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ANALYSIS OF THE CHANGE IN THE NUMBER OF PASSENGER SEATS OF URBAN PASSENGER TRANSPORT DEPENDING ON THE GRAVITY FUNCTION

Summary. *Current conditions for ensuring the implementation of urban mobility plans require high-quality functioning of urban passenger transport systems considering the minimising travel time and increasing travel comfort, as these factors affect passenger fatigue and their productivity during the working day. The study of changes indicators of the public transport system functioning from the gravity function is carried out in this paper, and the results of these studies are given. Based on the surveys of Lviv residents, the distribution of trips by public transport, private transport and taxis was carried out. It is determined that most often city residents use public transport (the share of such trips is 67 % of all movements made by transport). An approach has been developed to determine the number of public transport vehicles depending on their capacity through the total number of passenger seats taking into account this distribution. This approach allows determining the required number of vehicles on the route and using different vehicles by their capacity depending on the passenger flow on the route to ensure the comfort of the trip. Based on this, the analysis of the change in the total number of passenger seats from the indicator of the gravity function for vehicles of different capacities is carried out. In addition, an analysis of the regularities of changes in the number of passenger seats for different by capacity vehicles is carried out, and mathematical models of these regularities are developed. It is determined that at low values of indicator of the gravity function, there is a need for large capacity vehicles, while with the increase in this indicator, the demand for small and medium capacity vehicles increases from 34 % to 52 %. The developed mathematical models can be used for practical justification of the required number of vehicles on the route, taking into account their capacity to ensure the comfortable movement of passengers on the routes of urban passenger transport.*
Key words: *system of passenger transport, travel comfort, vehicle capacity, gravity function.*

1. INTRODUCTION

The growing level of motorization today is the cause of many problems in cities. The main problem is traffic jams in which city dwellers are forced to spend a lot of time every day. The consequence of time-wasting is an unjustified increase in costs because, firstly, there is an overuse of fuel, which, in turn, affects the pollution of urban air basins, secondly, there is a risk of being late for work, and thirdly, long stays in crowded vehicles lead to fatigue, which reduces work efficiency during the working day. Alternative types of travel are actively developing in the world – cycling, use of electric scooters, walking, etc. However, a very small proportion of urban residents use such travel types. The most common types are public and private transport. The main reasons for refusing to use public transport are problems with its functioning – irregular intervals in traffic, an outdated fleet of vehicles, a small number of public transport units on the route, etc. Therefore, the issue of improving the quality of the passenger transport system is essential for improving the mobility system in cities.

2. RESEARCH STATEMENT

The provision of the quality of the transportation process nowadays is an essential element in forming qualitative transportation systems in cities. The provision of comfort travel affects the choice of public transport by urban residents and affects their fatigue, which is reflected in the efficiency of work during the working day. The vehicle's technical condition and cleanliness and the cabin's occupancy determine comfort during the trip. However, given the uneven passenger flow on the routes during the day, to ensure optimal filling the cabin in terms of comfort is a challenge. Therefore, we have proposed an approach to determining the number of vehicles considering their capacity depending on the amount of passenger flow on the route. It is proposed to calculate the number of vehicles taking into account the total number of passenger seats, depending on the size of the gravity function.

3. THE AIM AND THE TASKS OF THE STUDY

The aim of the study is an analysis of the change of the number of passenger seats in urban passenger transport system depending on the gravity function. Due to the aim, such tasks are determined:

- to carry out the survey of Lviv residents on types of movement;
- to carry out field research about the characteristics of transport districts of Lviv city;
- to carry out the simulation of the change of studied indicators of the functioning of public transport systems depending on the values of the gravity function;
- to develop the models of the change of the number of passenger seats with different capacities of vehicles depending on the indicator of gravity function;
- to develop recommendations about the determination of the number of vehicles on the route based on the total number of passenger seats, taking into account the capacity of public transport.

4. ANALYSIS OF RECENT RESEARCH AND PUBLICATIONS

As traffic congestion is currently a significant problem in large cities in Ukraine and around the world, the main alternative is to use a variety of modes of transport, including public transport, cycling and walking. Much attention is paid to alternative modes of transportation, such as, for example, the use of electric scooters. However, such modes of transportation have limitations, such as weather conditions, the availability of infrastructure for comfort movement, and the ability to use by all social and age groups of urban residents. Therefore, public transport remains the main means of transportation. It raises the question of the quality of movement [1, 2].

