DOI: https://doi.org/10.30932/1992-3252-2019-17-222-241

Gravity Modelling of Car Sharing Based on PTV Visum

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ABSTRACT

Car sharing plays an important role in the transition to unmanned vehicles. This article discusses the positive and negative aspects of the existing car sharing system in Russia, as well as forecast trends using the examples of Moscow and St. Petersburg. Since car sharing in St. Petersburg is not yet sufficiently developed, and the forecasts of operators on the market capacity diverge, it is of interest to determine the conditions facilitating successful development of the service, and to evaluate the city's need for the number of cars used by car sharing services.

The objective of the research described in the article is to study the trends in development of car sharing services, to determine the estimates of the required number of cars for car sharing services, and intensity of their rental in a particular city district. To solve the problem, the gravity modelling method is used based on the PTV Visum 18 software. Whilst special tools of the developed line of PTV MaaS programs (Controller, Operator, Simulator, Modeller) are not applied, it allows to build transport models of the macro level and perform transport modelling taking into account new forms of mobility (car sharing, bike sharing, etc.) while planning and management of urban transport systems

The solution to the problem involved development of two models of transport demand for the selected district of the city: considering and without considering car sharing effect. In the process of modelling, we studied the structure of transport time expenditures following changes in the number of vehicles in the fleet and intensity of its rental regarding several operator tariffs. The critical number of cars used by car sharing services for the city district was determined under the conditions of the greatest competition of these cars with individual vehicles. It is shown that under current conditions, the effect of reducing time-related transport costs in the district is about 14 % when using one-year simulation horizon. The simulation results are consistent with the real data on trips and can be extrapolated to other city districts.

Keywords: *transport, urban transport, car sharing, transport modelling and simulation, PTV Visum.*

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Article received 15.08.2019, accepted 27.11.2019.

For the original Russian text of the article please see p. 222.

Background. Organizational measures of traffic offloading, among others, can provide a significant assistance to the created expensive intelligent transport systems. Those measures capable to make a significant contribution to solving urban transit problems comprise car rental (or car sharing) for short-term trips over short distances around the city and in its immediate vicinity.

In Russia, similar services, such as ride sharing (sharing payment between fellow travelers); carpooling (sharing a car with other people); bicycle, scooters, electric cars rental, etc. are currently only gaining momentum. City dwellers start to realize that it is better to share rather than to own. Introduction of modern technologies that allow to use these services using a smartphone is also an important factor of promoting those services. MaaS services (mobility as a service) implies that the user receives a ready-made solution on his smartphone how to get from one point of the city to another, considering traffic jams.

The related issue of traffic jams and pollution is very painful. Besides, the loss of time in traffic jams has a specific financial expression not only for residents, but also for the city budget. The estimate of the cost of traffic jams per day according to the formula [1] is impressive:

$M = T \cdot N \cdot (P \cdot S + F) = 1 \cdot 0{,}5 \cdot 10^{6} \cdot (2 \cdot 324 + 90) \approx 369$ mln rub.,

where M are total costs caused by traffic jams per day;

T is time spent in a traffic jam by one person, hours;

N is number of cars caught in traffic jams, $0{,}5 \cdot 10^6$ cars (in Moscow, according to Yandex estimates this figure is more than 10^6);

P is average number of passengers;

S is average salary per hour in St. Petersburg with 40-hour workweek, 2019, rub.;

F is cost of average fuel consumption per hour in a traffic jam, 2 l, 90 rub.

According to statistics, one short-term rental car is capable to meet the needs of a dozen users a day. Thus, only a single car instead of ten vehicles participates in the road traffic. According to experts, as a result, 3–4 of 5 cars will be excluded from the transport flow, which will positively affect the state of traffic. In the above formula, this is obviously a decrease in the parameter N by more than 60 %, resulting in significant savings.

Besides offloading traffic, the transition to rental with a per-minute payment can be motivated by the following:

1. High cost of owning a personal car.

According to the study of Avto.ru portal, on average, owning a personal car in Russia costs 32,2 thous. rub. per month [2], and the cost increases if there is an inflation.

