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Development of a Method for Selecting Bus Rapid Transit Corridors Based on the Economically Viable Passenger Flow Criterion

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Abstract: The creation of bus rapid transit systems requires significant investments in transport infrastructure. It often requires changes in roadway parameters, building boarding platforms, new bus depots, as well as creating a priority passage system at intersections with individual vehicles flows. In world practice, the routing of bus rapid transit (hereinafter—BRT) corridors is often based on the criterion of an opinion of transport experts who assess passenger flows and the location of main attraction points. This article describes an algorithm for building BRT corridors based on the criterion of economically viable passenger flow. The method is based on an iterative algorithm built on the principle of passenger flows redistribution over the transport network in the event of a change in its characteristics. Specifically, what changes is the speed of transit in certain areas due to inclusion of the area in a BRT corridor when the area reaches the threshold of economically viable passenger flow. A threshold value of passenger flow for different cities, grouped by population size, is determined on the basis of passenger flow statistics in globally operated BRT systems. The condition for exiting the iterative algorithm can be either the absence of new network areas where an economically viable passenger flow is achieved, or the achievement of 90% of the labor commuting share in the city during the time specified in the urban planning standard. This method can be used to identify new and extend existing BRT corridors in cities with populations from 100 to 2000 thousand people.

Keywords: bus rapid transit; economically viable passenger flow criterion; transport calculation; passenger flows redistribution

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1. Introduction

One of the United Nations (UN) sustainable development goals is to ensure the openness, safety, resilience and environmental sustainability of cities and towns. Goal 11.2 declares: “By 2030, provide access to safe, affordable, accessible and sustainable transport systems for all, improving road safety, notably by expanding public transport, with special attention to the needs of those in vulnerable situations, women, children, persons with disabilities and elderly persons” [1].

According to World Bank data, over the past 60 years the proportion of the world population living in cities has increased by 20% [2]. Today, more than 55% of people live in urban areas. The growth of the urban population is related to the increase in the area of the city and the distance from places of residence to places of work and study. In the absence of reliable and affordable public transport, people increasingly use private cars; as a result, transport systems become unbalanced, traffic jams are formed, and the anthropogenic impact on the environment increases, thus reducing the quality of life and standard of living. To maintain the average trip time at an acceptable level, support transportation of an increasing number of passengers, and reduce harmful human impacts on the environment, faster and more efficient transport systems are required.

The most common kind of public transport is the bus. Its popularity is due to the lowest cost of capital expenditures and the highest mobility [3,4]. Different dimension types of this kind of transport vehicles can use practically any road, and route laying options are limited only by the road network.

The combination of the advantages of the wheeled mode of transport, its low cost and mobility, as well as measures for increasing traffic speed, together with more spacious vehicles, has formed a new type of public transport. Bus rapid transit (BRT) is one of the bus transportation varieties. BRT is the main type of public urban passenger transport (hereinafter referred to as 'PUPT'), the passenger flow of which reaches 18,000 passengers per hour in one direction [5], and in some cases 43,000 passengers per hour. To achieve such capacity and speed, a BRT line must have the following characteristics:

1. Isolated lanes in the center of the carriageway or a separate roadway;
2. Vehicles of especially large capacity (often of an individual design);
3. Toll collection outside the vehicle;
4. Priority over other modes of transport at crossroads;
5. Passenger boarding and deboarding on platforms of the same level with vehicle floor [6].

In the 1970s, the countries of Latin America faced rapid growth of the urban population. High-performance, high-speed systems were required for transport services, but cities could not afford large infrastructure projects such as the construction of a subway. So, the population of the Brazilian city Curitiba in the early 1970s was about 600 thousand people. In 1974, at the initiative of the mayor of Curitiba, Jaime Lerner, a bus traffic system was opened, which later became the first BRT system—"Rede Integrada de Transporte".

The most widely developed BRT systems appeared in India and China [7,8]. A BRT economic model has proven to be very attractive to countries with developing economies and a rapidly growing population. BRT requires several times less capital expenditure as compared to the tram or subway. At the same time, it allows for the creation of a branched, extensive transport system within a short time, ensuring high-level transport services quality: high transportation speed, high carrying capacity, and high traffic frequency with proper routing.

