THE IMPACT OF THE COST OF PAID PARKING FOR PRIVATE CARS AND PUBLIC TRANSPORT FARE ON THE STRUCTURE OF URBAN MOBILITY

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ABSTRACT
The experience of European cities shows that with the introduction of free-fare public transport, the share of public transport trips increases insignificantly, while the number of trips by individual transport, bicycle and on foot decreases. The most common way to reduce the number of trips by private cars is to introduce parking fees and regulate the tariff. The paper examines the impact of public transport fare paid parking fees on the transport demand structure. The structure of transport demand is determined using simulation modeling on a transport macro-model of a large city with a population of 800 thousand people that do not have off-street transport. The paper proposes a criterion for determining generalized costs of travel by different transport systems, which converts monetary costs into time fares. This made it possible to take into account the costs of movement by different types of transport (private and public transport, CarSharing, taxi, pedestrian and bicycle movements). With the introduction of paid parking fees up to 80 rubles per hour, the share of private transport trips reduced from 45.5% to 37.3%. With the introduction of free public transport, private transport trips share reduced to 39.9% with a significant increase in the costs of the municipal budget.
Keywords: fare public transport, paid parking, public transport, transport demand, transport modelling, transport planning.

1 INTRODUCTION

It is impossible to imagine a modern city without sustainable mobility of the population. To ensure sustainable urban mobility, priority conditions are created for public transport and cyclists, compared to personal car users [1, 2].

The high level of quality of public transport services is the most important factor for the implementation of the concept of 'Mobility as a service' (MaaS) [3]. In countries with poor quality of public transport, the implementation of the MaaS concept is difficult and slow.

It is possible to improve the quality of transport services for city population by public transport and cycling through the introduction of lanes for route vehicles and a network of bike paths. The relationship between the structure of population mobility and infrastructure measures is considered in the paper [4].

Another direction of improving the quality of public transport is to create a priority at intersections for it [5]. In some cases, the reduction in the delay time of public transport passengers can go up to 21% [6].

The authors of the study [7–10] show that with the introduction of free-fare public transport, the total number of public transport trips increases due to the fact that public transport users take more trips and reduce the number of pedestrian movements and bicycle rides. The share of public transport users with the introduction of free fare increased insignificantly, thus the goals of achieving sustainable mobility in cities with free fare public transport were not achieved.

The results of a survey of residents of the cities in work [11] show that the most important factors when choosing public transport are well-developed route network and regularity. The travel fare is indicated as the most important factor by 9.8% of respondents. This suggests that for residents of megalopolises, the quality of public transport is more important than travel fare.

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Other important factors for choosing public transport are difficulties in finding a free parking space, parking fees and road congestion. The main reasons why residents travel by car are greater comfort, shorter travel time by car, and transportation of goods or purchases. This means that the concept of free-fare public transport does not meet the most important expectations regarding public transport. This study concludes that the introduction of free-fare public transport is not enough for transition from a private car to public transport.

The paper [12] describes the interrelation between public transport fare and availability and the area of residence location in the city.

An important influence on the share of public transport trips is the price and number of paid parking spaces in the central part of the city, as well as the level of infrastructure development for public transport, cyclists and pedestrians [13].

Changes in infrastructure for pedestrians affect the share of public transport trips. The number of pedestrian movements is related to the density of the route network and the availability of public transport stops [14].

One of the effects introduction of free-fare public transport in cities and reduction in the number of private transport users allows the following [15–17] ensuring mobility of population, especially of the lower-wealth groups of population.

In order to find balanced solutions for the development of the urban transport complex, municipal authorities should develop solutions taking into account opinions of city residents [18].

To assess the effectiveness of measures for the development of transport systems, transport modeling at the micro level is widely used. Macroscopic modeling is used to predict changes in transport demand and redistribute traffic flows on the road network [19–22].

The purpose of the work is to establish the dependence of changes in the transport demand structure on public transport fare and paid parking fee.

MATERIALS AND METHODS

The population mobility structure can be divided into two modes of movement: pedestrian movement and transport trips. Transport trips are divided into 3 types, which correspond to the types of transport: private transport, public transport and cycling. In studies, the structure of mobility includes 4 components. The paper studies the influence of the economic factor (travel costs) by two components: public transport fare and paid parking fees for private vehicles. The share of trips by types/methods in general transport mobility is determined by a mathematical additive model based on the main effects:

