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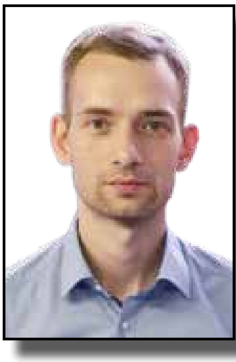
Testing the Methodology for Assigning Electric Buses to Municipal Regular Transportation Routes



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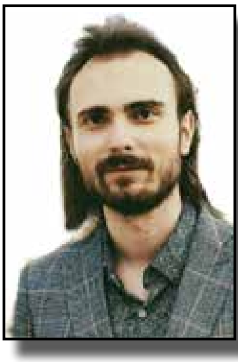

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ABSTRACT

The article is devoted to the issue of finding the optimal assignment of electric buses to a given set of routes.

Based on the results of the analysis of scientific research, four key technical and operational parameters determining the efficiency of using electric buses were identified: route length (L_m), operating speed (V_e), number of stopping points (N_{stop}) and daily traffic volume (Q).

The objects of the study were the routes serviced by State Unitary Enterprise «Mosgortrans», the operator managing the largest fleet of electric buses in Europe.

A statistical and cluster analysis of bus and electric bus routes of SUE «Mosgortrans» was conducted based on the selected parameters. The use of cluster analysis made it possible to classify the routes by the similarity of technical and operational parameters. The assessment of the conformity of bus routes with electric bus routes was made by comparing the average values of the standardised indicators in each of the clusters. A priority cluster of routes for operation of electric buses has been determined, and the main statistical parameters of the technical and operational indicators of the routes included in it have been determined.

To test the proposed methodology and solve the technological problems of organising the operation of rolling stock, taking into account the homogeneity of the route parameters in the cluster, a typical bus route has been selected and the main technological problems of the operation of an electric bus on the selected route have been solved.

Keywords: *electric bus, municipal routes of regular transportation, technical and operational indicators of the route.*

Authors' contribution: *M. V. Skorkin has carried out statistical and cluster analysis, built appropriate graphs, calculated values of dispatched fleet.*

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The original text of the article in Russian is published in the first part of the issue.
Текст статьи на русском языке публикуется в первой части данного выпуска.

BACKGROUND

Methodical approaches to choosing routes for electric bus service

The issues of electric bus operation in the formation of the rolling stock fleet structure are the subject of many scientific works by domestic and foreign researchers. The performed analysis allowed us to group the main areas of research in the selected area:

– comparative assessment of the operation of electric buses, trolleybuses and buses with different power units on municipal routes [1–5];

– analysis of electric bus charging concepts [6–11];

– planning the required number and location of charging stations [9; 12–15];

– standardisation of electric bus energy consumption and identification of parameters influencing it [16–21];

Based on the results of the performed analysis, it was established that one of the most important tasks when deciding to assign an electric bus to a route is the analysis and determination of technical and operational parameters influencing the choice of route [22–26].

The analysis of methodological approaches to organising the operation of electric buses made it possible to determine four priority technical and operational parameters that affect the choice of route (L_r, V_o, N_{stop}, Q). The analysis of these parameters in solving the problem of assigning an electric bus to a route will largely ensure the operation of the electric bus with the optimal range of residual charge of the battery and, accordingly, determine the charging time of the electric bus when performing trips [27].

The routes of State Unitary Enterprise «Mosgortrans» [Moscow City Transport], the largest operator of the ground urban passenger transport operating electric buses and buses on regular municipal routes, were selected as the object of the study [26]. As of March 2023, SUE «Mosgortrans» operated 1055 electric buses on 79 routes. The total number of routes serviced by SUE «Mosgortrans» was 694.

At the first stage, it is proposed to analyse the main statistical indicators of the technical and operational parameters of bus and electric bus routes.

Using the Sturges' formula, the optimal number of groups for each analysed parameter for bus and electric bus routes is determined:

$n_e = 1 + 3,322 \cdot \lg 79 = 7$ [groups],

$n_b = 1 + 3,322 \cdot \lg 615 = 10$ [groups].

