Improving the efficiency of route passenger transport systems by using recovered energy

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Abstract. This article analyzes the problems associated with increasing the efficiency of route passenger transport systems, with an in-depth consideration of tram subsystems. The focus is on using recovered electrical energy to optimize the operation of trams. The recovered energy produced during vehicle braking or deceleration can be effectively stored in on-board storage devices and then used to power the tram's traction system. The article makes the case for the relevance of this proposal, emphasizing not only the potential benefits in efficiency and resource savings, but also its significance in terms of reducing emissions and environmental sustainability of the public transport system. Schemes for implementing this approach are presented, including technical aspects of implementation and possible algorithms for controlling the energy storage and distribution system. An important element of the analysis is to determine the expected economic effect from the implementation of the proposed system. The authors of the article present an assessment of the economic benefits that can be achieved by reducing energy costs for traction and reducing the costs of maintaining and operating the transport system. Potential investments and financial aspects of implementing a new system are also discussed, which makes this study interesting both for engineers and technical specialists, as well as for economists and managers in the field of transport infrastructure.

1 Introduction

The tram is the oldest type of electric transport, the vehicles of which move along the laid rail track and are driven by traction electric motors that receive electrical energy from the overhead contact network (there are systems where ground current collection is used, as well as systems with autonomous running sections to preserve the aesthetic appearance of the central urban development, but they are single character and are rather an exception to the general rule). The tram, as a mode of transport, originates in the XIX century [6, 7, 8, 9] and in world practice there are examples of the use of this type of transport for urban, suburban, intercity and international transportation [1].

The tram is the most reliable, high-speed, comfortable, eco-friendly and economical. The tram has the highest carrying capacity among the types of land route passenger transport, which, in general, can compete only with the metro or the city railway [10, 11, 12, 13, 14].

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The implemented high accelerations and decelerations make it possible to increase the accessibility of the tram for passengers, significantly reducing the distances between stopping points without significantly reducing the speed of communication, which makes the tram indispensable for efficient passenger transport services in cities [15, 16, 17, 18, 19].

The advantage of trams over other modes of transport is also emphasized by the lowest specific consumption of electric energy per 1 km of mileage per 1 pass. This property is due to the low coefficient of resistance to movement in the wheel–rail interaction pair, as a consequence of the need for a lower thrust force to maintain high accelerations and the presence of a large run-out without significantly reducing the speed of movement [2].

2 Methods

The tram power supply system (Fig. 1) consists of external and internal power supply. From the external power supply side, the high voltage received via high-voltage power lines from power plants (thermal, wind, nuclear, etc.) is lowered and further distributed to consumers, which include tram traction substations. Traction substations are part of the tram's internal power supply system and are used to convert alternating current with a voltage of 6-10 kV to direct current with a voltage of 600 V. In urban conditions, the electricity needed for tram rolling stock is supplied from traction substations to tram lines mainly via cable networks using positive supply lines, from which it is then supplied to the contact wire [20, 21, 22, 23, 24, 25]. The trams themselves are connected to the contact wire using a current collector, through which electricity is supplied to the high-voltage equipment of the tram. The electric circuit is "closed" through the wheel pairs and the rail network, the negative supply line and the zero point of the traction transformer of the tram traction substation [3]
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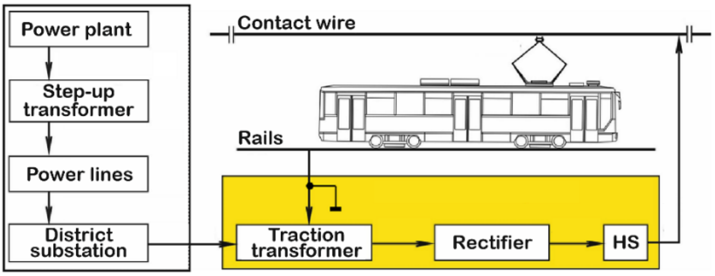

Fig. 1. Tram power supply scheme.

The contact network is partitioned (divided) into electrically isolated sections from each other, which are also called sections of the contact network. Such sections are separated from each other by insulators, which are called sectional insulators. Each section of the contact network receives power from the traction substation via a separate supply line. Partitioning is carried out to increase the reliability of power supply, reduce losses during transmission of electricity under the supply load, maintain constant voltage on each section of the contact network, ensure localization of emergency areas, disconnection of individual sections [26, 27, 28, 29, 30].