In case of a rental, one should not bear the costs associated with maintenance and repair of personal car, spend money on parking, gas, insurance (rented cars are insured, and the price of insurance is included in the tariff). The issue of vehicle security is also within the responsibility of a car sharing company.

The simplest calculation shows that only the direct costs of owning a personal car (having average price of 1,5 million rubles in 209 and annual mileage of 15 thousand km) make 137,5 thousand rubles per year. Direct costs provide for the cost of gasoline (consumption of 10 liters per 100 km, which amounts to 69 thousand rubles), the cost of compulsory motor liability insurance (5,5 thousand rubles), maintenance (25 thousand rubles), the cost of tires (4 thousand rubles), the cost of washing and of a windscreen washer (24 thousand rubles), transport tax (10 thousand rubles). For a car sharing car (hereinafter CS-car), these costs, even at a rate of 10 rubles/km, correspond to 35 thousand kilometers mileage. If we consider free parking, the benefit will be even higher. And it is known, there are still indirect losses, as a car depreciates by 30 % after 3 years of operation.

2. Reducing CO_2 emissions (the main cause of global warming) should have a positive impact on the environment. Preliminary estimate can be suggested that car sharing development will result in reduction of CO_2 emission by vehicles by 10 %.

The popularity of the service in Moscow is growing at a gigantic pace. In recent years, it has tripled, and the number of CS-cars is approaching 30 thousand units.

What are the prospects for service in St. Petersburg? According to operators' estimates (2018), the capacity of the car sharing market in the Northern capital is as follows: 7000 (Youdrive), 3000 (Delimobil), 3500 (COLESA.COM) [3].

However, the fleet should not be idle, hence there it is not possible to go to extremes when CS-cars occupy a third part of the paid parking zone in Moscow. The question arises: what is the real need of the city for this service under the current conditions? To answer that question a tentative simulation based on transport modelling can be used.

Problem statement

The article is devoted to development of car sharing in St. Petersburg. A district of the city (Petrodvortsovy district[1]) was selected as an object of the study. Given that estimates of the required number of CS-cars and intensity of their rent provided by different operators differ, it is proposed to use *transport modelling*. Thus, to obtain quantitative estimates, it is required to develop a transport demand model for the selected district using a software and considering car sharing system. Using modelling and simulation, it is possible to evaluate the dynamics and make a forecast of changes in the structure of transport costs considering car sharing, namely, a decrease in transport demand for individually owned transport[2] (IT). The simulation results must then be compared with real CS-cars' renting data in the selected district.

Car sharing conditions

Today in Russia, the car sharing system is far from perfect. In particular, there have been more frequent cases of traffic accidents with CS-cars (more than 200 traffic accidents since the beginning of 2019), the users of which are often those who do not have constant driving practice or, worse, drunk, disenfranchised drivers and etc. Then the car turns into a source of danger. To deal with this disaster, the traffic police are considering measures to identify drivers and their condition while driving a CS-car. Besides, the issue of banning the use of the service for traffic offenders is discussed.

The lack of documents regulating the activities of car sharing companies also poses a significant problem. Now, only Moscow possesses the city documents regulating the car services' activity and relevant public supervision over them.

Another problem is the lack of uniform registries that would store the data on the service companies and their subscribers. This centralization will simplify registration of drivers, because, in this case, it will be sufficient for a driver to register only once, and not to proceed with individual registrations in each company, and consequently there will be an opportunity to choose a car for rent that is located closer.

St. Petersburg takes second place after Moscow per the available fleet of CS-cars. As of March 2019, seven car sharing companies were operating in the city with the total fleet of 3515 cars [4]. This figure has little effect on the general situation in the city, which totaled more than 2,4 million cars in 2017 [5]. An important indicator is the number of inhabitants per a CS-car. For St. Petersburg now it is equal to 5,38 million/3515 = 1530 inhabitants per CS-car.

The authorities of St. Petersburg have embarked on demotorizing the city, unloading highways, and improving the environmental situation in the megalopolis. Despite the promising aspect of car sharing and all the advantages of the service, now there are several problems with short-term car rental.