Thus, in [3], the main criteria for public and private transport quality are identified. The results of a survey of private transport drivers showed that the main disadvantages while moving by private transport are the likelihood of getting into a traffic accident, loss of time in traffic jams, as well as lack of parking spaces. The main disadvantages for public transport passengers when traveling are the lack of vehicles on the routes and uncomfortable travel due to cabin occupancy. In general, the survey results on the quality of movement showed that travel by private transport is more comfortable.

Authors [4] carried out the research on the use of modes of transport in Mexico City, Mexica. There is a solid socio-cultural impact on the use of different modes of transport; in areas with poorer economic status, residents prefer public transport. In business areas, residents use private transport more often, which, among other things, means the low quality of public transport. The results of studies [5, 6] indicate similar results.

The authors [7] point out that the main factors that determine the choice of travel by private or public transport are travel time, level of comfort, and the cost of the driver or passenger when traveling by private or public transport. In [8, 9], the determining factor influencing the choice of public transport for travel is the occupancy of the vehicle cabin. The authors [9] also point out that the coefficient of occupancy of the cabin in the movement, waiting time for the bus, and travel time in public transport significantly impact passenger fatigue, which, in turn, affects efficiency and, consequently, reduces income.

Authors [10] identified four main criteria for the provision of the quality of public transport services: minimum waiting time for the bus, the minimum number of seats in a vehicle, minimum travel time to stopping public transport stopping point, and a minimum fleet of vehicles.

The authors [11] note that the determining factors in the level of development of the route network of cities are the potential availability of stay in public transport, travel time, bus occupancy, comfort and reliability of the public transport route system. In numerical terms, by the passenger survey results, 60 % of the total integrated indicator of service quality is the reliability of service, 21 % – the comfort of the trip, and 19 % is information service.

In [12], the analysis of two traffic variants on the route was carried out. The first – buses of the same passenger capacity work on the line regardless of the period of the day; the second is that during the off-peak periods, low-capacity buses operate on the line, and during peak periods, they are additionally provided with high-capacity buses to "help" them. In the first case, the size of the bus was determined by the amount of passenger flow during peak periods. The disadvantage of the second method is the problem of coordinating the schedule of buses because large buses may have a longer time of boarding and alighting passengers and thus can lag behind the schedule. There may also be a so-called "accumulation" of buses of different sizes on one route at one public transport stop.

The authors [13] analyzed the dependence of the required number of seats in a large 12-meter bus depending on the time of day. It is determined that the largest number of seats is required for routes with long distances and small passenger flows.

Thus, the comfort of the trip, the interval of movement, and the trip's time play a major role among all indicators of the quality of passenger service by public transport.

The main model that determines the number of correspondences between areas is the gravitational model, the main component of which is the function of gravity [1, 14]. In a simplified form, the attraction function is inversely proportional to the distance between transport areas or to the time of movement between correspondence points. Let`s consider the impact of this function on the functioning of public transport systems.

5. PRESENTATION OF THE MAIN MATERIAL

Surveys of Lviv residents were carried out to determine the type of movement. The survey concerned the number of trips by private transport, public transport, taxis, and the number of walks around the city. In total, 195 people aged 15 to 69 were interviewed. For the sample's representativeness, all age groups of the self-dependent population of Lviv took part in the study. The survey results showed that 65 % of all movements are carried out by transport. The distribution of trips made by transport is shown in Fig. 1.

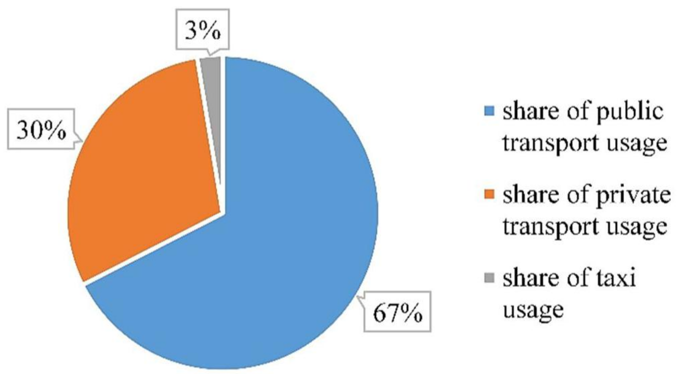

Fig. 1. The share of use of different types of transport by Lviv residents

As we can see, 67 % of respondents who use transport in general, use public transport. Therefore, it is essential to provide quality conditions for the use of public transport.