The length of sections of the tram line within the boundaries of the section depends on the intensity of tram traffic, the profile of the track, the location of stopping points and traffic lights [34, 38], the purpose of the sections, the technical speed of the trams, the adopted power supply scheme (centralized, decentralized), the selected section of the contact wire and other factors, according to the experience of operation in the conditions of Minsk can vary from 200 to 800 m . Figure 2 shows a fragment of the internal power supply scheme for a part of the tram line in the "Serebryanka" microdistrict in Minsk with the indication of conditional numbers and boundaries of sections of partitioning [4, 31, 32, 35, 36, 37].

Figure 3 shows a simplified diagram of the high-voltage electrical equipment of the tram rolling stock (the diagram is made conditionally, using the example of a 4-axis tram connected to a contact wire using a current collector T and is intended only for further explanation of the distribution of "electric energy flows" in the circuits of high-voltage electrical equipment of the tram receiving power from the contact network with a nominal voltage of 550 C).

Fig. 2. Schematic diagram of the partitioning of a part of the tram line in the "Serebryanka" microdistrict in Minsk

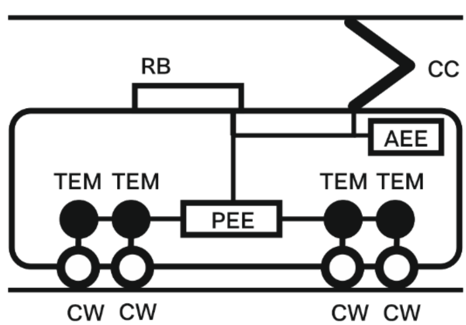

Fig. 3. Simplified diagram of high-voltage electrical equipment of the tram

By appointment, high-voltage electrical equipment is divided into power (PEE) and auxiliary (VO) high-voltage equipment. The device is designed to drive a tram using traction electric motors (TEM), each of which, in turn, drives the corresponding wheelset (CW). To extinguish the electricity generated by the TEM in braking mode, TR brake resistors are designed, as a rule, located on the roof of the tram.

Fig. 4 shows the schematic diagram of the tram operation in traction mode, while the high–voltage equipment of the tram receives power through the CC-AEE circuit||PEE–4xTEM–4xCP, TEM operate in the engine mode, create the torque necessary to create traction force and set the tram in motion.

TEM, being electric machines with the property of reversibility, can work not only in the engine mode to create torque and implement traction mode, but can also work as electric power generators, which, generating electric energy, reduce the speed of the tram (with the necessary intensity up to almost a complete stop). As a rule, the electrical energy generated in this way can be recovered into the contact network and directed to power other trams located within the boundaries of the contact network section, or extinguished in brake resistors with subsequent dissipation of the resulting heat in the atmosphere.

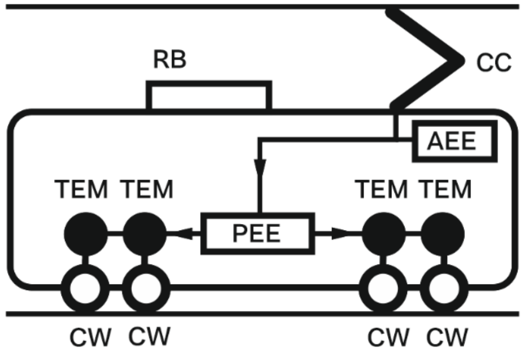

Fig. 4. Schematic diagram of tram operation in traction mode

Figure 5 shows the schematic diagram of the tram operation under the conditional number 1 in the recovery mode. At the same time, the TEM of this tram operate in generator mode, and the electric energy generated by them is directed along the 4xTEM–PEE–AEE circuit ||CC is the contact wire to the high–voltage equipment of the tram under the conditional number 2, which in turn receives power actually from the tram with the conditional number 1 through the Contact wire–CC–AEE circuit||PEE–4hTEM–4hCW, its TEM work in the mode of engines, create the torque necessary to create traction force and set the tram in motion. In this case, a prerequisite for the recovery mode for a tram under conditional number 1 is the presence of a tram with conditional number 2 within the boundaries of the contact network section in which it is located, which at the moment will become a consumer of recovered energy, moving in traction mode.