The issue of paid parking is paramount for development of car sharing in St. Petersburg. Currently, the paid parking zone is small and inefficiently functioning. As soon as this zone begins to expand, the interest in car sharing will increase significantly, since the service involves introduction of free parking for CS-cars, as it is done in Moscow. Besides, the city has local legislation that immediately affects the transport environment of the city and indirectly applies to car sharing. From July 1, 2020, commercial fixed-route taxis will stop working, which should in the future redirect some passengers to car sharing services and the others to public transport (PT). In the meantime, there is no reason for operators in St. Petersburg to develop this service without intensive support of the authorities.

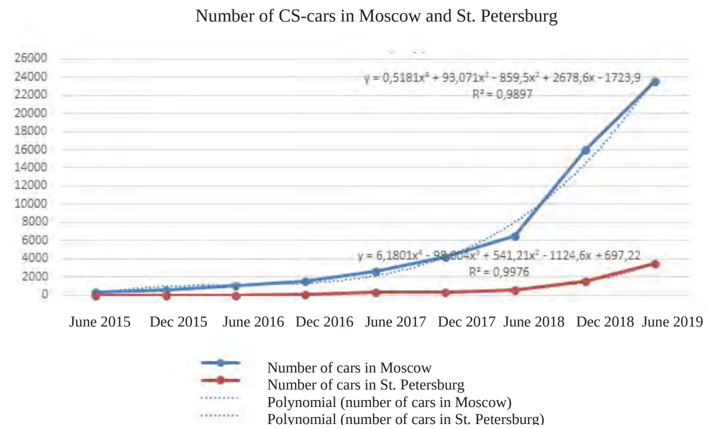
Pic. 1 shows the trends based on the statistics of changes in the vehicle fleet in Moscow and St. Petersburg from 2015 to 2018 [6; 7]. It should be noted that forecasts in this area due to a possible change in economic conditions cannot be considered completely reliable. One can only assume that if conditions implemented in St. Petersburg are similar to those existing in Moscow, given the ratio of the population of the cities, the trend in service development will strive to attain at least half-values of Moscow's indicators. According to the plans of Moscow city authorities, Moscow will have a CS-car per about 500 inhabitants and will catch up with the world leaders according to this indicator: Toronto (498), Madrid (500), Stuttgart (515) and New York (525) [7].

Prediction of the structure of transportation costs based on modelling

As noted earlier, there is a task of estimating transport demand considering car sharing based on modelling. The corresponding tools are available in PTV Visum 18 software [8]. Estimates obtained

[1] Petrodvortsovy district is located 30 km from St. Petersburg city centre, and has several sights, e.g., Peterhof State Museum. – *ed. note*.

[2] Private vehicles.



Pic. 1. Number of CS-cars (author's forecast for 2019 based in processing 2015–2019 data).

during the modelling process can be performed not only for car sharing, but also for the bike rental system (bike sharing).

The number of cars in a city district is a dynamic indicator that varies depending on time and day of the week. Some vehicles may be under repair or maintenance. Trips are carried out both within the districts and beyond. Their number is determined by such factors as urgency of the trip, date and time, traffic situation on the road, existing alternative ways and routes, well-being, accessibility of the destination, etc. Therefore, it is possible to operate only with weighted values.

The model, considering the restrictions made, does not cover the entire Petrodvortsovy district of St. Petersburg, but only the municipality of Peterhof. Another simplification is accounting of trips only inside Peterhof, that is, without trips to St. Petersburg and vice versa, though, obviously, jobs in the central areas of St. Petersburg are a natural center of gravity for remote districts, and Peterhof itself is also a center of attraction for excursion trips. Those factors can be further considered while building a more complete model.

At the same time the simplification assumed at that stage of research can be also justified by the fact that most of the jobs and attractions are concentrated in remote areas of St. Petersburg. For example, if the average time for a regular trip along St. Petersburg is 40 minutes, then in Petrodvortsovy district it is about 15 minutes according to the polls of residents. In addition, traffic jams form from the exit from the Ring Road from the side of St. Petersburg to the entrance to Peterhof, which makes the service not profitable enough for trips to the central districts.

The municipality of the city of Peterhof is part of St. Petersburg and includes microdistricts (communities) Old Peterhof, New Peterhof, Krasnie Zori and University. This district is special, given its museum attractiveness. The population of Peterhof as of 2018 was 82940 people [9].