In BRT technology, stopping points should be provided with roofed heavy-duty pavilions that are usually installed in the middle of the carriageway on traffic flow dividing lines. Often, their installation requires changes in roadway configuration to provide for broadening. Terminal stations and turning rings shall be designed individually. They need more space, larger pavilions, and larger vehicle parking platforms. Proximity to the beginning of a BRT corridor can be a determining factor when choosing a location for bus depot construction in order to reduce the costs of zero (depot) run. In especially complicated areas, it may be necessary to separate traffic flows at different levels, building, e.g., bus crossover junctions. The building of a BRT corridor is associated with large capital investments and construction of a transport infrastructure.

Effects to be provided by the new system, such as increased transport accessibility, reduced transport system load, and harmful emissions, depend on the well-considered BRT corridor routing. The purpose of this article is to develop a method for selecting a BRT corridor, and also to provide a calculation of BRT corridors using the city of Pskov as an example.

The rest of this paper is organized as follows. Section 2 presents an overview of BRT corridor selection methods and justification for selecting BRT corridors in accordance to the economically viable passenger flow criterion. Section 3 describes the developed method. Section 4 presents results of method application. Section 5 presents conclusions and further directions of the research.

2. Overview of BRT Corridor Selection Methods

The Institute for Transport and Development Policy (ITDP) suggests that at selecting a type of mass rapid transport, one should be guided primarily by financial feasibility and the required capacity. In many cases, there is only one transportation technology in a city. It is more practical to create a mass high-speed mode of transport, if possible, using the existing facilities. The availability of highly-qualified specialists familiar with the technology also reduces the costs of system creation. Another important aspect is self-financing. For poor cities, high-speed mass transport can be unfeasible due to the lack of budgetary funds to subsidize transportations [9]. Only highly efficient systems operating at full capacity and linking the required points of attraction can enable such self-financing mode.

Therefore, the selection of the type of high-speed mass transport boils down to the conditions of necessary and sufficient capacity, budget-affordable costs, and the technology that best meets the specific needs of a city (self-financing, availability of an existing technical infrastructure in the city for its creation) [10].

Usually, BRT corridors are defined by expertise [11–13]. Routing begins with the definition of the main attraction points of the considered territory. Passenger flows survey data and traffic simulation data can help identify the most constrained areas of the city's transport network [14–16], which will make it possible to create a BRT corridor in the most promising directions in terms of passenger flows. First of all, BRT should be organized for such directions. In terms of technical implementation, BRT is more convenient to plan on main highways of the city; normally such roads connect main points of attraction as well. In some cases, local residents participate in the determination of a BRT corridor through public hearing tools [12].

The ITDP has developed a BRT standard for the evaluation and ranging of the existing systems. On its basis, they developed a methodology for quality assessment of BRT systems being designed [17]. The assessment is made on the basis of a 100-point system. The highest number of points (38) can be scored for availability of basic BRT attributes (traffic priority, platforms at the vehicle floor level, toll collection outside the vehicle, availability of dedicated traffic lanes); for routing in the most popular corridor, a maximum of 3 points can be received. In general, this standard provides a possibility for infrastructure quality and service level assessment, but not assessment of the quality of BRT corridor routing.

Multiple works are dedicated to the assessment of BRT corridors using different criteria. Authors compare passenger traffic [18], speed and safety characteristics [19], emissions changes [20], and population effects [21]. However, most of them assess the effectiveness of existing transportation systems.

The work of Rea J. [22] used linear programming methods for modeling a public transport network to achieve the minimum travel time, taking into account the throughput of the transport network.

An example of a deterministic approach to the creation of rapid transport systems is the method by M. Ya Snitsar for the routing of rapid transport systems (RTS) lines [23–25]. This methodology suggests an automatic search of optimal RTS of different types using a computer. Initially, the need in RTS is established in a transport assessment model itself by calculating the labor commuting specific weight (share) criterion, γ, over time exceeding 40 or 30 min, depending on the population size.

After preliminary selection of a rapid transport type, its network is routed using an iterative algorithm. The initial data for starting the calculation is the street and road network (SRN) graph of the city and, if the considered option of rapid transport can pass outside the SRN (metro, high-speed tram), it should be the network of shortest links between main centers of the transport attraction. The general principle of the calculation is to determine a traffic load by the existing PUPT route networks using conventional transport calculation methods, and then distributing it between the PUPT route networks and the polygon of a potentially suitable high-speed PUPT network according to the minimum travel time criterion.