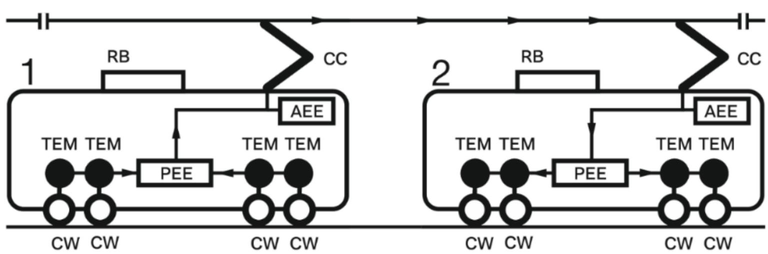

Fig. 5. Schematic diagram of the tram operation in the mode of electric regenerative braking

Tram traction substations are unidirectional in their design and provide only the transmission of electric energy to trams, and are not designed to receive (redistribute) energy in the opposite direction. Therefore, if there are no consumers in the form of other trams within the boundaries of the contact network section at the time of braking of the tram, recovery does not occur, and all the electric energy generated by the TEM is mainly extinguished in the braking resistors with subsequent dispersion in the atmosphere.

Figure 6 shows the schematic diagram of the tram operation in the mode of electric rheostatic braking, while the electric energy generated by the TEM is directed along the 4xTEM–PEE–TR (or TR||AEE — partially in some versions of electric circuits of trams).

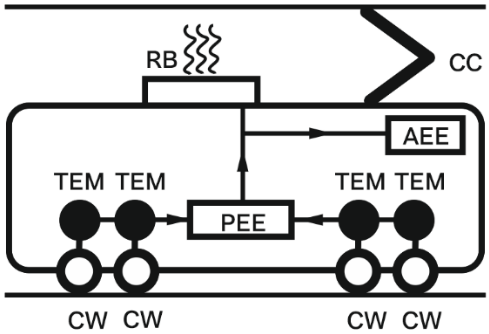

Fig. 6. Schematic diagram of the tram operation in the mode of electric rheostatic braking

The analysis of operational data and diagnostic data shows that the majority of tram braking is carried out precisely according to the scheme of electric rheostatic braking without energy recovery into the contact network due to the absence of other consumer trams on the section bounded by the boundaries of sections (or due to the activation of overvoltage protection). In this case, electrical energy is dissipated in the brake rheostats and is used in this way completely unproductively [33].

At the current level of development of electrochemical current sources, devices for accumulating charge and electric field energy (including electrochemical devices), it is of interest to implement a proposal aimed at equipping trams with onboard energy storage devices designed to accumulate recovered electrical energy for the purpose of its subsequent use for tram traction.

To implement this proposal, the following can be used as onboard energy storage devices installed in parallel with the RB:

a) supercapacitors (ionistors);

b) lithium-titanate batteries;

c) lithium-iron-phosphate batteries;

d) lithium-nickel-manganese-cobalt-oxide batteries.

The main technical characteristics of some on-board energy storage devices widely used in Belarus are given in Table 1 [5].

Table 1. Technical characteristics of some energy storage devices

Name of the parameter	**AOWEI S585V39-K7-A**	**4x40WB-LYP100AHA(B)**	**2xPP 320-689**
Drive Type	supercapacitors (ionistors)	lithium-iron-phosphate batteries	lithium-nickel-manganese-cobalt-oxide batteries
Capacity, F	1250	—	—
Energy reserve, kWh	34	51,2	41,4
DC operating voltage range, V	420…585	448…640	300…800
Discharge current	Up to 450 A	100 A (impulsively 300 A)	160 A (pulsed to 350 A)
Rated charging current, A	450	100	100
Maximum charge current, A	500	125	160
Weight, kg	1300	528	860

3 Results and Discussions

The results of observations based on the experience of tram operation show that the specific electricity consumption for tram traction lies in the range of 1.8..2.5 kWh/km for 15-meter trams and in the range of 2.2..3.05 kWh/km for 26-meter trams. Taking into account these indicators, as well as the fact that 15-meter and 26-meter trams use 4 TEM with a total capacity of 320 kW, it is advisable to use a more expensive, but effective version of ionistors as an energy storage device. At the same time, the energy reserve sufficient for the implementation of the proposal is 3.4 kWh.