$$\Delta_{car} = \Delta_{car0} - S_1(P_p - P_{p0})^2 + S_2 F_{bus}, \tag{1}$$

$$\Delta_{bus} = \Delta_{bus0} + S_1(P_p - P_{p0})^2 - S_2 F_{bus} \tag{2}$$

$$\Delta_{ped} = \Delta_{ped0} + S_1(P_p - P_{p0})^2 + S_2 F_{bus} \tag{3}$$

$$\Delta_{bike} = \Delta_{bike0} + S_1(P_p - P_{p0})^2 + S_2 F_{bus} \tag{4}$$

$$\Delta_{car} + \Delta_{bus} + \Delta_{ped} + \Delta_{bike} = 100\% \tag{5}$$

where Δ_{car0} is the share of private car trips under actual conditions; Δ_{bus0} is the share of public transport trips under actual conditions; Δ_{ped0} is the share of pedestrian movements under actual conditions; Δ_{bike0} is the share of bicycle trips under actual conditions; P_p is paid parking fees for private vehicles, rub./hour; F_{bus} is urban passenger public transport fare, rub.; S_j is sensitivity parameter to the change of the jth factor.

The hypothesis of the study is that with an increase in the financial costs of traveling by the ith method or type of transport, there is a decrease in the share of trips by this type or method of transportation and an increase in the share of movements by other types and methods.

Mathematical models and transport simulation models do not take into account other transport systems, such as CarSharing, BikeSharing and KickSharing. This is due to the absence or a very small number of these vehicles in Tyumen at the time of the study. In the future, as new transport systems appear in the city, they will be added to the transport model and its calibration will be carried out.

The transport model was developed in 2018-2019 with the economic indicators existing at that moment, such as household income, average wages and the share of working and unemployed citizens. Over time, with changes in the age structure (demographic characteristics) of citizens, socio-economic indicators in the city and development of territories, it is possible to change the general mobility of the population and redistribute demand by types of transport and methods of movement. In this case, it will be necessary to conduct simulations to determine the relevant parameters of the mathematical models.

Transport modeling makes it possible to estimate the change in the parameters of the urban transport system when the external and internal conditions affecting the system change.

Simulation was performed for the morning time, which is characterized by a large number of movements of people in the city. The majority of movements in the morning are carried out for work and educational purposes. The combination and calculation of time expenditures and financial costs were made for the “rush hour”. In the peak period model, it is possible to take into account the actual operating modes of traffic light objects, which reduces the error when taking into account the resistance at the nodes in the cost matrix and increases the accuracy of modeling.

In the model of Tyumen, the probability of a trip by the ith type of transport is determined based on the time spent on the ith type of transport or its resistance [22]. Resistance is travel cost calculated in rubles, minutes or another unit of measurement. Resistance is the sum of time cost (cost of a minute multiplied by travel time) and operating costs (cost of 1 km of vehicle mileage multiplied by travel length) [23].

In this paper, resistance is calculated as the sum of travel time and travel cost converted into time using a special coefficient presented in the formula (6).

$$R_i = T_i + k \cdot F_i, \tag{6}$$

where R_i – resistance for the ith transport system, min.; T_i – travel time, min.; k – coefficient for converting money into time, min./rub.; F_i – travel cost, rub.

As of September 2021, in the city of Tyumen, the average salary is 53,000 rubles/month (623 euros/month, 1 euro = 85 rubles). The median salary is 30,000 rubles/month (353 euros/month). The average salary in Russia is 54,700 rubles/month (644 euros/month); the median salary in Russia is 32,400 rubles/month (381 euros/month).

The coefficient for converting money into time is calculated based on the average salary for a standard 40-hour work week. As a result, this money–time ratio for the city of Tyumen in

2021 is 0.2 minutes per ruble or 12 seconds per ruble. The coefficient for converting money into time for the city of Tyumen in 2021 was 5 rubles per minute.

The average public transport fare for 2020 in Russian cities (with the exception of Moscow and St. Petersburg) is 23–50 rubles per trip. In Moscow and St. Petersburg, the fare may vary depending on different tariff.

In Moscow and St. Petersburg, the cost of paid parking ranges from 80 to 380 rubles per hour (depending on the area). In other cities of Russia, the cost of paid parking varies 30–50 rubles per hour.

In the city of Tyumen, when a person makes trips for work purposes with 22 working days per month, the cost of parking a personal car for 9 hours per working day is 5940–8910 rubles/month, i.e. parking costs are 11.2%–16.8% of the average monthly salary and 19.8%–29.7% of the median salary.

At the time of the study, the number of paid parking spaces in Tyumen increased from 585 to 1601 places. Further plans suggest an increase in the number of paid parking spaces to 5,600.