As noted in [15], a large number of Lviv residents are not satisfied with the quality of public transport. In particular, 53 % of respondents are dissatisfied with public transport services, 83 % are dissatisfied with the public transport regime, and 96.5 % of respondents believe that travel in public transport is uncomfortable.

Since the fleet of vehicles in Lviv includes buses of different capacities, and the process of purchasing new large buses is complex, a method has been developed to select the required number of buses on the routes depending on their capacity. The peculiarity of this method is to determine the required number of buses through the required number of passenger seats:

$$q_i = \frac{\omega_i}{t_{turn_i} \cdot I_i}, \tag{1}$$

where q_i – capacity of the vehicle on i route, units; ω_i – total number of passenger seats on the route, units; t_{turn_i} – turnaround time on the route, h; I_i – traffic interval on the route, h.

Knowing the capacity of buses on the route, we can find their necessary number (A_i):

$$A_i = \frac{\omega_i}{q_i}. \tag{2}$$

Field research on the characteristics of transport districts of Lviv city was carried out to determine the total number of passenger seats. The study was carried out for the whole city; the general number of transport districts was 328. In particular, the capacity of transport areas, the length of sections of the transport network, and the characteristics of the routes of the transport network of the city are determined. The value of passenger flow in transport areas ranged from 12 to 2338 passengers. According to the research results, based on the developed program, the modeling of changes in the number of public transport passenger seats depending on the values of the gravity function indicator was carried out. The research was conducted taking into account the different public transport capacities: 19 passengers, 45 passengers, 70 passengers, 110 passengers and 180 passengers. The dependence of the change in the total number of passenger seats on the degree of gravity function at different capacities of vehicles is given in Fig. 2.

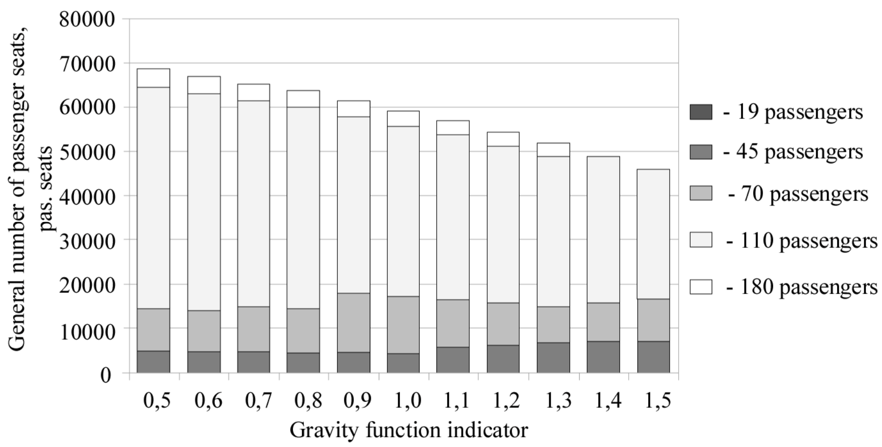

Fig. 2. The change of general number of passenger seats from the indicator of gravity function with different number of passenger seats

Thus, with the increase of the indicator of gravity function, the total number of passenger seats decreases. The following model can describe this dependence:

$$\omega = -8089.9 \cdot \mu^2 - 6361.8 \cdot \mu + 73646, \tag{3}$$

where μ – an indicator of the degree of gravity function.

Also, depending on the gravity function, the share of vehicles of different capacities changes. Therefore, a study of the distribution of the fleet of vehicles depending on their capacity is carried out. The results are shown in Fig. 3.