Thus, in practice, BRT passage corridors are selected based on an expert opinion, existing passenger flow data, and the arrangement of major attraction points. However, quantitative methods for tracing BRT corridors were not identified. On the other hand, M. Ya Snitsar proposes usage of the economically viable passenger flow method and the method described in this article will be built on its basis.

3. Method for Selecting BRT Corridors According to the Economically Viable Passenger Flow Criterion

Figure 1 shows a flow chart of the proposed iterative algorithm for BRT corridors determination [26,27]. At the first iteration, transport calculations are performed for the existing route networks (blocks 2 and 3). This can be any transport calculation, while the distribution of traffic flows over the network should depend on the duration of the correspondence. For example, a four-step model [28] or a multi-agent transport model based on chains of activities [29]. The initial data for the calculation is the transport supply, or the graph of the city's street and road network, public transport routes, as well as the level of motorization in the territory; next is transport demand, or data on the places of settlement of residents, places of employment, study, leisure and other activities, etc. The result of the transport calculation is a source-destination correspondence matrix, as well as the distribution of transport demand according to the transport graph models.

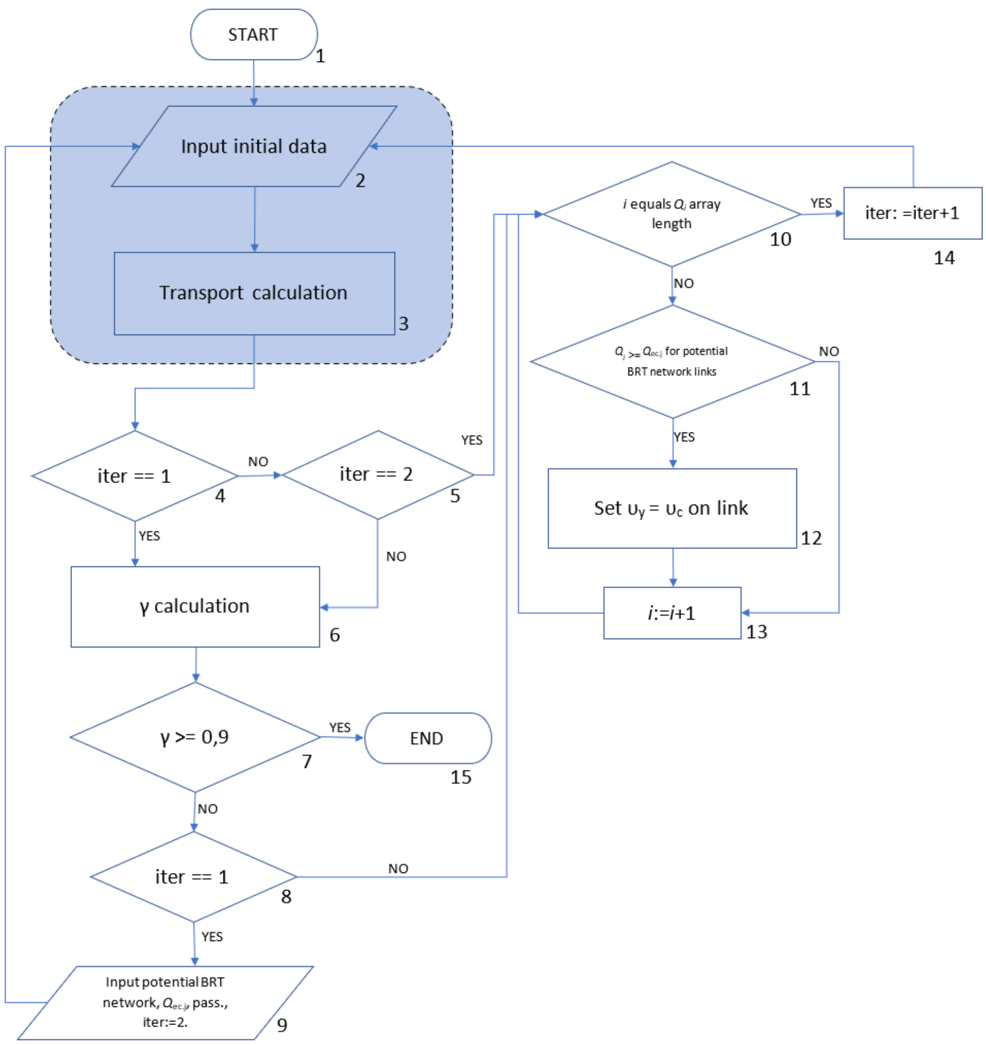

Figure 1. Flow chart of the algorithm for defining the BRT corridor.

