such a formula:

$$\chi^2=\sum_{i=1}^{n}\frac{(n_f-n_t)^2}{n_t} \qquad (3)$$

where n_f, n_t – the rates of empirical and theoretical distribution rows correspondingly.



a)



b)

Figure 1 – Distribution of density of recuperation part: a) Sample of Kryvyi Rih city; b) Sample of Mariupol city

Calculation results of criterion χ^2 are given in table 3.

Critical value of criterion χ^2 was determined for probabilities 0,95, 099, 0,999 and liberty degrees:

$$V = L - 1 - p\,, \tag{4}$$

where p – number of parameters that are evaluated according to a sample (p=2)

L – number of groups (ranges) for which there was devided a sample after rates union (not numerous rates n<5, were united).

Calculated and table values of criteria χ^2 for examined samples are given in table 4.

Table 3 – Calculation results of criterion χ^2

Interval number	Kryvyi Rih city				Mariupol city			
	Middle of recuperation part range	n_f	n_t	$\frac{(n_f - n_t)^2}{n_t}$	Middle of recuperation part range	n_f	n_t	$\frac{(n_f - n_t)^2}{n_t}$
1	0,037	11	8	1,125	0,015	6	4*	1,000
2	0,054	20	16	1,000	0,028	13	17	0,941
3	0,072	19	22	0,409	0,040	35	33	0,121
4	0,090	15	19	0,842	0,053	37	32	0,781
5	0,107	11	10	0,100	0,066	10	16	2,250
6	0,125	5	4	0,250	0,078	4	4	0,000
7	0,142	1	1*	0,000	0,091	2	1*	0,000
			$\chi^2 =$	3,726				5,094
Note «*» - united ranges								

Table 4 – Values of criterion χ^2

Designation of sample	Calculated value of	Number of liberty degrees	Probability level		
			0,95	0,99	0,999

	criterion χ^2		Critical value χ^2		
Kryvyi Rih	3,726	3	7,8	11,3	16,9
Mariupol	5,094	2	6,0	9,2	13,8

That is, the samples can be considered as those that have a normal lawof distribution with a probability not less than 0,95 for Kryvyi Rih city and 0,99 for Mariupol city.

As one can see in table 2 the received average values for samples of recuperation part are different that needs an argument if this difference is important or not.

The dispersions of recuperation part values calculated according to the samples are also different that needs a determination of chance of this difference or, on the contrary, regularity.

Formally this problem can be formulated in a next way. There are two independent samples *A* i *B* of different volume with normal distribution. It is necessary to find if the samples were taken from normal general totalities with a same dispersion.

In this case a zero hypothesis consists in equality of dispersions, that is:

$$H_0 : \sigma_A^2 = \sigma_B^2, \tag{5}$$

and an alternative one:

$$H_1 : \sigma_A^2 \neq \sigma_B^2 \tag{6}$$

A ratio of selective dispersions *F* that obeys Fisher distribution, is taken as a criterion of evaluation of the dispersions proximity degree.

$$F = \frac{\sigma_A^2}{\sigma_B^2} = 3,5 \tag{7}$$

For the received values of dispersions of two samples, a calculated value of criterion F is equal to 3.5, at the same time its critical value for 107 and 71 degrees of liberty is equal to 1,44. That means that one can consider the dispersions unequal with a probability 0,95.

To compare the average values of samples, a zero hypothesis looks like:

$$H_0 : \bar{x}_A = \bar{x}_B, \tag{8}$$

and an alternative one:

$$H_0 : \bar{x}_A \neq \bar{x}_B, \tag{9}$$

In a case when both dispersions are predicted to be unequal, a value of criterion *t* that is used to confirm a hypothesis, is calculated using selective dispersions by a value *t* that is close to Student's t-distribution:

$$t = \frac{\bar{x}_A - \bar{x}_B}{\sqrt{\frac{\sigma_A^2}{n} + \frac{\sigma_B^2}{m}}} \tag{10}$$

Critical value of criterion *t* is chosen for a number of liberty degrees that is calculated in such a way:

$$\upsilon = \frac{\left(\frac{\sigma_A^2}{n} + \frac{\sigma_B^2}{m}\right)^2}{\frac{\left(\frac{\sigma_A^2}{n}\right)^2}{n-1} + \frac{\left(\frac{\sigma_B^2}{m}\right)^2}{m-1}} \tag{11}$$

To receive the average values of two samples, a determined value of criterion *t* calculated by a formula 10 is equal to 5.08, at the same time its critical value for 107 liberty degrees calculated by a formula 11 and confinding probability 0,95 is equal to 1,66. That means that the dispersions can be considered as unequal with a probability 0,95.

