

## TRANSPORT SYSTEMS

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## RESEARCH OF THE FACTORS INFLUENCING THE OPERATIONAL PERFORMANCE OF URBAN PUBLIC TRANSPORT

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**Abstract. Problem.** Currently, there is no universal approach to improve the efficiency of the urban public transport operation. Different methods are used during the estimation of public transport operation cost and the quality of services for the passengers. It makes actual the development of the target function which will allow assessing the carrier cost and passenger expenditures, and therefore find the balance between the interests of these parties of the transportation process. Thus, the alternative to the existing approaches can be created and then used to organize passenger transportation and improve transport enterprise management. Development of this alternative is the actual task as the new target function will open the horizon to improve the methods of organization of public transport operation. **Goal.** The new approach to optimize the costs of public transport operation needs to be tested for the appropriateness for the planning of passenger service in cities. **Methodology.** The developed target function was derived as the result of the analysis of the economic and social factors influencing the efficiency of the urban public transport operation. **Results.** The use of the developed target function allows finding the optimal values of cost components for the passenger and the carrier. **Originality.** The obtained function to optimize the performance of public transport allows reducing the costs of suboptimal use of vehicles capacity, suboptimal allocation of the vehicles to the routes and the irrational organization of vehicles operating on the routes. **Practical value.** The results of the research clarify the controlled and uncontrolled parameters of the public transport system operation.

**Key words:** passenger transportation, public transport, optimal capacity, headway, waiting time.

### Introduction

When solving the problem of passenger transportation optimization, transport enterprises aim at achieving the balance between the fleet carriage capacity and the demand for transportation at a minimal cost [1]. This balance can be achieved through integrated solutions designed to optimize both the transportation process and enterprise management.

The imperfection of the national and local regulatory framework is also the reason for the inefficient UPT operation. The framework does not stimulate most carriers to reduce the costs and ensure the quality of passenger transport services. All of this makes it necessary to improve the UPT management.

### Analysis of publications

UPT management generally consists of two steps [1]:

- 1) preliminary organization of transportation;
- 2) current operations.

The first stage aims to design the route network (RN) as well as select proper public transport vehicles (PTV) and determine their number required for each route. At this stage, the following tasks should be solved:

- obtaining information about the passenger volumes;
- developing the rational RN;
- coordinating different types of UPT;
- regulating the speeds and modes of transport;
- adopting the fare system;
- calculating the operation and economic indicators.

The second stage activities ensure the functioning of the developed passenger transportation system. They are as follows:

- contracting the carriers for passenger transportation;
- defining the fares;
- determining the number of PTV for each route concerning the hour of the day, day of the week, and the season;

- planning the PTV schedules;
- informing the passengers;
- maintenance of the PTVs;
- controlling the frequency of UPT;
- scheduling the PTV to compensate for the interferences of internal and external factors on the transportation system.

External factors affecting the stability of the transportation process are as follows: time variation in the demand for UPT; fluctuations in the traffic volume during the day; traffic management parameters; weather conditions etc.

The improvement of UPT performance like any improvement in other branches of the national economy is impossible without a systematic approach to the solution of the constantly emerging problems and tasks. The systematic approach implies a clear statement of the purposes when addressing a particular group of tasks, identification of the problems, determination of the system structure, the exit actions to achieve the purpose [2]. Various elements are integral parts of the system, they are interconnected and work for a single purpose. This shows the integrity of the system [3]. Guided by the principles of the system approach, we represent the UPT as a set of controlled and uncontrolled factors, and output parameters (Fig. 1).

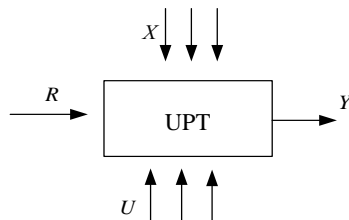


Fig. 1. Set of controlled and uncontrolled factors, and output parameters:  $Y$  – output parameters;  $X$  – uncontrolled input parameters (factors);  $U$  – controlled input parameters (factors);  $R$  – environmental exposure

