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Methodical Approach to Organisation of Transportation on Electric Bus Routes



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ABSTRACT

When developing projects for introduction of electric buses into operation and determining the required infrastructure, it is necessary to justify the concept and methodological approaches to choosing of routes, to estimate the number of charging stations, depending on their type, and to conduct economic assessment of the proposed solutions in specific operating conditions.

The article discusses the main issues of organising operation of buses with electric traction (electric buses) on the routes of public urban surface transport. A primary analysis of both current and prospective electric bus routes was carried out regarding the city of Moscow.

Adaptive calculation methods are proposed based on classical methods for determining the required number of vehicles for a route regarding a given transit capacity, passenger traffic flow, and a given traffic interval.

The current and prospective schemes for location of charging stations are considered, a method for determining their required number is proposed.

A methodological approach of determining direct costs associated with transportation has been adapted to operation of electric buses on the route.

Keywords: *urban surface passenger transport, operation of electric buses, charging stations.*

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Background.

The phased transition from operation of diesel buses to the use of buses with electric traction (electric buses) on the routes of the public urban surface passenger transport currently constitutes a global trend. Scientific and experimental research is being conducted on introduction of various versions of electric buses into operation in many countries of Europe, North America, in China, Japan, Korea, and other states [1]. In Russia, the city of Moscow has become the initiator of introduction of electric buses for urban public transport.

When developing projects and determining the required infrastructure, it is necessary to substantiate the concept and methodological approaches of selecting routes, organising transportation, to quantify the needs for charging stations depending on their type, and to conduct an economic assessment of the proposed solutions regarding specific operating conditions. Some specific issues of efficient organisation of operation of public transport are considered in the works [2–5].

Electric buses are a relatively new type of vehicles, and that predetermines the need for a balanced and objective substantiation of the choice of certain alternative options for technical, technological, organisational, economic, and other solutions.

An earlier analysis of regulation and organisation of passenger transportation by urban surface electric transport conducted by the authors made it possible to reveal that at present various systems of vehicle classification are used [in Russia], but the term «electric bus» has not been approved [6]. For the time being, only trams and trolleybuses are legally classified as urban electric vehicles.

Based on the requirements for admission of drivers for the right to drive electric buses, they belong to vehicles of «D» category, i.e., to buses. According to the concepts of battery charging speed, the electric buses can be divided into several classes and groups [6].

At present, researchers and industrial employees do not have a clear answer regarding economic feasibility of switching from diesel buses to electric ones. In some countries and cities, there are still adherents of converting urban transport to gaseous fuels, hydrogen, hybrid plants and other alternative fuels. In specific operating conditions and with specific infrastructure, each option can be economically justified. Type (class) of the bus, its passenger capacity, etc. are of great importance in justifying the transition to electric buses. Currently, both in the world and in particularly in Russia, when developing projects for introduction of electric buses into operation, vehicles with a length of 12 meters, which are large class buses, are usually considered. It is evident that buses of a class of a lower or higher capacity will have completely different economic features.

The issue of choice of the concept and economic assessment is currently a debated topic at the international level, and the unanimously accepted approach is missing [7–10].

Innovative development in any area of the economy is a field of searching for alternative options and concepts. Public transport is no exception. The tendencies of agglomeration enlargement throughout the world [4; 5], deterioration of the ecological situation in them [6], problems emerging due to an increase in the number of vehicles on the road network [1–4] force the city authorities to make decisions aimed at development of transport using alternative fuels.

Development of the route network of electric buses

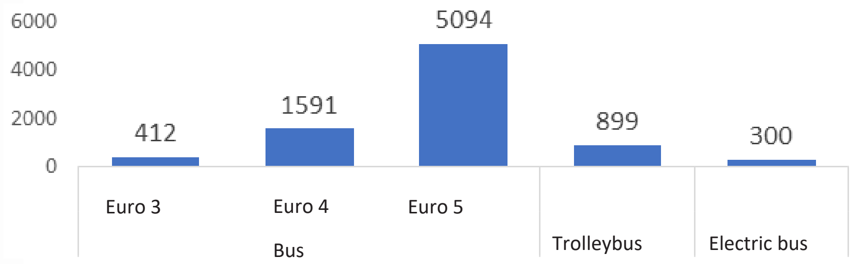
1049 municipal routes of regular transportation are registered in the city of Moscow, including 771 routes serviced by Mosgortrans [Moscow City Transport] State Unitary Enterprise in accordance with the register of December 27, 2019[1].