To build the model, the following data were used: kindergarten capacity (6100), school capacity (9600), number of children of preschool age (5600), jobs at enterprises (56300), jobs in service sector (13250), the number of employed persons (68800), the number of school pupils (8800) [9].

When creating the model, the car sharing coverage area was considered as described in the interface of the corresponding application of Delimobil operator, which is the only operator working in this district so far. The initial data for creating a transport demand model were compiled from the data on the total number of the population of Peterhof, the population by groups, correspondences, bus routes and the associated transport infrastructure.

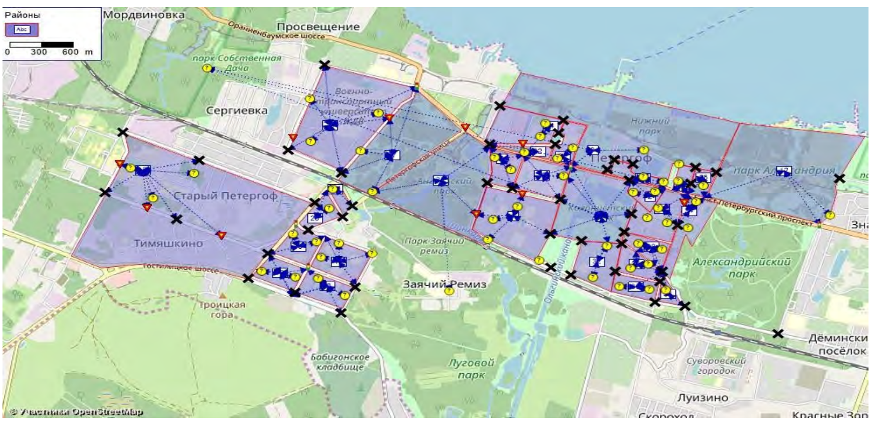
The calculation of transport demand is based on the standard four-step model (for example, [10, p. 26]). In the model embedded in the Visum program, these steps are as follow: demand generation (Trip Generation), demand distribution (Trip Distribution), mode selection (Mode Choice), redistribution (Traffic Assignment). The first two stages are preparations for creation of the model.

The construction of the model begins with introduction of elements of the road network, such as nodes, segments, areas, junctions, stops (stopping point, stopping area), bus routes. Pic. 2 shows a fragment of the demand matrix of population groups.

Junctions and exit roads connect the areas with the city's road network and are virtual segments. Some exit roads concern road transport, defining the time for a car to leave the district and to enter the streets of the city; pedestrians can also move

Количество: 30	Name	є	дошкольники	места_ВУЗ	места_сад	места_школа	население	рабочие_места	студенты	сфера_услуг	трудящиеся	школьники
1	Больница		0	0	0	0	0	2000	0	800	0	0
2	Парк колонистский		0	0	0	0	0	0	0	0	0	0
3	Жилой район (529)		100	0	1000	0	2890	300	350	200	1900	560
4	Парк (Форнтаны)		0	0	0	0	0	1250	0	900	0	0
5	Ракета		90	0	0	0	450	600	50	200	300	0
6	Институт морской		0	2300	0	2300	2300	10	0	150	0	0
7	Парк		0	0	0	0	0	0	0	0	0	0
8	Семёра		1000	0	0	0	10500	800	350	400	7800	280
9	Студгородок, СПбГУ		0	5500	0	5500	5500	540	0	230	150	0
10	Школы (411,419)		200	0	1000	0	1540	780	20	250	1200	0
11	Школа (567)		100	0	0	0	1500	220	220	100	950	560
12	Сад 33		50	0	0	0	830	115	70	70	500	280
13	Сад 16		40	0	0	0	1590	120	250	90	590	280
14	Госпиталь		20	0	0	0	450	450	48	240	100	0
15	Рынок		5	0	0	0	120	355	2	320	100	0
16	Школа 671		0	0	500	0	0	50	0	160	0	0
17	Детский сад 1		10	0	0	0	830	650	150	30	600	280
18	Сфера услуг (жара,пекин,брынза)		0	0	0	0	0	1000	0	1400	270	0
19	школа 415		300	0	500	0	850	120	200	90	300	0
20	аврора		400	0	0	0	1210	230	40	280	500	0
21	школа 416		160	0	500	0	2100	370	340	50	1500	0
22	каскад		170	0	0	0	2770	980	300	635	2000	280
23	Жилой район (сад 29)		100	0	0	0	2800	760	400	440	2000	280
24	Жилой район (полушка)		125	0	0	0	4200	710	550	700	800	0
25	Жилой район(школа 412)		70	0	500	0	3510	570	850	230	500	0
26	Жилой район		50	0	0	0	1500	490	150	290	500	0
27	школа 542		10	0	500	0	1310	400	150	700	900	0
28	Санаторий		0	0	0	0	0	390	0	245	0	0
29	парк АНГЛ		0	0	0	0	0	0	0	0	0	0
30	парк АНГЛ		0	0	0	0	0	0	0	0	0	0