### Purpose and objective

Any optimization problem can be solved using mathematical modelling, and the mathematical model should establish the relationship between the optimization parameter and the factors affecting it. In general, this model can be represented as follows:

$$\begin{aligned} Z &= \varphi(Y) = \varphi(X, U, R), \\ \varphi(X) &= f(X_1, X_2, \dots, X_n), \\ \varphi(U) &= f(U_1, U_2, \dots, U_n). \end{aligned} \quad (1)$$

The impact of environmental exposure ( $R$ ) will not be considered because of its insignificance. In addition to the selection of controlled parameters, the restrictions on these parameters should be identified. Thus, to solve the optimization problem it is necessary:

1) to develop a mathematical model of the object of optimization:

$$Y = f(X_1, X_2, X_3, U_1, U_2, U_3); \quad (2)$$

2) to determine the criterion of optimality and the target function:

$$Z = \varphi(\bar{Y}) = \varphi(\bar{X}, \bar{U}); \quad (3)$$

3) to identify possible restrictions that should be applied to the variables;

4) to select the optimization method that allows finding the desired values of the target function.

### Development of the approach to reduce the costs of UPT operation

Definition of the uncontrolled and controlled factors will allow obtaining the required output parameters of the UPT system, improving the efficiency of its functioning and ensuring sustainable urban mobility. Uncontrolled factors (Fig. 2) include places of passenger flows generation and attraction, and their generation potential. These places can be generally divided into places of employment and cultural facilities. Their location is influenced by the peculiarities of territorial, industrial and cultural development of urban area [1]. Such places almost always evolve slowly in short and medium perspective but have a significant impact on the place passenger flows formation – they predefine the location of terminal stops of the routes as well as intermediate stops which, in turn, affect the demand for transportation.

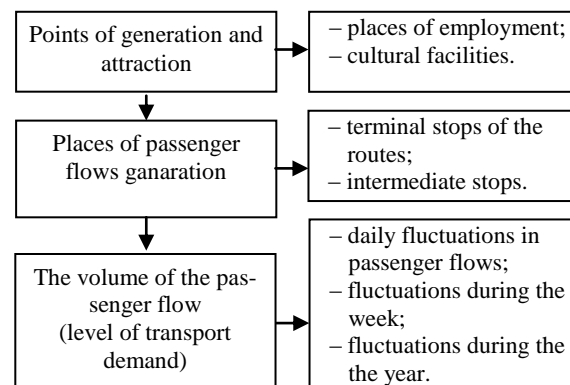


Fig. 2. The structure of the uncontrolled factors

It is well known [4, 5] that the passenger flow volumes fluctuate during the day as well as during the week and the year. On the weekdays, there are two peak periods: 1) short morning peak (1–1.5 h) with high volumes; 2) evening peak which is longer and not so intensive. During the peak periods, there can arise situations when the demand for trips is higher than PTV’s carrying capacity, and the occupancy rate reaches 1.1–1.2, which reduces the quality of passenger transportation [1, 4].

During the off-peak periods, there is a significant decline in passenger flow volumes. In these periods, private, cultural and general population trips take place. Without appropriate measures, the efficiency of PTV use in the mentioned period can decrease. To avoid it, the headways can be increased, which, in turn, leads to increased waiting times for passengers and, accordingly, increased trip duration. There is a different situation on the holidays – there exists a gradual increase in passenger flows until 11–12 PM, and then these flows gradually decrease [3–5]. Controlled factors affecting the UPT system are as follows (Fig. 3): modes of transport, routes, the form of PTVs operation on the route, technical parameters of the PTVs, information for passengers.