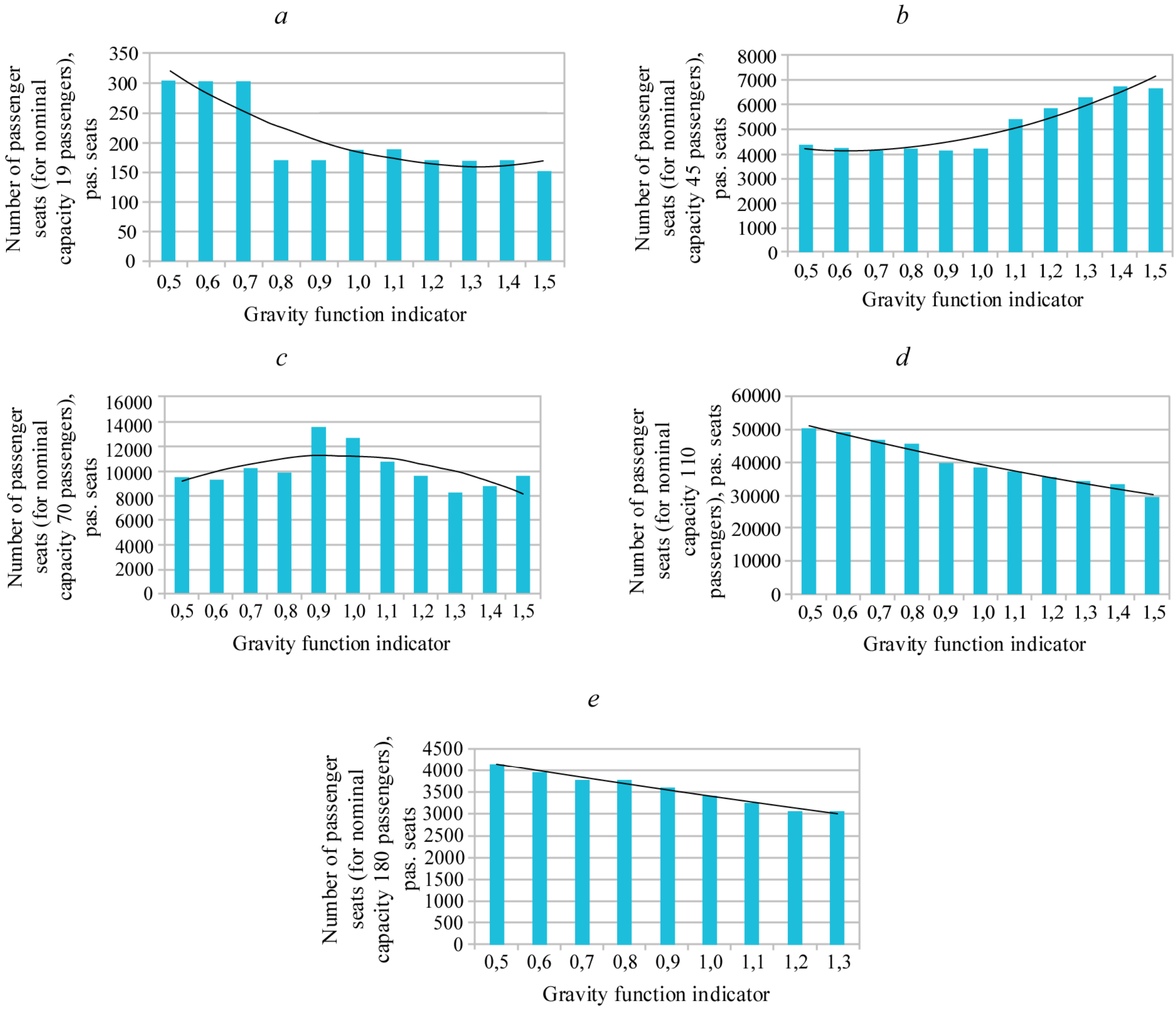

Fig. 3. Dependencies of the change of the number of passenger seats from the indicator of gravity function: a – for capacity 19 pas., b – for capacity 45 pas., c – for capacity 70 pas., d – for capacity 110 pas., e – for capacity 180 pas.

Thus, the dependence of the change in the number of passenger seats with a capacity of public transport of 19 passengers on the indicator of the gravity function (Fig. 3, *a*) is described by such a model with a coefficient of determination $R^2 = 0.78$:

$$\omega_{q_н=19} = 234.73 \cdot \mu^2 - 621.46 \cdot \mu + 572.26. \tag{4}$$

The mathematical model of the change in the number of passenger seats with a vehicle capacity of 45 passengers from the index of the gravity function (Fig. 3, *b*) is as follows:

$$\omega_{q_н=45} = 3750 \cdot \mu^2 - 4542{,}3 \cdot \mu + 5535. \tag{5}$$

The value of the coefficient of determination for this model is $R^2 = 0.91$.