Then, the base value of labor correspondence share is determined. This value should be less than standard time γ. In accordance to paragraph 11.2 of the Code of Rules "Urban Planning: Planning and Development of Urban and Rural Settlements" 42.13330.2016 (Russian regulatory act in the field of urban planning) [30], the time spent in cities for moving from places of residence to places of work for 90% of workers (one way) should not exceed the following parameters: 45 min for cities with a population of up to 2000 thousand people; 40 min for a population of up to 1000 thousand people; 37 min for up to 500 thousand people; 35 min for up to 250 thousand people; and 30 min for 100 thousand people and less. Indicated norms for spending time should be interpolated for intermediate estimates of city population. Then, the number of labor correspondence, which duration does not exceed the normative one, is divided by the total number of labor correspondence. If γ is less than 0.9, then the calculation continues (block 7). Since it is first iteration, we move to block 9 (block 8).

Further, in block 9, a potential BRT network is added as an economically viable passenger flow. A potential BRT network is a set of elements of a street and road network (traffic graph) along which the organization of BRT traffic is possible, as well as possible new transport links. When choosing such sections, one can take into account the class of the road or street, the width of the carriageway, the radii of curves, the availability of space for the installation of landing platforms, etc. Economically justified passenger flow $Q_{ec.j}$, pass., is the criterion mentioned earlier, on the basis of which a decision is made to include a section of the potential BRT network into the generated BRT network. These data are needed for further calculations.

At the second iteration, trips are distributed over two networks: the existing PUPT route network and the potential BRT network polygon, including the shortest links network. Therefore, to SRN are added potential links, which can be built or extended. These links are optional for calculations. Next, through blocks 4 and 5 we move to block 10. At this stage the cycle for potential participants of a BRT network, where passenger flow is greater than or equal to the assumed value of the economically viable passenger flow, starts (blocks 10–13). At areas where the passenger flow reaches an economically viable level, the speed of travel is increased to the speed of the BRT access.

After the cycle is completed, the third iteration begins, with newly introduced BRT areas in the network, at which a high traffic rate is assumed. This leads to an increase in passenger flow through these areas which, in turn, leads to an increase in passenger flow in adjacent areas of the network. Passengers try to choose a route that will take the least time. Such change in the attraction scheme leads to the emergence of new areas where BRT mode introduction will be justified. Further iterations of the calculation are based on passenger flows redistribution hypothesis through the increase in traffic speed in certain areas of the network, which leads to a passenger flow increase in these and the nearby areas of such network. Each iteration leads to an increase in γ due to increase in the BRT network and decrease in time of labor correspondence over the network. The calculation ends when γ reaches 0.9 or when no new sections are added to the generated BRT network at the next iteration.

The BRT Data website collects data on BRT systems from around the world [31]. Data on daily passenger flow in corridors and population size is available for 118 cities and agglomerations. The population size ranges from 100 thousand to 12.2 million people. The average daily passenger flow is from 1250 to 1.2 million passengers/day. The average passenger flow for a group of corridors arranged in cities with similar population size can be considered economically viable. Grouping is carried out in accordance with clause 11.2 of SP 42.13330.2016, starting from cities with a population of 100 thousand people or more. The number of cities in each group is shown in Figure 2.

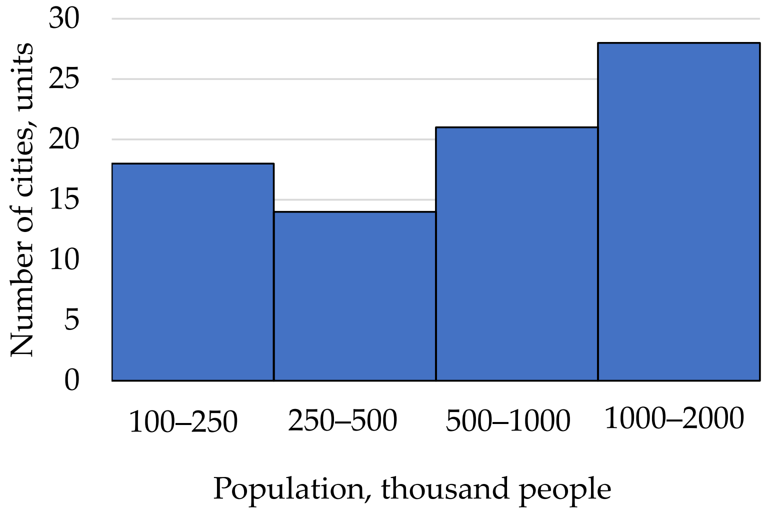

Figure 2. Grouping of cities by population size.