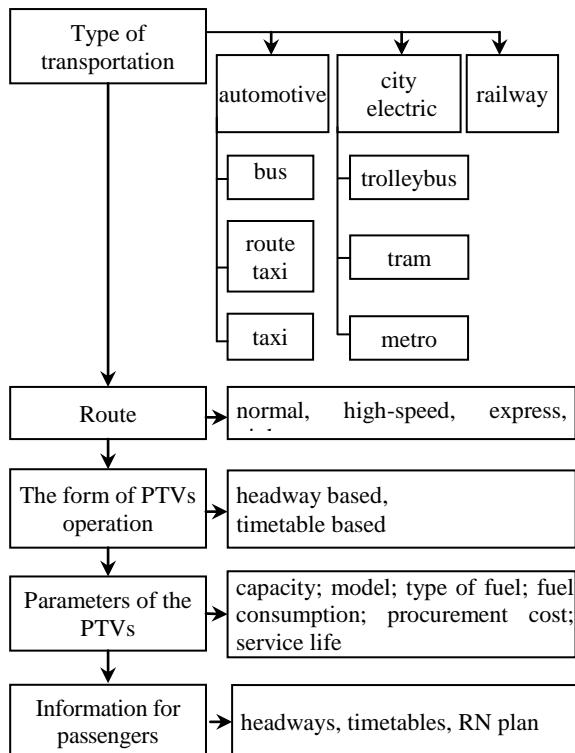


Fig. 3. The structure of the controlled factors

Passenger transportation in the city can be organized using automobile transport (bus, minibus, taxi), electrical transport (trolleybus,

tram, subway) and trains. The choice of a particular mode of transport depends on the scope of its rational use and is determined by the volume of passenger flow required for its efficient operation. According to the current legislation [6], the carriage of passengers by UPT can be assigned to the conventional, high-speed and express routes. PTV can operate on the route according to a certain headway or adhering to the exact schedule known to passengers. The choice of a particular form of operation depends on the passenger volume in a certain period, the available number and capacity of PTV, and is not supported by a clear criterion.

The vehicles for passenger transportation have the following main characteristics that affect the efficiency and quality of the transportation: capacity (nominal and maximum), manufacturer, model, fuel consumption (l/100 km), procurement cost and service life.

Information support for passengers is a complex of measures aimed at providing passengers with information necessary for planning their trips and the proper use of the UPT and includes: the headways for different periods of the day, advertising; distribution of handbooks for passengers and RN schemes; the maintenance of the PTVs and stops; keeping the information at the stops actual.

To justify measures to improve the efficiency of the PTVs use, it is necessary to know the impact of different operation factors on the performance indicators – the hauling capacity of the PTV, the cost of transportation and the quality of services for passengers. One of the main indicators characterizing the efficiency of the PTV use is the hauling capacity – the number of passengers carried out by PTV per unit of time [3]:

$$P_h = \frac{q_n \gamma_s \eta_{\text{exh}}}{t_o}, \quad (4)$$

where  $q_n$  is the capacity of the PTV;

$\gamma_s$  is the static capacity ratio for PTV;

$\eta_{\text{exh}}$  is the coefficient of passenger exchange;

$t_o$  is operating time, h:

$$t_o = \frac{l_M}{v_T} + t_{\text{min}}, \quad (5)$$

where  $l_M$  is the route length, km;

$v_T$  is the technical speed of the PTV, km/h;

$t_{\text{min}}$  is dwell time at the stops, h.

Higher productivity reduces the cost of transportation and increases income. Consequently, the self-containing of the transport operator increases, however, the quality of services for passengers can deteriorate [7]. Among the many factors that affect the performance of the PT fleet, it is possible to distinguish its structure, the organization of the transport process, maintenance and repair, the form of organization of the PTV operation on the route.

The cost of transportation can be expressed as the sum of all types of expenses related to the volume of transportation and passenger-kilometres [7]:

$$S_{\text{full}} = \frac{S_{\text{ec}} + S_{\text{n}}}{P}, \quad (6)$$

where  $S_{\text{ec}}$  is the sum of operating costs, rub.;

$S_{\text{n}}$  is the sum of non-operating costs, rub.;

$P$  is passenger-kilometres.

In the practice of transport enterprise operation, there exists a need to determine the cost of one operating hour ( $S_{\text{a.ч}}$ ) and the cost of one kilometre covered by PTV,  $S_{\text{km}}$ .

The cost of one operating hour equals to

$$S_{\text{ah}} = \frac{S_{\text{v}}}{v_{\text{o}}} + S_{\text{const}}, \quad (7)$$

and the cost of 1 covered kilometre can be represented as:

$$S_{\text{km}} = S_{\text{v}} + \frac{S_{\text{const}}}{v_{\text{o}}}, \quad (8)$$

where  $S_{\text{v}}$  is the sum of costs per 1 covered kilometre; rub/km;

$S_{\text{const}}$  is the sum of fixed costs per 1 operating hour of PTV, rub/h;

$v_{\text{o}}$  is operating speed, km/h.