Fig. 7 shows a schematic diagram of the tram operation in the electric braking mode with energy storage in the onboard storage H, while the electric energy generated by the TEM is directed along the 4xTEM–PEE–N circuit (or N||AEE — in the corresponding versions of the electric circuits of trams).

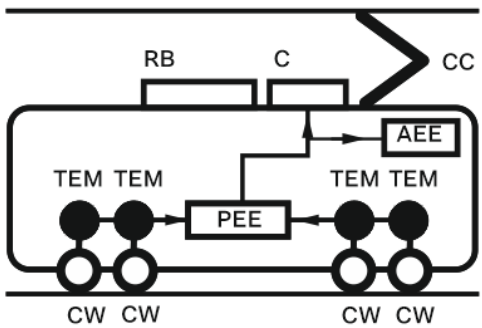

Fig. 7. Schematic diagram of tram operation in electric braking mode with energy storage

In the proposed scheme, even if there are no consumers within the boundaries of the section of the contact network section, the generated electric energy will be dissipated on the RB only if the H cannot accept the volume of electric energy generated by the TEM.

Figure 8 shows a schematic diagram of the tram operation in traction mode powered by an onboard storage device, while the high–voltage equipment of the tram receives power via the H-AEE circuit||PEE–4xTEM–4xCP, TEM operate in the engine mode, create the torque necessary to create traction force and set the tram in motion. At the same time, various algorithms for using the energy accumulated in the drive can be implemented in this scheme (for example, operation in buffer mode or controlled use of the drive's electric power for traction when the charge level reaches up to 80% of the capacity with its discharge to 30% and subsequent charge to 80%, etc.).

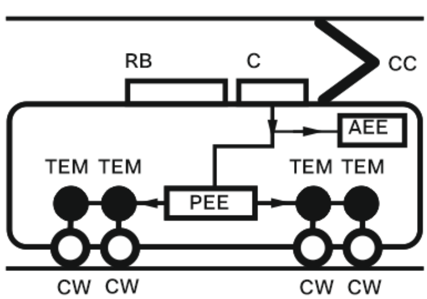

Fig. 8. Schematic diagram of the tram operation in traction mode powered by onboard storage devices

Analysis of the data collected during the processing of readings of onboard electric energy meters shows that due to recovery, it is possible to "return" from 12% to 20% of electric energy. On average, a tram fleet serving the route network with a line output of 100 units on weekdays and 50 units. on weekends, it has an annual electricity consumption of 13,564,000 kWh (seasonally adjusted) with a tariff at current prices of 0.26 BYN/kWh (as of 01/13/2022, exchange rates of 1 BYN = 2.5689 USD, 100 RUB = 3.4465 BYN are set).

The cost of installing onboard storage devices (ionistors) at an estimated price of one storage device of 20,550 BYN for 125 trams (taking into account the output coefficient of 0.80) is estimated at 2,568,750 BYN. At the same time, the annual savings with 16% use of recovered energy will amount to 564,264 BYN, thus, the installation of onboard storage devices will pay off in 4.5 years, with a life cycle of 15 years, the net effect of savings will be 5,895,186 BYN.

4 Conclusions

In conclusion, it is worth noting that the considered proposal is quite promising and has great scientific and technical innovation potential. Modern trends formed under the influence of directions for the development of ecological modes of transport, green economy, rational use of natural resources, achievements in the field of electronics and electrical engineering allowed, rationally reviewing the stereotypes formed in the design and operation of tram rolling stock, to propose the use of ionistors as onboard energy storage and thereby rationally approach the use of electricity obtained through the use of the property reversibility of electric machines.