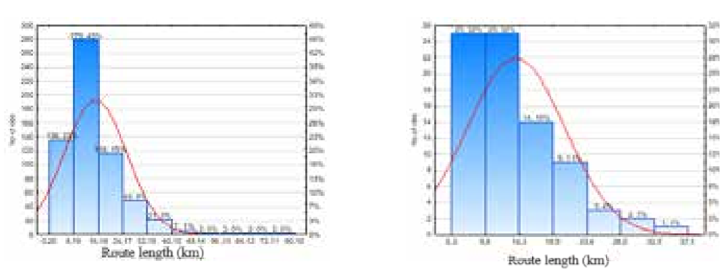
Statistical analysis of technical and operational parameters of routes

A comparative analysis of the lengths of bus (Pic. 1a) and electric bus (Pic. 1b) routes revealed that electric buses are used on shorter routes, this is due to the provision of charging infrastructure and the energy capacity of traction batteries, which has a direct impact on the range.

Thus, on bus routes the average route length is 15,1 km, the minimum and maximum values are 0,2 km and 80,1 km, respectively; the modal interval of the length of bus routes is 8,19–16,18 km (279 routes, 45 %). On electric bus routes, the average route length is 13,8 km, the minimum and maximum values are 6,6 km and 37,1 km, respectively; the modal interval of the length of electric bus routes is 5,2–9,8 km (25 routes, 32 %) and 9,8–14,3 km (25 routes, 32 %).

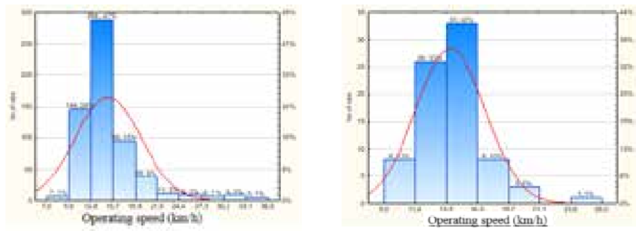
Pic. 2 shows the histogram of the distribution of operating speed on bus (a) and electric bus routes (b).

The analysis of the distribution graph of the operating speed of buses shows (Pic. 2a) that the average value of the operating speed is 15 km/h, the minimum and maximum values are 7 km/h and 36 km/h, respectively; the modal speed range for bus routes is 12,8–15,7 km/h (288 routes,



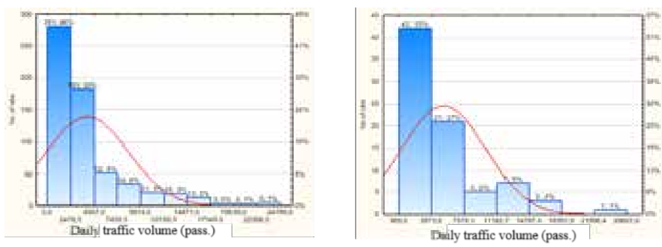
a) L_r of bus routes　　*b) L_r of electric bus routes*

Pic. 1. Distribution of route lengths (km) [Source of values – GIS «Mosgortrans» software package. The graph created by the authors].



a) V_o of buses *b) V_o of electric buses*

Pic. 2. Distribution of operating speed on routes (km/h) [Source of values – GIS «Mosgortrans» software package. Graph created by the authors].



a) Q on bus routes *b) Q on electric bus routes*

Pic. 3. Distribution of daily traffic volume (passengers) [Source of values – GIS Mosgortrans software package. The graph created by the authors].

47 %). On electric bus routes (Pic. 2b), the average value of the operating values is 14,1 km/h, the minimum and maximum values are 9 km/h and 26 km/h, respectively; the modal range of the operating speed on electric bus routes is 11,4–13,9 km/h (26 routes, 33 %) and 13,9–16,3 km/h (33 routes, 42 %).

Pic. 3 shows the results of the analysis of the distribution of the daily volume of transportation on bus (a) and electric bus routes (b).