Table 1 presents arithmetic averages of the average daily passenger flows in corridors of the cities by groups. In Figure 3, Table 1 is presented in a graphical form.

Table 1. Average daily passenger flow in cities by groups.

Group	Population, Thousand People	Average Daily Passenger Flow, Thousand People
1	100–250	15.9
2	250–500	39.4
3	500–1000	41.3
4	1000–2000	86.3

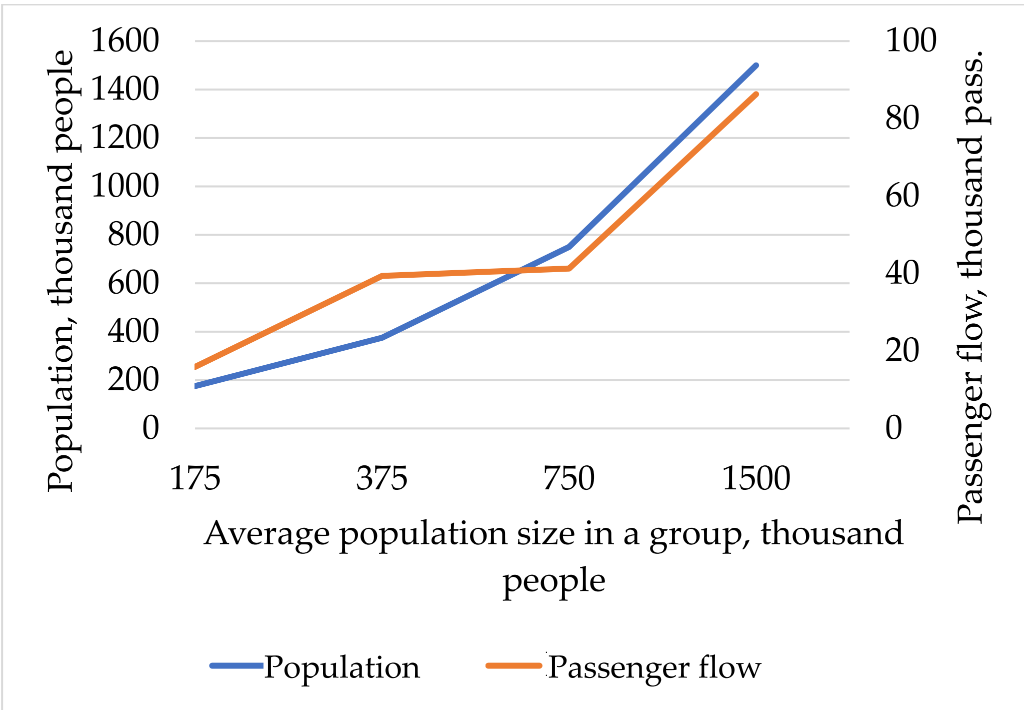

Figure 3. Graph of passenger flow change with population growth.

As it can be seen from Table 2, passenger flow is growing disproportionately to population growth. However, the growth is close to linear.

Table 2. Comparison of indicators between the formed groups.

Compared Groups	Changes in Population, %	Changes in Passenger Flow, %
1–2	214	248
3–4	200	209

Thus, the assumption of a direct relationship between the city's population and passenger flow can be considered partially correct. In this regard, certain values of passenger flows are used in the calculation according to the method, depending on the city population. The calculated value can be changed based on obtained passenger flow charts at the second iteration of the calculation.

To confirm the correctness of average daily economically viable passenger flow selection, a feasibility study can be used. The justification shall be made on the basis of annual profit, profitability, and capital investments payback period indicators. The cost of a 1 km of vehicles run is determined in accordance with the effective order of the Ministry of Transportation of Russia. If economic indicators of the project show its low efficiency, the calculation according to the iterative algorithm should be re-started using an increased value of economically viable passenger flow.

Thus, for the first time in the practice of creating BRT corridors, a numerical method for choosing the route of passage is proposed. The method can be used to calculate the BRT corridor only in urban areas with a population of 100 to 2000 thousand people. The reliability of the result obtained directly depends on the quality of the initial data used: transport demand and supply in the study area.