References

1. Kot, E.N., (2018). Tram system of Minsk — problems and prospects. Socio-economic problems of development and functioning of transport systems of cities and zones of their influence. Materials of the XXIV International Scientific and Practical Conference, Minsk, BNTU, pp. 197-222.
2. Semchenkov, S.S., (2004). Trams of Minsk today. Minsk, Informpress, 87 p.
3. Rules of technical operation of the tram, (1996). Approved by Order of the Minister of Housing and Communal Services of the Republic of Belarus 03.09.1996, No. 101, Minsk, Belinkommash, 100 p.
4. SN 3.03.02–2019. Tram and trolleybus lines, (2020). Official publication 2019-12-16, Minsk, Stroytechnorm, Vol. IV, 57 p.
5. Kapski, D.V. et.al., (2019). Assessment of the possibility of using trolleybuses and electric buses in Polotsk and Novopolotsk. Organization and safety of road traffic, Tyumen, Tyumen Industrial University, pp. 266-273
6. Semtchenkov, S. and Kapski, D., (2022). Vestnik of Polotsk State University. Part B. Industry. Applied Sciences, **45(3):** 85-90.
7. Semtchenkov, S. and Kapski, D., (2022). Development of rational work schedules for drivers of route passenger transport using the sectoral method. ACTA Polotsk State University. Part B. Industry. Applied Sciences, **46(10):** 64-72.
8. Abdurazzokov, U., Sattivaldiev, B., Khikmatov, R., & Ziyaeva, S. (2021a). E3S Web of Conferences, **264**, 05033. https://doi.org/10.1051/e3sconf/202126405033
9. Abdurazzokov, U., Sattivaldiev, B., Khikmatov, R., & Ziyaeva, S. (2021b). E3S Web of Conferences, **264**, 05033. https://doi.org/10.1051/e3sconf/202126405033

10. Dashdamirov, F., Abdurrazzokov, U., Ziyaev, K., Verdiyev, T., & Javadli, U. (2023).. E3S Web of Conferences, **401**, 01070. https://doi.org/10.1051/e3sconf/202340101070
11. Faizullaev, E. Z., Rakhmonov, A. S., Mukhtorjanov, U. M., Turdibekov, S., & Nasirjanov, Sh. I. (2023). E3S Web of Conferences, **401**, 03022. https://doi.org/10.1051/e3sconf/202340103022
12. Fayzullaev, E., Tursunbaev, B., Xakimov, S., & Rakhmonov, A. (2022, June). AIP Conference Proceedings (Vol. **2432**, No. 1). AIP Publishing.
13. Fayzullayev, E., Khakimov, S., Rakhmonov, A., Rajapova, S., & Rakhimbaev, Z. (2023). Traffic intensity on roads with big longitudinal slope in mountain conditions. E3S Web of Conferences, **401**, 01073. https://doi.org/10.1051/e3sconf/202340101073
14. Ikromov, A. (2023, March). AIP Conference Proceedings,**2612 (1).** AIP Publishing.
15. Kasimov, O. (2023). Method for regulation of permissible irregularity of brake forces on front axle. E3S Web of Conferences, 401, 02033. https://doi.org/10.1051/e3sconf/202340102033
16. Kasimov, O., & Tukhtamishov, S. (2023). Mathematical model of braking process of car. E3S Web of Conferences, 401, 02034. https://doi.org/10.1051/e3sconf/202340102034
17. Keldiyarova, M., Ruzimov, S., Bonfitto, A., & Mukhitdinov, A. (2022, October). Comparison of two control strategies for range extender hybrid electric vehicles. In 2022 International Symposium on Electromobility (ISEM) (pp. 1-6). IEEE.
18. Khakimov, S., Fayzullaev, E., Rakhmonov, A., & Samatov, R. (2021). Variation of reaction forces on the axles of the road train depending on road longitudinal slope. E3S Web of Conferences, 264, 05030. https://doi.org/10.1051/e3sconf/202126405030
19. Kulmukhamedov, Z., Khikmatov, R., Erbekov, S., & Saidumarov, A. (2022, June). Maximum temperature values of the engine and auto motor vehicles units in conditions of elevated ambient temperatures. In AIP Conference Proceedings, 2432(1), 030040). AIP Publishing LLC.
20. Kulmukhamedov, Z., Khikmatov, R., Saidumarov, A., & Kulmukhamedova, У. (2021). Theoretical research of the external temperature influence on the traction and speed properties and the fuel economy of cargo-carrying vehicles. Journal of Applied Engineering Science, 19(1), 68–76. https://doi.org/10.5937/jaes0-27851
21. Kutlimuratov, K., Khakimov, S., Mukhitdinov, A., & Samatov, R. (2021). Modelling traffic flow emissions at signalized intersection with PTV vissim. E3S Web of Conferences, 264, 02051. https://doi.org/10.1051/e3sconf/202126402051
22. Mavlonov, J., Ruzimov, S., Tonoli, A., Amati, N., & Mukhitdinov, A. (2023). Sensitivity Analysis of Electric Energy Consumption in Battery Electric Vehicles with Different Electric Motors. World Electric Vehicle Journal, 14(2), 36. https://doi.org/10.3390/wevj14020036
23. Mukhitdinov, A., Abdurazzokov, U., Ziyaev, K., & Makhmudov, G. (2023, March). Method for assessing the vehicle energy efficiency on a driving cycle. In AIP Conference Proceedings, 2612, (1), 060028). AIP Publishing LLC. https://doi.org/10.1063/5.0114531
24. Mukhitdinov, A., Ziyaev, K., Abdurazzokov, U., & Omarov, J. (2023). Creation of the driving cycle of the city of Tashkent by the synthesis method. In AIP Conference Proceedings, 2612, (1), 060029. https://doi.org/10.1063/5.0126363