At present, SUE Mosgortrans is the main operating enterprise of buses using electric traction [in the country] and the sole in the city of Moscow.

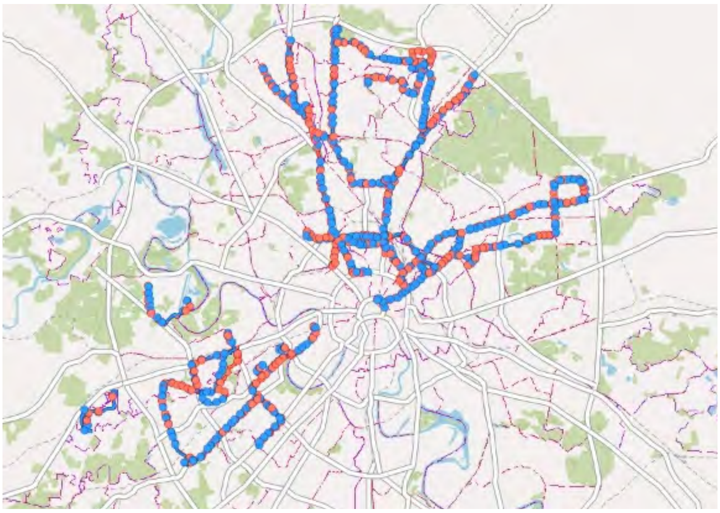
The analysis of the structure of vehicles of SUE Mosgortrans as of 01.01.2020 showed that the total number of vehicles was 8926 units (Pic. 1), including 300 electric buses.

According to the information of the single information system (SIS) in the field of procurement, in 2018 two contracts were

[1] Official website of the Mayor of Moscow. Register of municipal routes for regular transportation of passengers and luggage by road and surface electric transport in the city of Moscow dated December 27, 2019. [Electronic resource]: https://www.mos.ru/dt/documents/view/223682220/. Last accessed 23.03.2020.



Pic. 1. Structure of vehicles of SUE Mosgortrans (data provided by SUE Mosgortrans).



Pic. 2. Routes of buses with electric traction (the map was compiled on the basis of data from the official website of SUE Mosgortrans using GIS Mosgortrans software).

concluded for supply of 200 buses with electric traction to the North-Eastern branch with the provision of services for their subsequent maintenance and repair for 15 years. According to the results of the competition, 100 units of KamAZ-6282[2] and 100 units of LiAZ-6274[3] model were delivered.

According to the decisions taken in 2018[4], 100 units of KamAZ-6282 model were purchased with delivery to Filevsky bus and trolleybus depot of the Central branch of SUE Mosgortrans.

In 2020, it is planned to supply 200 electric buses of KamAZ-6282 model to the territory of the operating site of the First trolleybus depot and 100 electric buses of LiAZ-6274 model to the operating site of Filevsky bus and trolleybus depot of the Central branch of SUE Mosgortrans[5, 6].

As of the first quarter of 2020, electric buses operate on 23 regular routes. The general operational characteristics of the routes are presented in Table 1. The routes are shown in Pic. 2.

In accordance with development plans for 2020, it is planned to convert 10 trolleybus and 14 bus routes into electric bus routes. The future route network of SUE Mosgortrans for buses with electric traction is shown in Pic. 3.

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[2] Official website of SIS. Electronic auction No. 0173200001417001533. [Electronic resource]: https://zakupki.gov.ru/epz/order/notice/ea44/view/supplier-results.html?regNumber=0173200001417001533. Last accessed 23.03.2020.

[3] Official website of SIS. Electronic auction No. 0173200001417001534. [Electronic resource]: https://zakupki.gov.ru/epz/order/notice/ea44/view/supplier-results.html?regNumber=0173200001417001534. Last accessed 23.03.2020.

[4] Official website of SIS. Electronic auction No. 0173200001417001532. [Electronic resource]: https://zakupki.gov.ru/epz/order/notice/ea44/view/supplier-results.html?regNumber=0173200001417001532. Last accessed 23.03.2020.

[5] Official website of SIS. Electronic auction No. 0173200001419001670. [Electronic resource]: https://zakupki.gov.ru/epz/order/notice/ea44/view/common-info.html?regNumber=0173200001419001670. Last accessed 23.03.2020.