Pic. 2. Fragment of table of demand of population groups (screenshot in Russian: left column «name» shows facilities (hospital, park, schools, etc.); other columns show distribution of above described data (on school capacity, jobs, etc.) with regard to those facilities).



Pic. 3. Areas with nodes of street and road network.

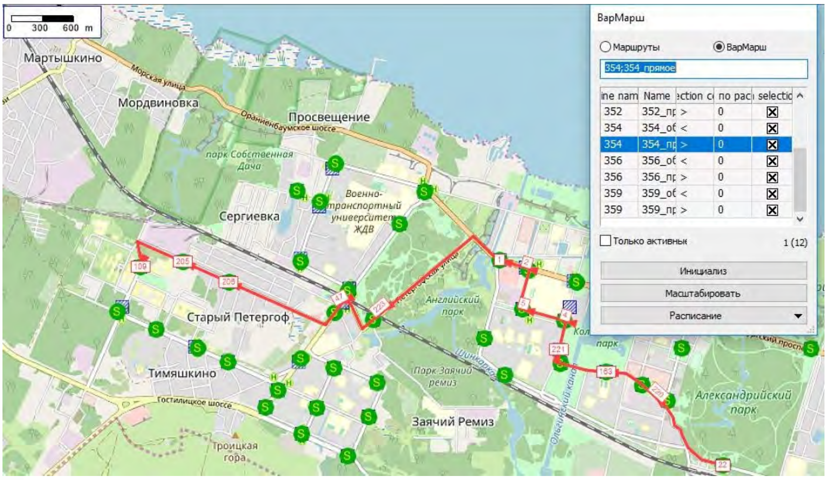
along them. Other exit paths belong exclusively to pedestrians and are connected to nodes to which stops are attached. After all considered elements are constructed and all PT routes are created, it is necessary to calculate transport demand. Fragments of the view of the districts with nodes and stop areas, PT stops and a route are shown in Pics. 3, 4.

Next, the procedures for generating traffic, the distribution of traffic by the districts, the choice of transportation mode, redistribution of traffic are performed (for Peterhof, the values of distribution of transportation mode were selected as 40 % of trips with IT and 60 % with PT). During the last stage, the intensity of traffic flows is calculated. The above distribution is based on data from the research center of the supejob portal, obtained from surveys in St. Petersburg, that showed that 10 % of commuters get to work on foot, 35 % use IT, and 55 % use PT.

When creating the procedure for choosing the transportation mode (the third step of the four-step model), the logistic regression model is used (logit function, while the combined exponential distribution is used at the second stage). The selected values of the curve parameters are standard for the transport distribution and mode selection models in PTV Visum for cities and districts with less dense population for the study of transport demand.

The results of the calculation of transport demand are matrices of inter-district correspondence with the obtained time values, as well as final matrices for IT and PT. The total demand for IT is 41226, and for PT 103598 min/year.

This model is only a preparatory one and is to serve a sample for comparison with the model, to which the car-sharing service will be further added. We will not dwell on the technology of introducing the car sharing service into the model, since this technology is described in the corresponding example from the distribution package of Visum program.



Pic. 4. Fragment of a map with stops and a PT route.

Simulation results in Visum

According to [11], as of March 2019, the average CS-car lease duration in St. Petersburg was about 40 minutes, and the average check is about 300 rubles. (The taxi fare (economy tariff), if the trip lasts from 1 hour to 2,5 hours is 15 rubles/min [12]).