25. Mukhitdinov, A., Ziyaev, K., Omarov, J., & Ismoilova, S. (2021). Methodology of constructing driving cycles by the synthesis. E3S Web of Conferences, 264, 01033. https://doi.org/10.1051/e3sconf/202126401033
26. Nurmetov, K., Riskulov, A., & Ikromov, A. (2022). Physicochemical aspects of polymer composites technology with activated modifiers. In AIP Conference Proceedings, 2612, (1), 020011. https://doi.org/10.1063/5.0106358
27. Sanjarbek, R., Mavlonov, J., & Mukhitdinov, A. (2022). Analysis of the Powertrain Component Size of Electrified Vehicles Commercially Available on the Market. Communications - Scientific Letters of the University of Zilina, 24(1), 74–86. https://doi.org/10.26552/com.C.2022.1.B74-B86
28. Уusupov, U., Kasimov, O., & Anvarjonov, A. (2022). Research of the resource of tires of rotary buses in career conditions. In AIP Conference Proceedings, 2612, (1), 030073. https://doi.org/10.1063:/5.0089590
29. Уusupov, U., & Mukhitdinov, A. (2023). Evaluation of the influence of the longitudinal slope of carriage roads on the tire life. E3S Web of Conferences, 401, 03025. https://doi.org/10.1051/e3sconf/202340103025
30. Avdeychik, S., Goldade, V., Struk, V., Antonov, A., & Ikromov, A. (2020). The phenomenon of nanostate in material science of functional composites based on industrial polymers. Theoretical & Applied Science, (7), 101-107.
31. Ziyaev K, Omarov J., (2024). Research of passenger traffic in public transport, AIP Conference Proceedings, 3045(1), 040030, DOI: 10.1063/5.0197314
32. Mukhitdinov, A., Уusupov, U., Tukhtamishov, S., Urinbayev, Q., (2024). Results of the study of the influence of an average longitudinal slope of routes on the life of tires in the quarry, AIP Conference Proceedings, 3045(1), 040041, DOI:10.1063/5.0197301
33. Khankelov, T. K., Rustamov, K. J., Irisbekova, M., & Sabirova, D. K. (2024). Substantiation of the main parameters of a hammer crusher for grinding municipal solid waste. In E3S Web of Conferences, 515, 03019). EDP Sciences.
34. Abdurazzoqov, U., Anvarjonov, A., (2024). State of transport system organization in developed cities, AIP Conference Proceedings, 3045(1), 040012, DOI:10.1063/5.0197302.
35. Rustamov, K. J., Alimukhamedov, S. P., Egamshukurov, P. S., & Mirxoliqov, S. M. U. (2024, March). Scientific foundations of the system of technical operation of road-building machines. In AIP Conference Proceedings (Vol. 3045, No. 1). AIP Publishing.
36. Rustamov, K., & Rustamova, N. (2023, June). Determination of the main parameters of the mechanisms of a two-stage compressor and their kinematic analysis. In AIP Conference Proceedings, 2789(1). AIP Publishing.
37. Komilov, S., Rustamov, K. J., Akramova, L., Egamshukurov, P., & Tastanova, G. (2024). Development of mining operations in deep quarries using automobile and combined transport. In E3S Web of Conferences, 515(1), 03014. EDP Sciences.
38. Rustamov, K., Rustamova, N., Nazarov, A., & Abdukodyrova, M. (2024, March). The state of the transport services market and development trends. In AIP Conference Proceedings (Vol. 3045, No. 1). AIP Publishing.