[6] Official website of SIS. Electronic auction No. 0173200001419001671. [Electronic resource]: https://zakupki.gov.ru/epz/order/notice/ea44/view/supplier-results.html?regNumber=0173200001419001671. Last accessed 23.03.2020.

Table 1

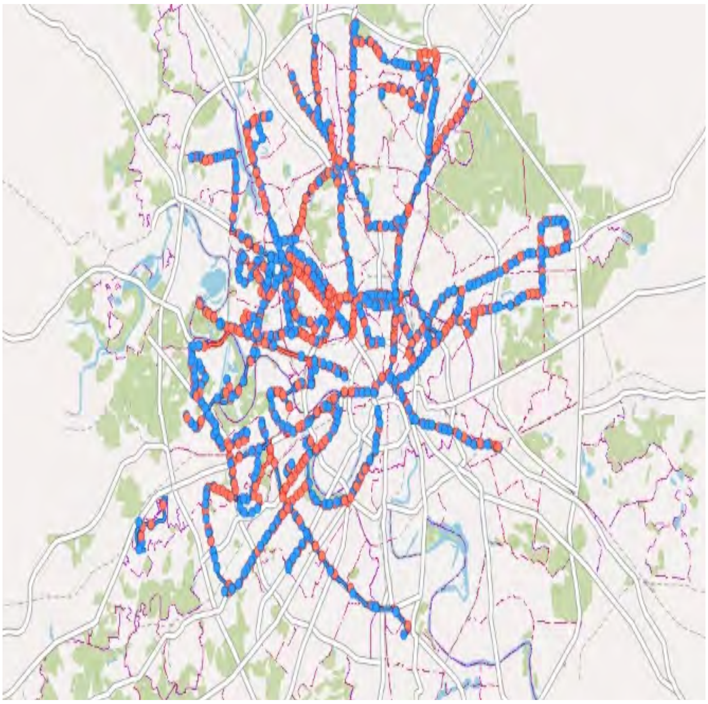
Operating indicators of routes

No. of route	End points	Fleet	Release total /SLC/ LC/MC/SC (un)	Time of turnaround trip (mi)	Route length (km)	Operating speed (km/h)	Minimal interval (min)	Maximal frequency (un/h)	Transportation peak/inter-peak/ day (pass)
93	VDNH (south)–Medvedkovo metro	EL	6/-/-/6/-	86,4	10,9	15,1	17,6	3,4	803/991/2218
107	Filevsky park metro–Matveevskaya platf.	ELC	6/-/6/-/-	53,8	6,6	14,7	11,3	5,3	713/729/1691
205K	Kievsky station–Ul. Dovzhenko	ELC	6/-/6/-/-	41,5	6	17,4	9	6,7	933/725/1950
622	Ozernaya metro–Slavyansky bulvar metro	C	9/-/9/-/-	87,3	14	19,2	10,7	5,6	1621/1573/3969
649	Yasny pr.–Ostashkovskaya ul.	EL	5/-/5/-/-	59,7	6,4	12,9	16,7	3,6	403/380/879
778	Rizhsky station–Spartakovskaya pl.	EL	4/-/4/-/-	42,3	5,4	15,3	13	4,6	432/485/1153
791	Kievsky station–4-Setunsky pr.	ELC	7/-/7/-/-	32,9	4,6	16,8	5,9	10,1	1521/1101/3479
810	Rizhsky station–Tikhvinskaya ul.	EL	3/-/-/3/-	43,9	3,6	9,8	25	2,4	-/-/-
832	Krylatskoe–Sport center Krylatskoe	ELC	5/-/5/-/-	43,4	5,4	14,9	9	6,7	658/639/1554
Sk1	TMK/Sibur–Hub	ELC	3/-/3/-/-	36	5,9	19,7	23,1	2,6	-/-/-
H3	Ussuriiskaya ul.–Kitay-gorod metro	EL	6/-/6/-/-	138	20,4	17,7	37,5	1,6	-/-/332
T14	Severyaninskiy overpass–Elektrozavodsky bridge	EL	16/-/16/-/-	143,7	15,2	12,7	12	5	-/-/-
T17	Ozernaya metro–Kievsky station	ELC	20/-/20/-/-	103,4	12,6	14,6	5,8	10,3	6846/6473/16629
T25	Prosp. Budennogo–Lubyanka metro	EL	11/-/11/-/-	82,4	7,6	11,1	9	6,7	-/-/-
T34K	ul. Kravchenko–Kievsky station	ELC	17/-/17/-/-	96,2	10,9	13,6	6,3	9,5	5937/4947/12032
T36	VDNH (south)–Dmitrovskoe sh	EL	15/-/15/-/-	112,9	13,1	13,9	9,2	6,5	-/-/-
T42	Rizhsky station–Petrovskiy park metro	ELC	14/-/14/-/-	56,8	5,8	12,2	6	10	-/-/-
T47	Beskudnikovsky per.–Samotechnaya pl.	EL	20/-/20/-/-	95,7	12	15,1	6	10	6737/5275/15090
T56	Bazovskaya ul.–Tverskaya Zastava	EL	20/-/20/-/-	109,6	13,8	15,1	4,7	12,8	1736/2469/6279
T73	6-mkr. Bibireva–VDNH (south)	EL	34/-/34/-/-	105,4	12,4	14,1	3,7	16,2	-/-/-
T76	Kholmogorskaya ul.–VDNH metro	EL	28/-/28/-/-	69,3	8,8	15,2	2,9	20,8	-/-/-
T80	6-mkr Bibireva–Ostashkovskaya ul.	EL	10/-/10/-/-	68,3	7,1	12,5	8,8	6,8	-/-/-
T83	Ussuriiskaya ul.–Preobrazhenskaya pl. metro	EL	17/-/17/-/-	78,3	8,9	13,6	5,8	10,3	-/-/-