Travel cost for different types of transport is calculated based on tariffs. For example, the cost of a taxi ride is calculated based on the Economy tariff in Yandex.Taxi [24]. For CarSharing, based on the tariff in Cars7 service, the cost of travel by private transport is determined using the calculator of the analytical agency Autostat [25] that estimates the cost of owning a car. Travel cost for different types of transport is calculated using the formulas (7)–(10).

$$F_{taxi} = 80 + 6 \cdot (L - 2)\,, \tag{7}$$

$$F_{cs} = T \cdot 7.9\,, \tag{8}$$

$$F_{car} = L \cdot 7.5\,, \tag{9}$$

$$F_{bus} = n \cdot 27\,, \tag{10}$$

where F_i – travel cost for the ith transport system, rub.; T_i – travel time, min.; L_i – travel length, km; n – rides number by a transport type.

For all transport systems, when calculating the resistance in the transport model, in-vehicle travel time (min) was taken into account. For private transport, additional factors were taken into account, such as price of paid parking (ruble/hour) and paid parking time (hours). For public transport, approach time on foot, (min), vehicle waiting time (or rental) (min), vehicle return time (min), egress time (min), walk time to transfer (min) and waiting time for the second vehicle (min) were taken into account [26].

Table 1: Resistance for various types of transport.

Expenses	Vehicle type					
	Bike	Ped.	Car	Taxi	CarSharing	Bus
Total travel time, min.	54	121	28	34	34	48
Total travel cost, rub.	0	0	258	146	269	27
Resistance, min.	54	121	80	63	88	53

Table 1 shows an example of resistance calculation for a trip from the central part of Tyumen to a peripheral area (overhead line length is 7.7 km). The lower row of the table shows the calculated resistance value. The maximum resistance value for this correspondence is for pedestrians, and the minimum value is for cyclists and public transport users. The average resistance value is for taxi.

Changes in parking fees and public transport fare leads to an adjustment of the cost matrices for work and business trips. Changing public transport fare leads to an adjustment of the cost matrices for all trips (work, service, educational and social). On the basis of cost matrices, correspondence matrices are distributed by different types of transport over districts [22]. With an increase in the costs of the *i*th type of transport, the need for this type of transport decreases and is redistributed over other types.

3 RESULTS

The influence of paid parking fees on the structure of transport demand and mobility of the population was presented earlier in the paper [13].

The results of modelling the impact of public transport fare are presented in Figure 1.

With introduction of free fare public transport, the share of public transport trips in Tyumen increases, while the share of trips by other types of transport decreases. Traffic parameters are also defined, for example, when the cost of public transport trips increases, travel time by individual transport increases and the average speed decreases. These changes are directly related to the increase in the number of individual transport users and intensity of individual transport traffic in the city. At the same time, the changes in traffic parameters are quite insignificant (<4%).

A two-factor model of the dependence of the share of movements by the *i*th type of transport on paid parking fees and public transport fare is presented in Figure 2 and in Tables 2 and 3.

With an increase in paid parking fees up to 80 rubles per 1 hour, the share of private transport trips is significantly reduced from 45% to 37%. With a further increase in parking fees, the share of trips practically does not change.

Taxi cars are taken into account in the simulation model as private cars. Therefore, with an increase in parking fees over 80 rubles, the decrease in the share of trips by private transport is insignificant.

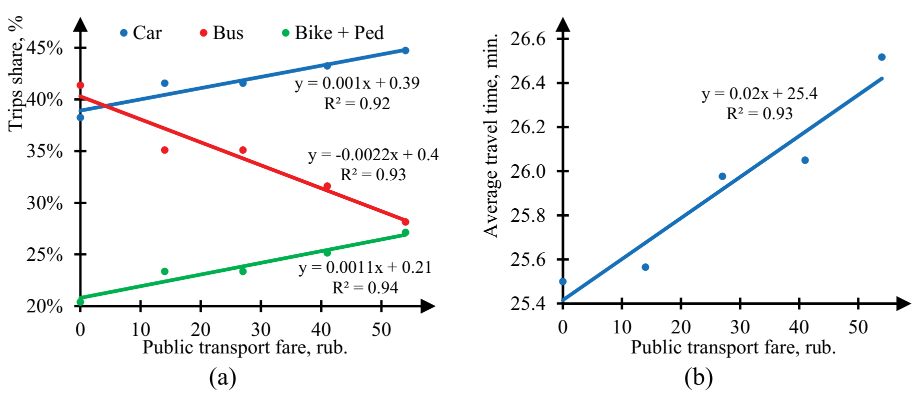
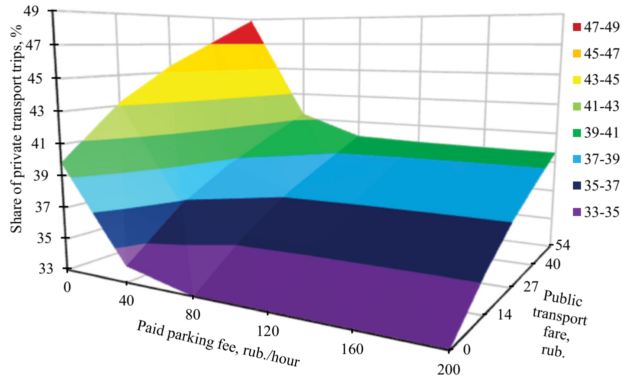
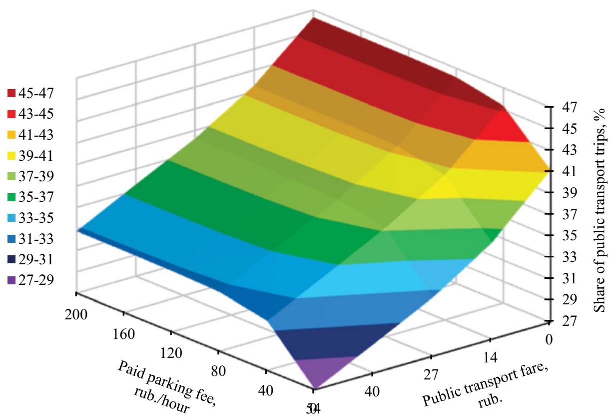