The costs per passenger trip in RN can be determined using the formula:

$$S_{\text{km}} = \frac{S_{\text{km}} l_{\text{ave}}}{q_{\text{ave}} \gamma_{\text{s}}}, \quad (9)$$

where  $S_{\text{km}}$  is the average cost of 1 kilometre covered by PTV, rub/km;

$l_{\text{ave}}$  is the average passenger trip length, km;

$q_{\text{ave}}$  is the average capacity of PTVs.

Reducing the cost of transportation of one passenger or the reduction of the average cost per 1 kilometre covered by PTV is possible due to the increase of the capacity ratio.

Based on Fig. 4, where the values  $S_{\text{km}} = 1,75$  bel. rub./km, the carrier revenue for the carriage of one passenger – 0.17 bel. rub,  $q_{\text{ave}} = 90$  passengers,  $l_{\text{ave}} = 4,93$  km were taken for the calculation, it becomes clear that at the current cost of the transportation of 1 passenger, the carrier break-even operation will be achieved at  $\gamma_{\text{c}} = 0,37$ . For example, the replacement of PTV at a certain route by the PTV of a lower capacity during the peak period, ceteris paribus, causes the decrease in  $S_{\text{km}}$  and the growth in  $\gamma_{\text{c}}$ , and thereby the unprofitable PTV operation reduces. This does not lead to an increase in travel time and does not reduce the quality of passenger service.

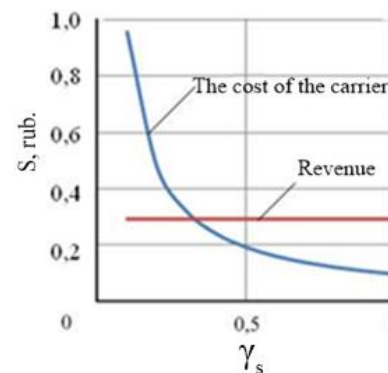


Fig. 4. The dependence of the cost of 1 passenger trip  $S$  on the capacity ratio

The quality of passenger transport service is a set of properties of the transportation process and the transportation system that determines their compliance with the regulatory requirements.

Properties of the transportation process and transportation system determine the level of organization of passenger transportation. Among these properties is the level of RN development, passenger time expenditures (travel time, access and egress time, waiting time), the capacity ratio for PTVs; level of comfort; regularity (percentage of on-time PTV trips), information for passengers.

The level of RN development determines the potential availability of UPT. When determining the level of RN development, the RN density can be used – it is the ratio of the total length of the street network covered by UPT routes to the area of the city. The average density of the RN for the cities with only bus system should equal 2.0–2.5 km/km<sup>2</sup>. In the case of simultaneous operation of several UPT modes in the city, the

total RN density can reach 3.0-3.5 km/km<sup>2</sup>. Exceeding the reference values for the RN density leads to an increase of the routes duplication resulting in reduced speeds of PTV, and their carrying capacity decreases [1, 3, 7].

The passenger time expenditures consist of time to access the stop and egress it, travel time and waiting time (at the first stop or during transfer). The time spent by the passenger for waiting is not productive and should be analysed to minimize it.

Access and egress time can be estimated as follows [4]:

$$T_{\text{walk}} = \frac{60}{v_{\text{walk}}} \left( \frac{1}{3\delta} + \frac{l_{\text{walk}}}{4} \right), \quad (10)$$

where  $v_{\text{walk}}$  is walking speed, km/h;

$\delta$  is the average RN density, km/km<sup>2</sup>;

$l_{\text{walk}}$  is the average length between adjacent stops, km.

The analysis of formula (10) shows that the access and egress time can be reduced by increasing the RN density or reducing the average length between adjacent stops on the route. According to TPK 45-3.03-227-2010, the distance between the stops should be 0.35–0.6 km on average, for express routes and usual bus routes it should be equal to 0.8–1.2 km and 1.5 km respectively. The rules of passenger transportation in Belarus [5] state that the distance between the stops in the residential area with tower blocks should be 350-800 m, and the areas of private house building – up to 500–1000 m. At the current level of RN development in the cities, the access and egress time remain unchanged.