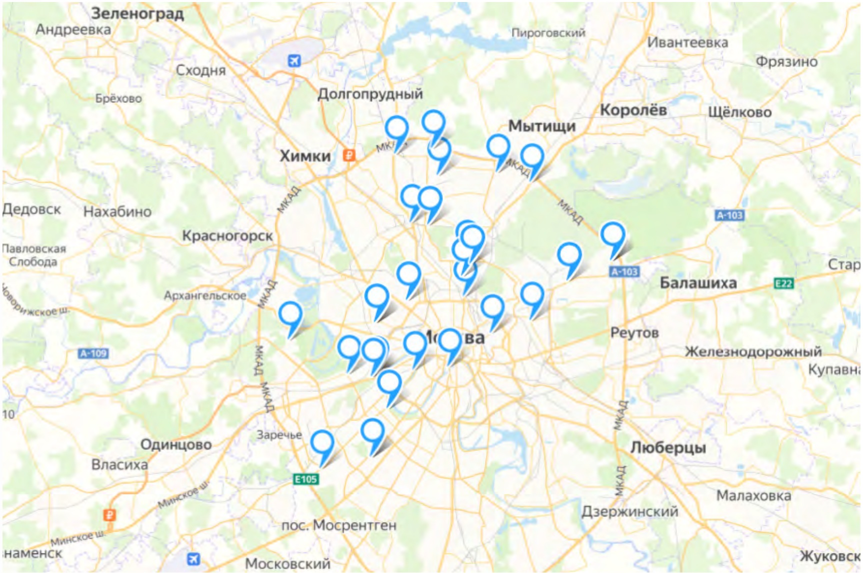
Source: Mosgortrans GIS software system.

When developing a project to create an infrastructure for operation of highly environmentally friendly electric vehicles, and introducing electric traction buses with dynamic charging, it is proposed to consider not only the prospects for development of the route network of electric buses of SUE Mosgortrans, but also the existing transport infrastructure of trolleybuses.

First, it is proposed to implement bus routes, which completely coincide with trolleybus routes. The analysis of the route



Pic. 3. Prospective electric bus route network. Source: GIS Mosgortrans software package.



Pic. 4. Layout of location of charging stations. Source: Tender documentation. Terms of reference.

network made it possible to identify 12 such routes (Table 2).

At the same time, it is proposed to exclude express routes and routes served by buses of a super large class (903, 907, T144K, T63, T71), since the operation of electric buses on these routes can have a significant impact on quality of transportation services for the population.

Calculation of the required number of charging stations

According to the analysis of the tender documentation, along with supply of buses with electric traction, supply, and installation of 98 charging stations is envisaged. The layout of location of charging stations is shown in Pic. 4.