The tariff of Delimobil operator is 7 rubles/min, and if you have traveled more than 120 km, then the tariff 8 rubles/km is applied [13]. Thus, when travelling 10 km in half an hour at an average speed of 30 km/h, considering traffic jams in the city, you can spend 210 rubles, and 420 rubles per hour, respectively.

At the same time, a trip with IT (considering the insurance) corresponds to a tariff of 11 rub. per km. As shown above travelling around the city for 10 km at a speed of 30 km/h, considering traffic jams, takes about half an hour. Thus, the cost of travelling half an hour is 110 rub. (or 220 rub. per hour). However, given all payments associated with the net cost of car ownership, the cost of one minute of a trip can be estimated at 19 rub. if it takes an hour [12]. Given other costs of owning a personal car, the cost of a minute is much higher.

For trips inside Peterhof for modelling, we consider two cases. Tariff of Delimobil is 7 rub./min. To compete with IT, the tariff must obviously be lower than IT costs, i.e. lower than 220 rub., for example, 180 rub./hour (3 rub./min is taken as reference being the tariff used during the period of promotion campaigns of operators). The cost of a trip with PT is set based on zone tariff at 40 rubles.

The real option that exists in Peterhof is the case of «free floating cars» that are not tied to a rental station. Since the distribution procedure is performed during the simulation, the results are random in nature. However, as follows from the graphs below, nonrandom trends are also observed. In the modelling process, a uniform distribution was used for IT, scheduled distribution with a training procedure was used for PT.

We study the time-related costs for IT and PT depending on the change in the number of CS-cars. The simulation results for the case of 7 rub./min tariff are shown in Pic. 5.

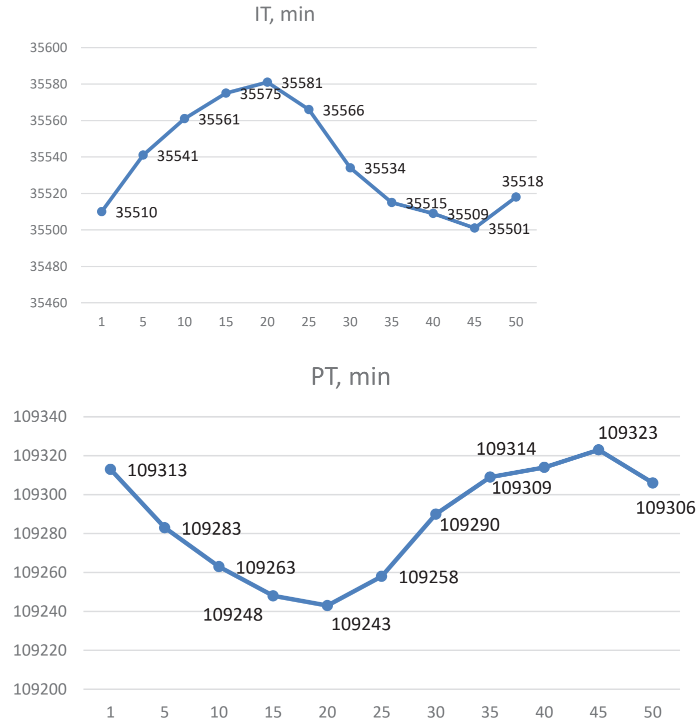
The minimum value of the number of cars in this mode is strictly greater than 0. When the number of CS-cars in the network changes, the maximum IT costs are observed with 20 CS-cars and, accordingly, the minimum costs are observed for PT (to which, according to the developers, car sharing is related). We can conclude that 20 cars mean a critical number for this area under the current conditions, and this number corresponds to the greatest competition between CS-cars and IT.

2. Dependence at a tariff of 7 rub./min on changes in rental intensity, that is, the number of rented cars per hour, when their fixed number is equal to 20 pcs, is shown in Pic. 6.