The waiting time is determined by three factors: the headway, the on-time performance and the capacity of PTV:

$$T_{\text{wait}} = \frac{I}{2} = (0,5 + P_{\text{ref}}) I_{\text{eff}}. \quad (11)$$

The route headway can be calculated as:

$$I = \frac{q \cdot 60}{Q_{\text{max}}}. \quad (12)$$

According to formula (12), the increase of the PTV capacity leads to an increase in the headway on the route within the same passenger flow volume in the period under review (Fig. 5). It leads to an increase in the waiting time and adversely affects the quality of passenger service.

The average travel time is determined by the formula:

$$t_{\text{tr}} = \frac{l_r}{v_c} = \frac{l_r}{v_t} + n \cdot t_{\text{int}}, \quad (13)$$

where  $l_r$  is the route length, km;

$v_c$  is the operation speed on the route, km/h;

$v_t$  is technical speed of the PTV, km/h;

$n$  is the number of stops on the route;

$t_{\text{int}}$  is dwell time at intermediate stops.

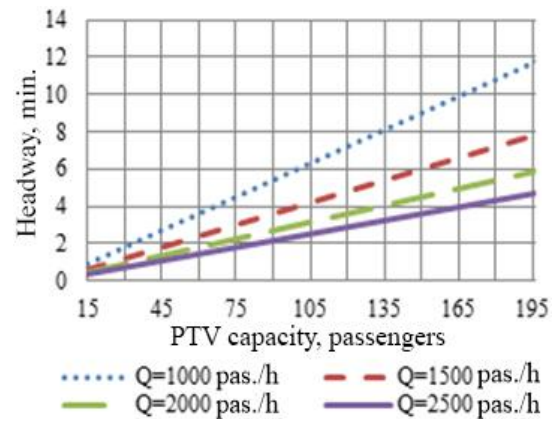


Fig. 5. Dependence of the headway on PTV capacity at different values of passenger flow volume

It is possible to reduce the passenger's travel time by increasing the PTV speed, reducing the dwell time at intermediate stops and waiting time at the first stop and during transfer. The PTV operating speed depends, on the one hand, on the parameters of traffic flow and traffic management system and, on the other hand, on the technical characteristics of PTV and the number of stops with corresponding dwell time. Fig. 6 shows the dependence of PTV run time on the technical speed at different values of dwell time at the stops.

The analysis shows that the dwell time at the stops has no significant effect on the PTV run time, and dwell time reduction may cause a decrease in the quality of passenger transportation due to the deterioration of the boarding and alighting conditions.

The use of PTV capacity is characterized by the capacity ratio ( $\gamma_s$ ) which equals the ratio of the number of passengers in the vehicle ( $q_{\text{fact}}$ ) to the nominal capacity ( $q_n$ ) [8]:

$$\gamma_s = \frac{q_{\text{fact}}}{q_n}. \quad (14)$$

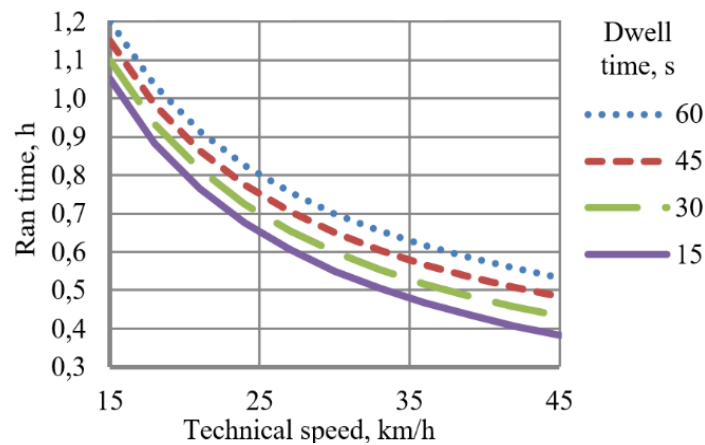


Fig. 6. The dependence of PTV run time on the technical speed at different values of dwell time at the stops

The efficiency of PTV use during the day is characterized by the dynamic capacity ratio ( $\gamma_d$ ):

$$\gamma_d = \frac{P_{\text{fact}}}{P_{\text{max}}} \quad (15)$$

It equals the ratio of the actual passenger-kilometres per day ( $P_{\text{fact}}$ ) to the PTV hauling capacity ( $P_{\text{max}}$ ).