A general perspective layout of location of ultrafast charging stations is shown in Pic. 5.

Table 2

Operating characteristics of bus routes

No. of route	End points	Release total/SLC/LC/MC/SC (un)	Time of turnaround trip (min)	Route length (km)	Operating speed (km/h)	Minimal interval (min)	Maximal frequency (un/h)	Transportation peak/inter-peak/day (pass/)
903	Kholmogorskaya ul.–Prosp.Mira metro	27/15/12/-/-	80,3	13,4	20	2,8	21,4	9657/10121/26521
907	Kashirskoe sh., 148–Dobryninskaya metro	15/15/-/-/-	97,7	17,8	21,9	9,2	6,5	6338/7429/17725
T18	Rizhsky station–Strelbishchensky per.	14/-/14/-/-	108,8	10,7	11,8	6,6	9,1	5217/5095/12910
T26	Karacharovsky overpass–Avtozavodsky bridge	12/-/12/-/-	105,8	13,8	15,6	10,7	5,6	8113/6711/18298
T32	Ussuriiskaya ul.–Garazhnaya ul.	17/-/17/-/-	141,8	17,1	14,5	13	4,6	2472/2811/8281
T51	Pl. Solovetskikh Yung–Izmailovskaya metro	11/-/11/-/-	49,2	4,8	11,7	4,8	12,4	5640/4855/14926
T63	138-kv Vykhina–Taganskaya metro	15/15/-/-/-	105,2	14,1	16,1	8,2	7,3	8500/9801/24023
T67	Kashirskoe sh., 148–Avtozavodskiy bridge	6/-/6/-/-	112,5	18,2	19,4	23,1	2,6	1650/1971/4803
T71	Kashirskoe sh., 148–Dobryninskaya metro	15/15/-/-/-	123,4	17,8	17,3	9,7	6,2	7501/6863/18749
T86	Serebrynniy bor–Sokol metro	12/-/12/-/-	93,4	11,7	15	8,6	7	5274/3713/11646
T88	Prosp. Budennogo–Komsomolskaya pl.	6/-/6/-/-	51,3	5,4	12,6	10,9	5,5	1942/1668/4929
T144K	Kravhcneko ul.–Oktyabrskaya metro	10/-/10/-/-/	51,3	8,8	20,6	6,9	8,7	3607/4708/9961

The primary step to determine the required number of charging stations is to assess the number of vehicles operated on the route. When calculating the number of vehicles A_o, the necessary initial data are:

1. Data on passenger traffic flow in the context of hours of the day, days of the week and stopping points (entry/exit).

2. Passenger capacity of an electric bus.

3. Operating data of the route (time of turnaround trip, route length, operating speed, etc.).

In this case, the passenger capacity is determined considering the number of seats and standing places (no more than eight people per square meter of the area which is not occupied by seats).

Calculation of A_o must be performed separately for the spring-summer period and the autumn-winter period, weekdays and weekends, rush hours and inter-peak hours.

The analysis of various approaches of calculating A_o made it possible to group them according to three indicators:

1. According to the given performance of the bus using electric traction.

2. According to the passenger flow.

3. According to the set traffic interval.

A feature of calculating time of the turnaround trip t_{ta} when determining A_o, regardless of the choice of the target indicator, is the need to consider the battery charging time, respectively:

$T_{ta} = \sum t_m + \sum t_{st} + \sum t_{tst} + \sum t_{ch}$,

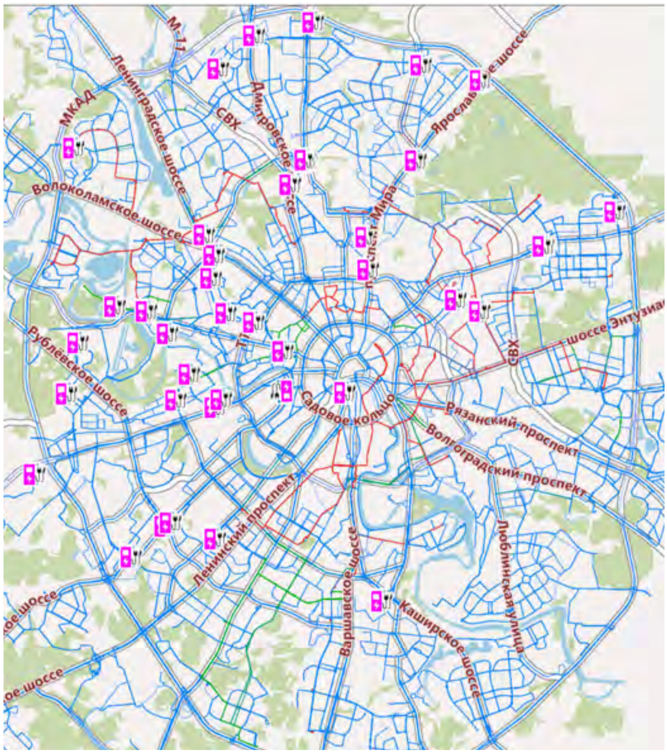
where t_m – time of movement on the route;