Figure 1: The impact of public transport fare on (a) the structure of transport demand (b) the average travel time by individual transport.



(a)



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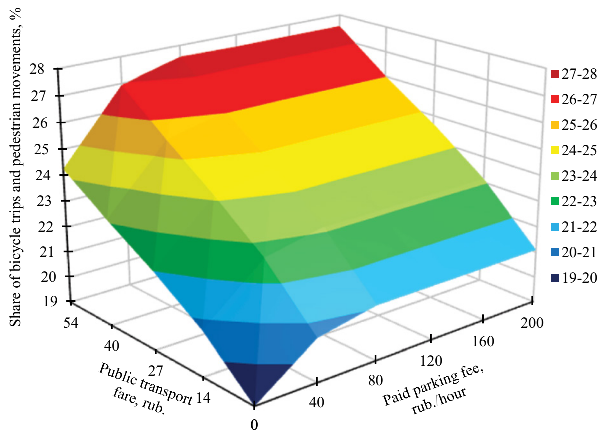

(c)

Figure 2: Influence of paid parking fees and public transport fare on share of movements in cities (a) by private transport, (b) by public transport and (c) pedestrian and bicycle movements.

Table 2: Change in the share of public transport trips.

Share of public transport trips, %		Public transport fare, rub.				
		0	14	27	40	54
Paid parking fee, rub./hour	0	41.2	36.0	32.5	29.7	26.9
	40	45.4	40.5	37.2	34.4	31.7
	80	46.2	41.4	38.0	35.4	32.5
	120	46.3	41.5	38.2	35.5	32.7
	160	46.3	41.6	38.2	35.5	32.8
	200	46.3	41.6	38.2	35.6	32.8

Table 3: Change in the share of private transport trips.

Share of private transport trips, %		Public transport fare, rub.				
		0	14	27	40	54
Paid parking fee, rub./hour	0	39.9	43.2	45.5	47.2	48.9
	40	34.0	36.8	38.7	40.1	41.4
	80	32.7	35.5	37.3	38.6	39.9
	120	32.6	35.3	37.1	38.5	39.8
	160	32.6	35.3	37.1	38.4	39.7
	200	32.6	35.3	37.1	38.4	39.7

The type of dependence in the two-factor model of the share of movements by the ith type of transport on public transport fare is repeated as it is in the one-factor model.

With an increase in public transport fare from 27 to 54 rubles, the share of private transport trips increases from 45% to 49%. With an increase in public transport fare from 27 to 54 rubles, the share of public transport trips is reduced from 33% to 27%.

In order to improve the quality of public transport services when epidemiological restrictions are imposed on public transport, carriers need to increase the number of rolling stock. Such requirements will significantly increase the cost of transporting passengers, which will lead to an increase in public transport fare.

With an increase in public transport fare from 27 to 54 rubles, the share of public transport trips is reduced by 5.6%. However, with the introduction of paid parking for private cars (80 rubles per hour) and public transport fare of 54 rubles, the share of public transport trips increases by 5.6%.

With an increase in public transport fare from 27 to 54 rubles, the share of private transport trips increases by 3.4%. However, with the introduction of paid parking for private cars (80 rubles per hour) and public transport fare of 54 rubles, the share of private transport trips is reduced by 9%.