The average daily traffic volume on bus routes is 4200 passengers, the minimum and maximum numbers are 0 passengers and 24785 passengers, respectively; the modal range of daily traffic volume is 0,0–2478,5 passengers (281 routes, 46 %) and 2478,5–4957,0 passengers (183 routes, 30 %). On electric bus routes, the average daily traffic volume is 5270,1 passengers, the minimum and maximum numbers are 369 passengers and 25601passengers, respectively; the modal range of daily traffic volume is 369,0–3973 passengers (42 routes, 53 %) and 3973,6–7578,1 passengers (21 routes, 27 %).

In conclusion, the analysis of the number of stopping points (SP) on electric bus (a) and bus routes (b) was performed (Pic. 4).

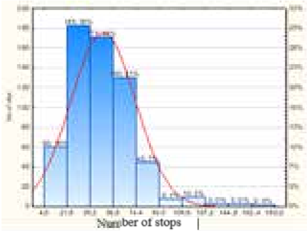
The average value of the number of SP on bus routes is 48,9 units, and the minimum and maximum are 4 units and 180 units, respectively; the modal interval is 21,6–39,2 units (183 routes, 30 %) and 39,2–56,8 units (171 routes, 28 %). The following indicators were calculated for electric bus routes: the average value of the number of SP is 49,7 units, the minimum and maximum are 15 units and 99 units, respectively; the modal interval of the number of stops falls within the range of 27–39 units (19 routes, 24 %).

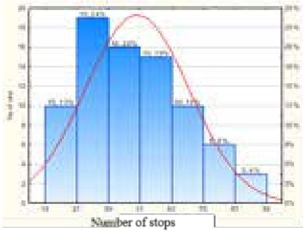
RESULTS

Clustering routes by selected parameters

The solution to the problem of assigning electric buses for operation on a route can be optimised using a multivariate statistical procedure for cluster analysis of routes, tested earlier [28; 29].

«The use of cluster analysis involves the implementation of a scientifically based partitioning of a set of municipal routes of regular transportation of ground urban public passenger transport $X\{x_1, ..., x_i, ..., x_j, ..., x_n\}$ into non-intersecting subsets $C\{c_1, ..., c_i, ..., c_j, ..., c_n\}$ according to the specified parameters $G\{g_1, ..., g_i, ..., g_j, ..., g_n\}$. The partitioning is performed in such a way that, in accordance with a given metric ρ: $c_i=\{x_i, x_j \mid x_i, x_j \epsilon X$ and $\rho(x_i, x_j) < \sigma\}$, where σ is a measure of closeness, each route $\{X\}$ fell into one cluster and belonged to one and only one subset of the partition. Accordingly, routes belonging to the same subset are similar, while routes belonging to different clusters are heterogeneous. The criterion for determining the similarity or difference of clusters is the





a) N_{stop} of bus routes *b) N_{stop} of electric bus routes*

Pic. 4. Number of SP on the route (performed by the authors).

distance between points on the scatter diagram» [28].

The heterogeneity of the units of measurement of the specified parameters poses the problem of normalising the original values, for the purpose of a reasonable expression of the values on the same scale. Normalisation of the parameters (the transition from the original values *G* to the normalised values *Z*) is performed by dividing the centered value by the standard deviation of the parameter, according to the formula:

$$Z = \frac{(g_i - \overline{g})}{\sigma},$$

where Z – normalised value of the parameter g; $\overline{g}$ – average value of the parameter g; σ – standard deviation.

Along with standardisation of variables, there is an option to assign a certain weight *W*, which would reflect the significance of each of the corresponding variables. In the problem under consideration, we will assume the equivalence of the influence of all parameters, $W = 1$.

It is proposed to classify routes using the classical method of hierarchical cluster analysis, where the Manhattan distance will be used as a measure of proximity. The clustering procedure is performed using the Ward's method.

The results are presented in the form of a horizontal dendrogram (Pic. 5), where the abscissa axis contains the values of the unification distance, and the ordinate axis contains the values of the route numbers.

To determine the number of clusters, a threshold distance of ≈ 225,52 was set based on the results of the analysis of the route unification process graph (Pic. 6) and the table of object unification steps.