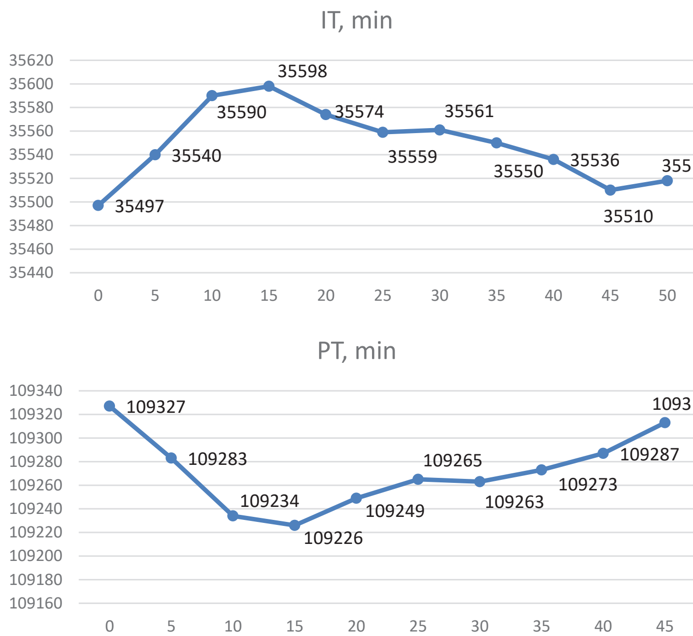
There is a tendency towards a decrease in IT costs with increasing intensity of CS-renting (the peak falls on 15 cars in the network, when the load on IT is the greatest) and, accordingly, to an increase in PT costs. It can be assumed that at an intensity of 15 cars rented per hour, competition with IT is the greatest.

3. Finally, we consider a hypothetical case of a deliberately low tariff of 180 rub. per hour. The simulation results are shown in Pic. 7.

With the increase in the number of CS-cars, there is a tendency to decrease in IT time-related



Pic. 5. Time-related costs for IT and PT depending on the number of CS-cars.

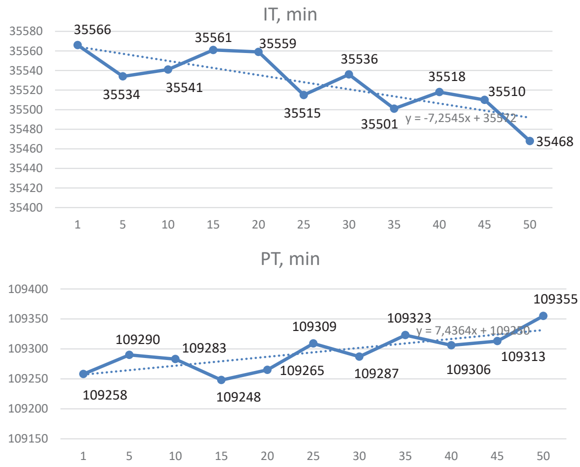


Pic. 6. Time-related costs depending on intensity of CS- renting for IT and PT.

costs and to increase in PT costs (since car sharing is included in the PT system). In addition, the percentage of citizens who previously used other types of PT but can now also use car sharing grows. Again, a traditional PT may be required to get to the CS-car parking lot. As a result of the calculations, the program generates correspondence matrices and the total demand for IT and PT. If we consider costs of IT with a critical number of CS-auto (20 pcs., Pic. 5), then the possible gain in IT costs relative to a system without car sharing is defined as (41226–35580)/41226 • 100 % = 14 %.

Activity of car sharing service in St. Petersburg

Table 1 shows a list of areas with population data, as well as the number of CS-cars. As the information about rented cars is missing (statistics that may be tracked by company services), in this



Pic. 7. Trends of dependence of time-related costs for IT and PT depending on the number of CS-cars.