DISCUSSION OF THE RESULTS OF THE STUDY

An unequality of average values and dispersions for investigated cities shows that there are present different movement conditions that influence a recuperation part of electrical energy by trolleybuses.

Then the confinding bounderies of the values of a part of consumption and average value (see table 5) should be calculated separately for every city using a method of international standard [42] and reference tables [43, 44].

Table 5 – Confinding bounderies of sample and of average values of recuperation part

City	Average value of recuperation part (two-way case), %				Maximum value of recuperation part, no more (one-way case), %	
	Confinding probability, P= 0,95		Confinding probability P=0,99		P=0,95	P=0,99
	Minimum value	Maximum value	Minimum value	Maximum value		
Mariupol	5,73	6,97	5,53	7,17	10,71	12,59
Kryvyi Rih	4,11	5,11	3,95	5,27	8,96	10,8

SUMMARY

As a result of investigation there was found that a power recuperation part in the vehicles with an electrical traction unit that is powered from a contact system, has got a normal law of distribution.

The parameters of normal law of distribution in general case are individual for every city in Ukraine because the movement conditions influence them.

For the examined Ukrainian cities an average value of recuperation part varies within:

- from 5,29% to 6,27% of general consumed power for Mariupol city for a condinding level 0,95;
- from 4,32 % to 4,91 of general consumed power for Kryvyi Rih city for a condinding level 0,95;

A maximum recuperation part for the examined cities of Ukraine does not exceed, with a confinding probability 0,95, the next values:

- 7,45 % for Mariupol city;
- 6,28 % for Kryvyi Rih city.

A further investigation should be aimed at finding an influence of concrete movement conditions on a power recuperation part of the vehicles with an electrical traction unit that is powered from a contact system.

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Андрусенко С., Будниченко І., Дембіцький В. **Оцінка показників долі рекуперації енергії тролейбусами в умовах міського руху**

Дослідження витрат електричної енергії електробусами, тролейбусами особливо актуальним є на даний момент, в часи необхідності економного використання енергетичних ресурсів. Визначення витрат електричної енергії під час випробувань або окремих досліджень дає лише загальне уявлення про показники, однак в реальних умовах експлуатації транспортних засобів з електричним приводом, коли діє ряд зовнішніх чинників, таких як умови руху, кваліфікація водія, інтенсивність руху і т.п., величина витрат електричної енергії може значно коливатися, особливо чутливим до різноманітних факторів є показник кількості рекуперованої електричної енергії транспортним засобом. Придбання тролейбусними парками України нового сучасного рухомого складу дає можливість проводити об'ємні дослідження витрат електричної енергії не лише окремими тролейбусами, а й на окремих маршрутах та визначати цей показник для тролейбусного парку загалом.

Аналіз літературних джерел свідчить про відсутність визначення долі рекуперованної енергії під час руху транспортного засобу за встановленим маршрутом. Сучасні тролейбуси обладнані лічильники постійного струму, які надають інформацію про кількість рекуперованої енергії за час роботи транспортного засобу на маршруті. Даний факт був покладений в основі проведених досліджень.

В роботі показано, що значення долі рекуперації електричної енергії транспортними засобами з електричною тяговою установкою, що живляться від контактної мережі, розподіляються за нормальним законом. Встановлено, що параметри нормального закону розподілу є індивідуальними для кожного міста України, оскільки на них суттєво впливають умови руху. Визначено довірчі границі для подальшого оцінювання застосування цієї функції в системах керування тролейбусами.

Ключові слова: електроенергія, витрати електроенергії, рекуперована енергія, закон розподілу, тролейбус.

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