The comfort of transportation. In UPT, the concept of "comfort" can be characterized by the comfort of waiting for boarding, boarding as itself and travel.

The comfort of waiting for boarding depends on the level of informational support for passengers concerning the UPT routes and the ways to access them.

The usual practice is to organize a PTV operation with a certain headway. At small headways which are less than 10-15 min, the PTV runs can be considered regular. From a quality point of view, it is important to monitor PTV on-time performance.

The level of on-time performance is an indicator to quantify the regularity of movement. It is determined by the ratio of the number of runs performed following the schedule to the total number of runs according to schedule.

Passengers put a value upon direct trips which allow them to get to the destination without transfer. Quantitatively, this can be characterized by the transfer ratio  $K_n$  which shows the average number of boarding per trip. The transfer ratio depends on the city planning, RN typology, availability of high-speed and express connections and it ranges between 1.1 for the cities with a population below 250 thousand people and 1.4 for the cities with a population below up to 1 million people. Based on the quality assessment for each indicator (differential

quality assessments), the integral estimate of the quality which includes particular quality indicators is introduced [7–11].

Thus, after analysing the controlled and uncontrolled factors and their influence on UPT, the UPT performance parameters were defined (Fig. 7).

Given the above, the target function representing a reduction of the cost for the organization and implementation of passenger transportation allowing the achievement of greater operator self-containing and higher transportation quality is established. It is based on the optimization of the PTV capacity and headways, and the distribution of the vehicles between the routes. This function can be represented as follows:

$$Z = Z_{\text{opt}} + Z_{\text{alloc}} + Z_{\text{oper}} \rightarrow \min, \quad (16)$$

where  $Z_{\text{opt}}$  is the losses from suboptimal use of PTV capacity;

$Z_{\text{alloc}}$  is the losses caused by the suboptimal allocation of PTV to the routes;

$Z_{\text{oper}}$  is the loss from the irrational organization of PTV operation on the route.

Losses from the suboptimal use of the PTV capacity can be determined as the sum of losses caused PTV's work on the  $j$ -th route in the  $i$ -th period of the day:

$$Z_{\text{opt}} = \sum_{i=1}^m \sum_{j=1}^n Z_{h ij} \rightarrow \min_q, \quad (17)$$

where  $i$  is the number of hours per day,  $m = 24$ ;

$j$  is the period of PTV work on the routes;

$n$  is the number of routes on which the PTV operation is organized;

$j$  is the number of the UPT route.

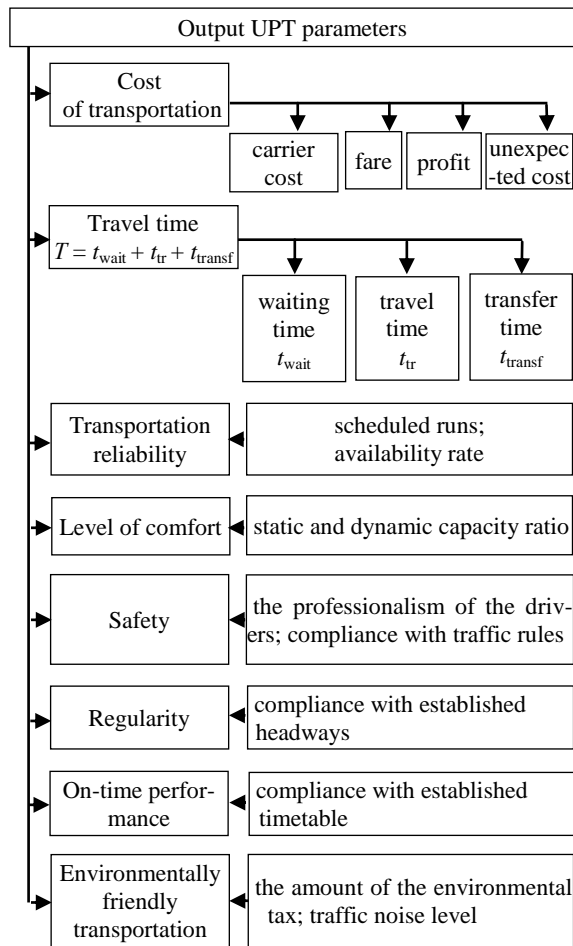


Fig. 7. UPT output parameters

Losses caused by the suboptimal assignment of the PTVs on the routes can be represented as the costs caused by the operation of the PTV of the  $k$ -th capacity on the  $j$ -th route in the  $i$ -th hour of the day, which is different from optimal:

$$Z_{\text{alloc}} = \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^r Z_{\text{alloc } ijk} \rightarrow \min. \quad (18)$$

Losses from the inefficient form of organization of the PTV on a certain route can be defined as the costs of operation at a certain headway on the  $j$ -th route in the  $i$ -th hour of the day:

$$Z_{\text{oper}} = \left( \sum_{i=1}^m \sum_{j=1}^n \begin{cases} Z_{\text{rat } ij} & \text{if } Z_{\text{rat } ij} \leq Z_{\text{irrat } ij} \\ Z_{\text{irrat } ij} & \text{if } Z_{\text{rat } ij} > Z_{\text{irrat } ij} \end{cases} \right) \rightarrow \min_i. \quad (19)$$

The substitution of the expression (17)-(19) into the formula (16) will result in:

$$Z = \sum_{i=1}^m \sum_{j=1}^n Z_{h ij} + \sum_{i=1}^m \sum_{j=1}^n \sum_{k=1}^r Z_{\text{alloc } ijk} + \left( \sum_{i=1}^m \sum_{j=1}^n \begin{cases} Z_{\text{rat } ij} & \text{if } Z_{\text{rat } ij} \leq Z_{\text{irrat } ij} \\ Z_{\text{irrat } ij} & \text{if } Z_{\text{rat } ij} > Z_{\text{irrat } ij} \end{cases} \right) \rightarrow \min. \quad (20)$$

This formula represents the target function allowing cost reduction due to the definition of the optimal capacity and the headways for PTVs on UPT routes.

### Conclusion

During the research, the target function allowing the reduction of the cost of PTV operation on UPT routes is determined. This function is based on the optimization of the headways and PTV capacity when assigning them to UPT routes and making the choice on the form of PTV operation – conventional, high-speed or express.

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### Дослідження факторів, що впливають на ефективність роботи міського громадського транспорту

**Анотація. Проблема.** На сьогодні не існує універсального підходу до оцінювання ефективності функціонування міського громадського транспорту, і для оцінювання витрат на експлуатацію громадського транспорту та якості обслуговування пасажирів використовуються різні методи. Це робить актуальним розроблення цільової функції, яка б слугувала альтернативою наявним та дозволила б оцінити витрати перевізника та пасажирів і знайти баланс між інтересами цих сторін перевізного процесу. Таку альтернативну функцію можна використовувати для організації пасажирських перевезень, удосконалення управління транспортними підприємствами та оптимізації їхніх витрат. Це завдання є



актуальним, оскільки нова цільова функція дасть змогу вдосконалити методи організації роботи громадського транспорту в містах та підвищити якість транспортного обслуговування міського населення. **Мета.** Новий підхід до оптимізації витрат на роботу громадського транспорту потрібно перевірити на придатність для використання в плануванні транспортного обслуговування пасажирів та організації роботи підприємств перевізників. **Методологія.** Розроблена цільова функція була отримана внаслідок аналізу економічних та соціальних факторів, що впливають на ефективність роботи міського громадського транспорту. **Результати.** Використання розробленої функції дозволяє знайти оптимальні значення складових витрат пасажирів громадського транспорту та перевізника. **Оригінальність.** Отримана функція дозволяє зменшити витрати від неоптимального використання місткості транспортних засобів громадського транспорту, неоптимального призначення транспортних засобів на маршрути та нерациональної організації їхньої роботи. **Практичне значення.** Результати дослідження уточнюють керовані та некеровані фактори, що впливають на роботу системи громадського транспорту.

**Ключові слова:** пасажирські перевезення, громадський транспорт, оптимальна пасажиромісткість, інтервал руху, час очікування.

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