Table 1

Number of rented cars per city districts

No.	District	Number of residents	Free at 02:00 a.m	Free at 10:00 a.m.	- departed, + arrived	Total rented (morning)	Ratio of CS-cars and adjusted number of residents[1]	Ratio of rented CS-cars and adjusted number of residents[2]
1	Kurortny	78131	12	8	-4	4	51	8
2	Vyborgsky	518709	27	61	34	34	339	55
3	Primorsky	568516	121	103	-18	18	371	60
4	Kronshtadtsky	44321	12	2	-10	10	29	5
5	Vasileostrovsky	208713	38	48	10	10	136	22
6	Petrogradsky	131356	8	26	18	18	86	14
7	Kalininsky	533597	256	142	-114	114	348	57
8	Krasnogvardeisky	357498	30	50	20	20	233	38
9	Admiralteisky	161911	18	25	7	7	106	17
10	Central	216939	3	18	15	15	142	23
11	Kirovsky	336248	76	109	33	33	220	36
12	Moskovsky	354525	127	124	-3	3	231	38
13	Frunzensky	394972	27	79	52	52	258	42
14	Nevsky	527861	234	121	-113	113	345	56
15	Petrodvortsovy	143154	18	2	-16	16	93	15
16	Krasnoselsky	397609	115	50	-65	65	260	42
17	Pushkinsky	217983	34	4	-30	30	142	23
18	Kolpinsky	191847	17	7	-10	10	125	20
TOTAL:		5383890	1173	979		572	3515	571

[1] The next to last column which is the ratio of the number of the residents of a district to the total city population multiplied by total number of CS-cars (according to operators' data) shows how many cars could be in the considered district. For example, for Kurortny district it is equal to 78131/5383890 • 3515 = 51.

[2] The last column is calculated in the same way but regarding the number of CS-cars really rented. For example, for Kurortniy district it is calculated as 78131/5383890 • 572 = 8.

example, we have to focus on a map of free CS-cars of all city operators [14].

The actual number of free CS-cars in the city according to the data at 2 a.m. on weekdays is approximately 1173 cars. Apparently, the rest of 3515 cars making CS-fleet are either not on the move or rented around the clock. In the morning on a weekday at 10 a.m., 979 free cars were tracked. It should be stipulated that these are data concerning only morning trips to job locations, which, of course, do not cover all possible trips during the day.

For Petrodvortsovy district there were 18 free CS-cars at 2 a.m. At 10 a.m. after some cars left, and some other cars arrived, there were two free cars, that is, 16 cars were rented, which coincides with the ratio calculated in the last column of the Table 1. This value is close to the simulation results considering current operator's tariffs (20 CS-cars in the area, which are rented with an intensity of 15 cars/hour).

The table also shows where and how many CS-cars arrive for job purposes and which areas they leave. The table also shows that the entire Petrodvortsovy district should account for 143154/1530 = 93 CS-cars. The percentage of really rented cars is 16/93 = 0,17. For comparison, Nevsky district has almost the same rate 56/345 = 0,16. At Peterhof, taking into account the number of inhabitants there should be on average 82940/1530 = 54 CS-cars, and in fact there are no more than 20 cars. Thus, it is possible to evaluate the activity of car sharing in Peterhof relative to the average value in the city with a coefficient of 16/54 = 0,3. The above estimates and coefficients, of course, do not pretend to be a full-fledged statistical study, but show trends.

The most promising areas for introducing new services are districts on the borders of the city, as there is a potential demand on the trips towards large interchange nodes, for instance from Petrodvortsovy district to Krasnoselsky or Kirovsky district, where the user can transfer to the PT, especially to take metro, and continue on to the destination.

The actual number of CS-cars in St. Petersburg is within the range of calculated values indicated in Table 1, and that confirms the sufficient provision of the city with car sharing service. However, this does not mean that the quantity of the CS-cars will not increase, since each company seeks to occupy a key place in the city, increasing the level of service, particularly by renewal of vehicles, updating of car models, and by gradually removing old models. Also, new and small companies start operations in several city districts and seek to increase areas covered.

Conclusions. The article has determined car sharing development conditions and forecasts for the city of St. Petersburg. Simulation based on gravity modelling was performed for Petrodvortsovy district, that allowed to note positive effect of the existing car sharing system on the development of transport system, to suggest quantitative estimates of the number of CS-cars and their rental intensity, particularly regarding their influence on competition with IT. The estimates found are consistent with the actual data on car rental.

The effect of introduction of intelligent transport systems to reduce travel time, according to Rosavtodor [Federal Road Agency], can be of 35–40 % [15]. The simulation of car sharing effect showed reduction of travel time by 14 % indicates that car sharing and similar services can significantly complement developed intelligent transport systems with regard to grown transport accessibility for population.

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