t_{st} – idle time at intermediate stopping points for embarking/disembarking passengers;

t_{tst} – technological idle time at terminal stopping points;

t_{ch} – battery charging time which is defined as the product of the required number of charging cycles by time spent on one charge cycle.

It should be noted that $\sum t_{ch} > 0$, when operating buses with electric traction within the models of slow and ultra-fast charging. For buses powered by electric traction with dynamic charging, $\sum t_{ch} = 0$ since the battery



Pic. 5. Prospective layout of location of charging stations. Source: Mosgortrans GIS software system and tender documentation.

can be powered when driving from the trolleybus overhead line.

In the future, it is proposed to calculate the required number of buses with electric traction, depending on the selected indicator.

For a given performance of a bus powered by electric traction, the calculation of A_o is performed according to the formula:

$$A_o = \frac{Q \cdot (l_{tr} + V_{ts} \cdot \beta \cdot (\sum to + \sum tch)}{T_r \cdot q \cdot \gamma_{pc} \cdot C_{pr} \cdot V_t \cdot \beta},$$

where Q – performance of a bus on electric traction;

l_{tr} – trip length;

V_{ts} – technical speed;

β – coefficient of mileage use;

T_o – time of route operation;

q – passenger capacity;

γ_{pc} – coefficient of passenger capacity use;

C_{pr} – coefficient of rotation of passengers on the route.

According to data of the passenger flow, the calculation of the required number of buses with electric traction A_o is made according to the formula:

$$A_o = \frac{Q_{max} \cdot t_{ta}}{q \cdot \gamma_{pc}},$$

where Q_{max} is maximal passenger intensity on the route segment.

According to the set interval of movement the calculation of A_o is made according to the formula:

$A_o = 60t_{ta}/I_{ti}$,

where I_{ti} is a set interval of electric buses traffic.

The calculation of the number of charging stations depends directly on the chosen concept of the mode of charging electric buses.

Thus, the power supply system of a bus powered by electric traction with dynamic recharging can become the basis of a single charging infrastructure for the entire electric transport of the city, thanks to the connection of objects with a contact network[7]. The use of contact networks will make it possible to avoid large earth works, which will shorten the project implementation time.

Due to dynamic charging when moving from the contact network, buses with electric

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[7] Order of the Ministry of Transport of the Russian Federation dated April 18, 2013 No. NA-37-r «On enactment of Guidelines for calculation economically substantiated cost of transportation of passengers and luggage on urban and suburban routes with public road and urban surface electric transport». [Electronic resource]: https://www.mintrans.ru/press-center/news/5761. Last accessed 23.03.2020.

traction of any class can work steadily for 24 hours on the route, without wasting time on charging the batteries.

Charging stations for private electric vehicles, taxis and shared cars can be integrated into the catenary support.

The traction substation with installation of blocks of capacitances for the efficient use of recuperation and solar photoelectric cells will increase energy efficiency.

At night, businesses that line the overhead networks use power for slow charging stations for municipal and commercial electric vehicles.

Calculating the number of charging stations for electric buses with slow and ultra-fast charging requires additional calculations. Currently, there is no uniform approach of calculating the required number of charging stations. The calculation of the required number of charging stations when choosing the concept of slow and ultra-fast charging is proposed based on the data of the terms of reference regarding procurement of electric buses and in four stages:

1. Calculation of specific energy consumption on the route:

$W_{sp} = ((1{,}68 \cdot V_o)/16) + 1)$, kW • h,

where V_o is operating speed;

1,68 – power consumption for traction in kW • hs at a speed of 16 km/h (average speed according to the ToR regarding purchase of electric buses);

+1 means additional amount of 1 kW • h consumed by climate control equipment.