The analysis involves determining the step number *m*, the unification at which occurred at a significantly greater distance than at step *m*-1, with the subsequent determination of the number of clusters equal to *n*–*m*, where *n* is the number of routes in the cluster.

The analysis results show that the number of clusters is 4, with the possible subsequent selection of any route from the formed homogeneous groups. Brief descriptive statistics of the parameters of each cluster are presented in Table 1.

Based on the results of the analysis, it was found that the routes included in cluster No. 1 are characterised by a relatively short route length, low operating speed, close to the average value of the number of stopping points and the highest average daily passenger flow.

The routes included in cluster No. 2 are also characterised by a high route length, operating speed and average values of the number of stopping points and average daily passenger flow.

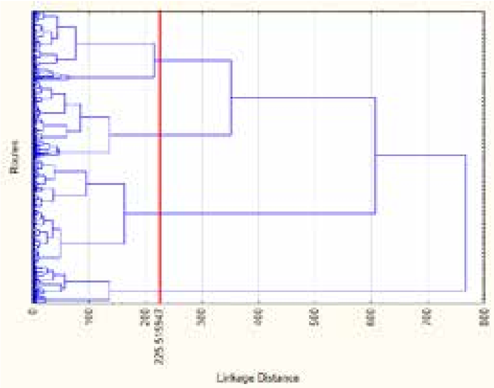
The routes included in cluster No. 3 are characterised by the lowest values of the average route length, operating speed, number of stopping points, and a relatively low value of the average daily passenger flow.

The routes included in cluster No. 4 are characterised by the greatest route length, operating speed and number of stopping points, as well as the lowest value of the average daily passenger flow.

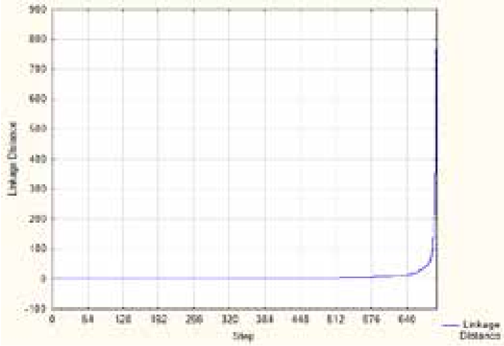
To justify the choice of routes and to create homogeneous groups of clusters, an assessment was made of the share of electric bus routes in each cluster (Table 2).

Additionally, the difference in the average values of the normalised parameters of bus and electric bus routes relative to the average values of the parameters of the obtained clusters was calculated. A hypothesis was put forward about the normal distribution of the values of all parameters. Based on the results of the analysis, the greatest correspondence was established for three of the four selected parameters (L_r, V_o, N_{stop}) of cluster No. 4 of bus routes to electric bus routes.

To test the proposed methodology and solve the technological problems of starting operation of the fleet considering the homogeneity of the



Pic. 5. Dendogram of cluster analysis [performed by the authors].



Pic. 6. The process of combining routes into clusters [performed by the authors].

route parameters in cluster 4, route No. 116 (Fili Park – Belorussky Railway Station) was selected.

Testing the proposed methodology

Operational data for route No. 116 (Fili Park – Belorussky Railway Station) for March 25, 2023 are provided in Table 3.

To determine the required number of rolling stock, the nominal passenger capacity was calculated considering the requirements of the Social Standard ($S^{H}_{1\ pass}$ = 0,33 м²)[1].

According to measurements, the area intended for standing passengers (S_{st}) is 8,14 m², the total area of the electric bus ((S_{total}) is 31,62 m², the area allocated for seats (S_{seat}) is 23,48 m², respectively n_{st} = 24 pass., q_n = 57 pass.

In Pic. 7, the hatching shows the floor area intended for standing passengers.

The calculation of the time required to charge the traction batteries was carried out taking into account the studies [24–27]. Calculation of the specific energy consumption on the route:

$$W_{sp} = \frac{1,68 \bullet V_e}{16} + 1 \approx 2,6[kW \bullet h],$$

where 1,68 – power consumption for traction in kW•h at a speed of 16 km/h (average speed according to the technical specifications for the purchase of electric buses), as well as an additional 1 kW•h for the operation of the climate control system.