The data obtained were processed using correlation and regression analysis (Table 4). Mathematical models of the demand structure are presented in formulas (11)–(13).

$$\Delta_{car} = 37.9 - 0.033(P_p - 150)^2 + 0.14F_{bus}, \tag{11}$$

Table 4: Statistical characteristics and model parameters.

Statistical characteristics, model parameters	Value for models		
	Δ_{car}	Δ_{bus}	$\Delta_{ped+bike}$
Multiple correlation coefficient, R	0.85	0.96	0.95
Calculated value of student criterion t	8.44	17.2	16.73
Table value of student criterion t_p	2.04	2.04	2.04
Average approximation error,%	4.63	3.27	2.44
Fisher Dispersion Ratio F	3.56	11.69	11.11
Fisher test F_p	1.91	1.91	1.91

$$\Delta_{bus} = 42.2 + 0.022(P_p - 150)^2 - 0.25F_{bus} \quad (12)$$

$$\Delta_{ped+bike} = 19.8 + 0.011(P_p - 150)^2 + 0.11F_{bus} \quad (13)$$

The correlation between the share of movements in models and the variables is significant since the condition $t > t_p$ is satisfied. The developed models are adequate, since the condition $F > F_p$ is satisfied and the average approximation error is less than 5%. Correlation values greater than 0.99 indicate high bond strength.

4 CONCLUSION

Tariffs for transport services and the costs of traveling using private vehicles affect transport behaviour, i.e. the choice of the transportation method and type of transport. The choice of a transportation method of by city residents determines the transport demand. If the transport offer does not match the level of demand for certain types of transport, an imbalance appears. A lack of transport offer causes deterioration in the quality of transport services and a negative reaction of residents. With an excess of transport offer, inefficient use of resources is noted. The transport offer depends on a large number of factors. One of the important factors is the level of development of transport infrastructure, which affects the stock of handling and transportation capacity of highways.

The tariff for public transport trips in Tyumen at the time of the study is 28 rubles (27 rubles for non-cash payment). The maximum value of the tariff during the simulation is 54 rubles. It should be noted that this is a fairly high fare, which cannot actually be realized in the coming years. The increase in tariffs occurs gradually by the amount of 1–2 rubles not more often than once per year. However, this fare value of 54 rubles is accepted in the study, as it approximately corresponds to the cost of a subway trip in Moscow.

Similarly, we can talk about parking fees in Tyumen. The actual cost of 1 hour of parking is regulated by municipal level documents in the range of 20–80 rubles. Parking fee higher than 100 rubles seems unlikely for Tyumen.

The COVID-19 pandemic has made significant changes in the mobility structure of urban residents. In 2021, the traffic intensity in the city of Tyumen recovered to the level of 2019, before the outbreak of the pandemic.

During the second wave of the pandemic in the autumn and winter of 2020, in the absence of restrictions on the work of enterprises and movement of people, the decrease in the volume of passenger transportation by public transport amounted to 35.3% and 33.9% in November and December, respectively, relative to 2019.

A sociological survey of city residents of the Russian Federation allowed to determine the change in people's behavior during the pandemic when choosing a method of movement and type of transport. During the pandemic in 2021, 43.7% of respondents changed the number of movements in the city. 29.9% of respondents decreased the number of trips with work purposes, and 25.1% of respondents decreased the number of trips with educational purposes. 46% of respondents are afraid of getting infected with coronavirus in public transport. During the pandemic, 26.7% of respondents partly refused to travel by public transport, and 6.8% of respondents completely refused to travel by public transport. Respondents who have a private car in their family, but sometimes use public transport, reduced the number of trips by public transport during the pandemic and replaced them with trips by private transport (25%), and 14% of respondents began to use taxis and carsharing, while 21% preferred to walk.

If in the short term (up to 1–1.5 years) the situation with the incidence of coronavirus COVID-19 will not be eliminated or minimized, then it will be necessary to calibrate the transport model of the city. The model will need to take into account changes in the mobility structure, taking into account the increased influence of the factor of physical safety of passengers of public transport.

The results of the research on this topic can be used in the practical activities of municipalities in two directions:

- forecasting changes in the structure of transport mobility when changing the tariff policy on urban transport;
- determining tariff values and the level of infrastructure development for transport systems to achieve the specified parameters of transport mobility of the population.

In October 2021, after a year's discussion, representatives of the Russian Ministry of Transport removed the issue of introducing free travel in urban public transport until 2035. This confirms the complexity of making such a decision, the need to take into account a large number of factors and conditions and careful planning of activities.

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