2. Calculation of the total energy consumption on the route:

$W_r = W_{sp} \cdot L_r$, kW • h,

where W_{sp} – specific energy consumption on the route;

L_r – route length.

3. Calculation of time required for charging traction batteries:

$t_{ch} = (W_r \cdot 24)/70$, min,

where W_r – energy consumption on the route;

70 – used capacity of the battery kW • h.

4. Calculation of the required number of charging stations:

$N_{ch} = t_{ch} / I$, un.,

where I – planned interval of arrival of buses with electric traction to the charging station.

The calculation of the planned interval of arrival should be carried out considering overlaying of routes, served by buses with electric traction.

Economic assessment of proposed solutions

The economic assessment of introduction and operation of electric buses on urban routes is a relatively new, but relevant subject of research, both for foreign and domestic scientific and practical community.

Currently, domestic and foreign researchers have already developed general methodological approaches of economic assessment of operation of buses with electric traction on urban routes. At the same time, the proposed methods and the results of their approbation do not allow making unambiguous conclusions about advisability of switching to operation of buses with electric traction.

At the same time, it should be noted that there are no regulatory legal acts in the country on calculations of economic justification of the cost of operating buses with electric traction, while there are regulations regarding trolleybuses, trams, diesel buses, etc.

The issue of choosing the concept of economic assessment is currently a debatable topic, and there are no unambiguously accepted approaches at the international level.

The further described approach is based on the methodological recommendations of the Ministry of Transport of the Russian Federation, approved by order of April 18, 2013 No. NA-37-r [14] and is recommended for use in determining direct costs associated with transportation.

The purpose of this methodological approach is to determine the cost of 1 kilometre of a bus run using electric traction.

Initial data in the calculation are:

1. Operating parameters of the routes.
2. Traffic schedule.
3. Transportation volume (actual or planned).

It is proposed to make calculation for each *i* brand and model of a bus with electric traction according to the formula:

$$\sum_{i=1}^{n} S_{aoikm} = P_{DWikm} + P_{fikm} + P_{eimovkm} + P_{olikm} + P_{ti\text{км}} + D_{ikm} + P_{cnikm} + P_{tsikm} + P_{chsikm},$$

rub./1 km of mileage,

where P_{DWikm} – driver's wage fund;

P_{fikm} – fuel costs when equipping electric buses with autonomous diesel heaters, l/h;

$P_{eimovkm}$ – energy costs for movement (charging);

P_{olikm} – costs for operating and lubricating materials;

P_{tikm} – costs for operation of tires;

D_{ikm} – depreciation;

P_{cnikm} – costs for the cable network;

P_{tsikm} – costs for traction substations;

P_{chsikm} – costs for charging stations.

When operating a bus with electric traction, the costs do not include the costs of maintenance and repairs, since they are included in the cost of the vehicle according to the terms of the life cycle contract.

Calculation of the cost of 1 seat/kilometre, of 1 passenger/kilometre, and of transportation of 1 passenger, is to be performed according to the formulas, respectively:

$S_{pass.seat.km\ i} = S_{ik}/q_i$, rub.,

$S_{pass.kmi} = S_{pass.seat.kmi}/\gamma$, rub.,

$S_{pass.i} = S_{pass.\ km\ i} \cdot l_{av}$, rub.,

where q_i – passenger capacity of i brand and model of an electric bus;

γ – average coefficient of use of passenger capacity,

l_{av} – average distance of a trip of one passenger, km.

Conclusion.

The article has analysed the current level and highlighted the immediate prospects for development of operation of buses with electric traction on municipal routes of the city of Moscow.

The general issues of organising operation of buses with electric traction on the routes of public urban surface transport have been considered. The proposed methods for calculating the required number of vehicles on the route are based on classical approaches, considering the peculiarities of operation of electric buses. Similarly, a method is proposed for calculating the required number of charging stations on the route, considering data of terms of reference for purchase of electric buses.

A methodological approach of economic assessment of introduction of electric buses into operation is proposed, based on determination of direct costs related to transportation.

This methodological approach can form the basis for development of projects for introduction of electric buses into operation.

Further research is aimed at development of a frequency method of assessing quality of transport services provided to customers on electric bus routes.

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