Calculation of total energy consumption on the route:

$$W_m = W_{sp} \bullet L_m \approx 80,8 \text{ [kW•h]}.$$

Calculation of the time required to charge traction batteries:

$$t_{ch} = \frac{W_m \bullet 24}{201} = 9,7[\text{min}].$$

According to calculations, 80,8 kW•h or 40,2 % of the battery capacity is consumed per turnaround trip, which is the optimal value for operation [27]. The charge level of the battery depending on the mileage is shown in Pic. 8.

The calculation of intervals depending on the number of electric buses on the route is shown in Table 4.

Taking into account the volume of passenger traffic per hours of the day, at the first stage the required number of electric buses on the route and the headway are calculated.

Having determined the estimated number of electric buses based on hourly values of passenger traffic, the required number of electric buses is then adjusted, taking into account:

– the level of quality of transportation;

– the coefficient of technical readiness of the rolling stock;

– the optimal value of the headway;

– the coefficient of occupancy of the rolling stock.

During rush hours an adjustment is made considering possibility of the public transport enterprise to operate extra fleet, in other words, deficit coefficient:

$$A_{ad}^{peak} = A_{es}^{peak} \bullet k_{def} [\text{min}],$$

where A_{ad}^{peak} – adjusted value of electric buses on the route;

A_{es}^{peak} – estimated value of the number of electric buses on the route;

k_{def} – electric bus deficit coefficient.

The maximum number of electric buses is operated during rush hours for 2–3 hours.

[1] Order of the Ministry of Transport of the Russian Federation dated January 31, 2017 No. NA-19-r «On approval of the social standard of public transport services for the carriage of passengers and baggage by road and urban ground electric transport».

Table 1

Descriptive statistics of the parameters of the cluster of bus and electric bus routes [the table of values obtained from the results of own calculations]

Parameters	Cluster №	Average	Median	Standard deviation	Sample variance	Min.	Max.	Number
L_r	C1	11,06	9,80	5,36	28,76	0,20	24,50	89
	C2	18,73	16,00	8,64	74,69	7,50	61,60	183
	C3	9,03	8,40	3,77	14,19	1,30	19,00	258
	C4	22,21	18,35	12,52	156,75	6,40	80,10	164
V_o	C1	13,85	14,00	2,72	7,40	9,00	30,00	89
	C2	15,97	14,00	4,87	23,74	9,00	36,00	183
	C3	13,54	13,00	2,55	6,52	7,00	24,00	258
	C4	16,40	14,50	5,11	26,09	10,00	34,00	164
N_{stop}	C1	49,65	45,00	24,27	588,80	4,00	124,00	89
	C2	56,46	57,00	16,06	257,81	5,00	97,00	183
	C3	31,67	32,00	10,53	110,88	5,00	63,00	258
	C4	164,00	67,54	28,43	808,26	4,00	180,00	164
Q	C1	12207,04	12219,00	5362,86	28760228,54	2682,00	25601,00	89
	C2	5425,30	4446,00	3257,89	10613819,60	1092,00	19688,00	183
	C3	2407,89	1937,00	1774,58	3149119,90	0,00	10045,00	258
	C4	1822,06	1635,50	1230,50	1514141,73	18,00	7440,00	164

Table 2

Share of electric bus routes in the cluster [performed by the authors]

Cluster	Share of electric bus routes
1	8,9 % (7 routes)
2	7,6 % (6 routes)
3	36,7 % (29 routes)
4	46,8 % (37 routes)

Table 3

Operational data of the route [The source of values is the GIS Mosgortrans software package. The graph was created by the authors]

Indicator	Value
Daily operated fleet: total/OBK/BK/SK/MK (units)	10/-/10/-/-
Average daily planned turnaround time (min.)	111
Route length (km)	31,386
Operating speed (km/h)	15
Minimum interval (min.)	24
Maximum frequency (units/hour)	2,5
Number of stops (pcs.)	66…68

Adjustments in the «pre-peak», «inter-peak» and «post-peak» zones are carried out taking into account the quality of passenger service, according to the formula:

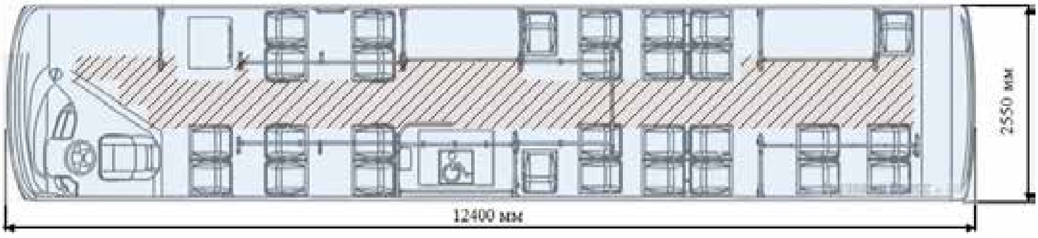
$\gamma = A_{esi} / A_{adi}$

The adjustment of «pre-peak», «inter-peak» and «post-peak» zones is carried out taking into account certain types of route (main roads – I_a = [5–10] min, regional I_a up to 15 min, social – I_a = [19–28] min) of the optimal values of headways depending on the time of day or depending on the type of route, according to the formula:

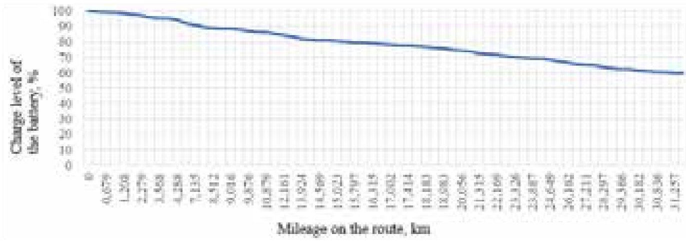
$A_{min} = t_{total} / I_{enterprise}$ [units].

The adjusted values for the number of electric buses on the route are shown in Pic. 9.

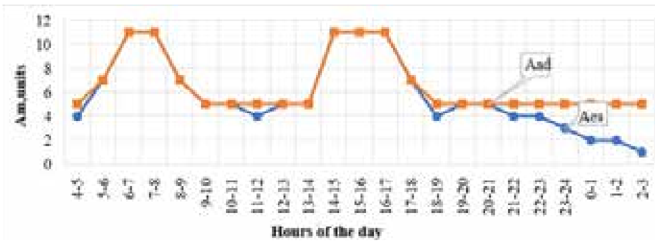
The direction of further research is to determine the optimal location and calculate the required number of charging stations, taking into account the overlap of electric bus routes.



Pic. 7. Scheme of the electric bus KAMAZ-6282 (top view) [performed by the authors].



Pic. 8. The charge level of the battery depending on the mileage on the route No. 116 [performed by the authors].



Pic. 9. Adjusted values of the number of operated electric buses per hours of the day [performed by the authors].

Table 4

Headway depending on the number of electric buses [performed by the authors]

Number of electric buses A_e, units	Headway I_a, min
1	135,2
2	67,6
3	45,1
4	33,8
5	27
6	22,5
7	19,3

CONCLUSION

22 methodological approaches were analysed and 4 priority technical and operational parameters influencing the choice of route (L_r, V_o, N_{stop}, Q) were identified.

A statistical and cluster analysis of bus, electric bus and the entire set of routes of the State Unitary Enterprise «Mosgortrans» was carried out according to the selected parameters. The share of electric bus routes in clusters was assessed. Additionally, an assessment of the conformity of bus and electric bus routes was made by comparing the average values of the normalised indicators of the entire set of electric bus and the resulting clusters of bus routes. Based on the analysis results, a hypothesis was put forward about the greatest conformity of cluster No. 4 of bus routes with electric bus routes. To test the proposed methodology and solve the technological problems of starting the operation of rolling stock, taking into account the homogeneity of the route parameters in cluster 4, route No. 116 (Fili Park–Belorussky Railway Station) was selected.

The main technological problems of starting the operation of an electric bus on the selected route were solved.

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