The dependence of the change in the number of passenger seats with a public transport capacity of 70 passengers on the indicator of the gravity function (Fig. 3, *c*) has the lowest coefficient of determination – $R^2 = 0.37$. This can be explained by the fact that this capacity of vehicles is used on routes that have a transitional nature, on which the amount of passenger traffic varies. The mathematical model of such dependence has the form:

$$\omega_{q_н=70} = -10084 \cdot \mu^2 + 19162 \cdot \mu + 2105{,}4. \tag{6}$$

The mathematical model of change in the number of passenger seats for public transport with a capacity of 110 passengers from the indicator of the gravity function (Fig. 3, *d*) is regular with the coefficient of determination $R^2 = 0.97$:

$$\omega_{q_н=110} = 4743,6 \cdot \mu^2 - 230147 \cdot \mu + 64899. \tag{7}$$

The highest value of the coefficient of determination $R^2 = 0,98$ is for the dependence of the change in the number of passenger seats with a vehicle capacity of 180 passengers on the indicator of gravity function. The mathematical model of such dependence has the form:

$$\omega_{q_н=180} = 19,481 \cdot \mu^2 - 1445,15 \cdot \mu + 4843,5. \tag{8}$$

Thus, we can say that with the increase in indicator of gravity function, the need for vehicles with high capacity decreases (from 63 % to 48 %), while the demand for small and medium capacity vehicles increases (from 34 % to 52 %). It is expedient to analyze the change in the total number of passenger seats from other parameters in further research.

5. CONCLUSIONS AND RESEARCH PERSPECTIVES

According to the study results, Lviv residents make 65 % of their travels by transport, of which 67 % – by public transport, 30 % – by own vehicle and 3 % – by taxi. Considering these results, research on the change in a general number of passenger seats from the indicator of gravity function was carried out. It is determined that the total number of passenger seats decreases with the increase of the gravity function.

The analysis of the change in the number of passenger seats for different capacities of vehicles from the indicator of the gravity function was also carried out. Mathematical models of the dependences of these changes for capacities of vehicles of 19 passengers, 45 passengers, 70 passengers, 110 passengers and 180 passengers are determined. The lowest value of the coefficient of determination is for a capacity of 70 passengers – 0.37, other values ranged from 0.78 to 0.98.

It is determined that with the increase of the gravity function, there is an increase in the need for small and medium capacity vehicles from 34 % to 52 %, while the demand for large capacity vehicles decreases – from 63 % to 48 %.

The obtained regularities can be used for practical justification of the number of vehicles of a certain capacity on the route depending on the number of passenger seats. Further research is also reasonable to analyze the dynamics of changes in the total number of passenger seats from other parameters.

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АНАЛІЗ ЗМІНИ КІЛЬКОСТІ ПАСАЖИРОМІСЦЬ МІСЬКОГО ПАСАЖИРСЬКОГО ТРАНСПОРТУ ЗАЛЕЖНО ВІД ФУНКЦІЇ ТЯЖІННЯ

Анотація. *Сучасні умови щодо забезпечення виконання планів міської мобільності вимагають якісного функціонування систем міського пасажирського транспорту з урахуванням мінімізації втрат часу на переміщення та підвищення комфортності поїздки, оскільки ці чинники впливають на стомлюваність пасажирів та продуктивність їхньої праці протягом робочого дня. У роботі проведено дослідження зміни показників функціонування системи* *громадського транспорту від показника функції тяжіння, а також наведено результати цих досліджень. На основі проведених опитувань жителів Львова проведено розподіл поїздок громадським транспортом, приватним транспортом та таксі. Визначено, що найчастіше мешканці міста користуються громадським транспортом (частка таких поїздок становить 67 % з числа усіх переміщень, які здійснюються транспортом). З урахуванням цього розроблено підхід до визначення кількості транспортних засобів громадського транспорту залежно від їх місткості через загальну кількість пасажиромісць. Такий підхід дозволяє визначати не лише необхідну кількість транспортних засобів на маршруті, а й використовувати різні за місткістю транспортні засоби залежно від пасажиропотоку на маршруті для забезпечення умов комфортності поїздки. На основі цього проведено аналіз зміни загальної кількості пасажиромісць від показника функції тяжіння для транспортних засобів різної місткості. Також проведено аналіз закономірностей зміни кількості пасажиромісць для різних за місткістю транспортних засобів та розроблено математичні моделі цих закономірностей. Визначено, що при невисоких значеннях показника функції тяжіння існує потреба в транспортних засобах великої місткості, натомість при збільшенні цього показника збільшується потреба в транспортних засобах малої та середньої місткості з 34 % до 52 %. Розроблені математичні моделі можуть використовуватися для практичного обґрунтування необхідної кількості транспортних засобів на маршруті з врахуванням їх місткості для забезпечення комфортного пересування пасажирів на маршрутах міського пасажирського транспорту.*

Ключові слова: *система пасажирського транспорту, комфортність поїздки, місткість транспортного засобу, функція тяжіння.*