4. Results

To check the methodology in practice, a test calculation has been carried out using the city of Pskov as an example. The trip matrix is calculated according to the method proposed by E. A. Merkulov [32]. The number of trips is calculated for a year. The Pskov population is 210 thousand people [33], the threshold value of labor commuting time is in the interval from 100 thousand people (30 min) to 250 thousand people (35 min). This means that the share of labor trips up to 34 min should be calculated, γ_{34}. The only public transport in Pskov is the bus. The route network runs mainly along the main streets network. The length of the network is 88 km. The length of the routes is 204 km, which is more than 2 times the length of the network, which indicates a high level of duplication.

To calculate the trip matrix, it is necessary to define transport districts between which traffic will be calculated. Boundaries of the districts are primarily assumed to be natural geographical barriers of the city—rivers, railways, fortress walls. Districts are defined so that their borders lie on the geographical obstacles and main streets are their axial lines. The transport regions scheme of Pskov is shown in Figure 4. In each transport region, the center of attraction is determined on the basis of its geometry, and also on concentration of residential buildings and labor areas. From the district centers, perpendiculars are drawn to the street road network (hereinafter referred to as the SRN) of the city.

A graph of the transport network used for calculation is assumed to be SRN areas, along which the PUPT routes pass, as well as areas of main roads and streets. The graph of the transport network is split into areas at the points of potential passenger flow change: at crossings and in the centers of transport areas. With a split according to this principle, 100 areas of the road graph have been obtained.

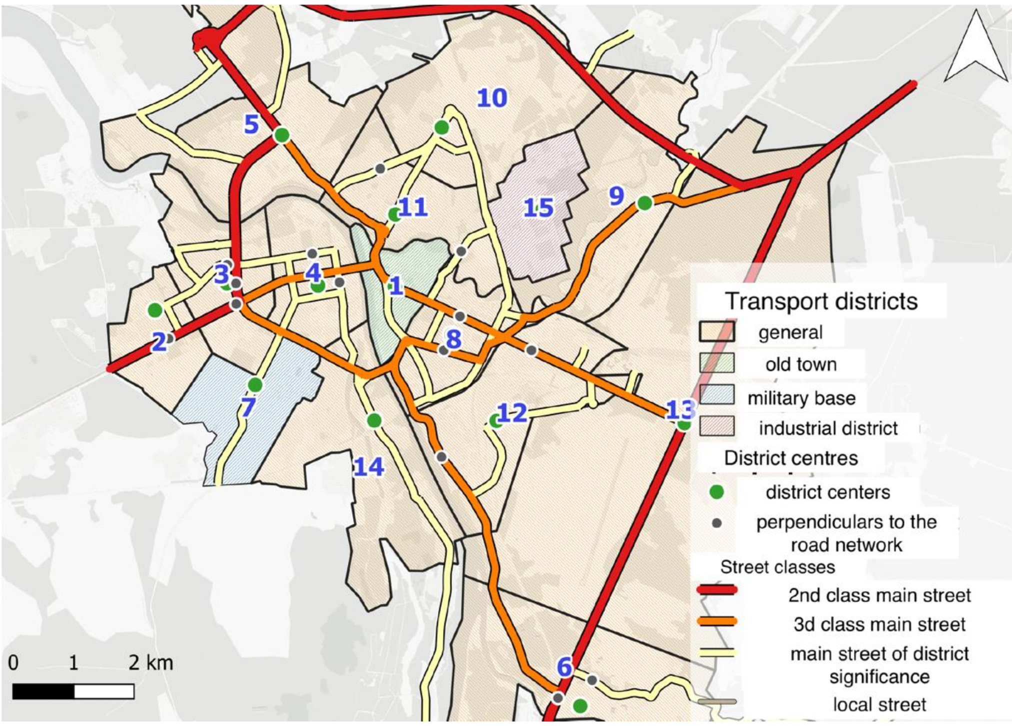

Figure 4. Pskov transport districts.

The hypothesis of the distribution of trips between transport attraction centers along the shortest routes has been assumed. Knowing the length of network graph areas, shortest trip routes between areas can be defined for the existing PUPT.

Trips taken by the city population by transport and on foot are associated with time spending. This "lost" time increases with the size of the urban area. Each resident seeks to spend less time on such trips, so they choose a place of work closer to their place of residence, and travel as little as possible for cultural and domestic purposes. Then, the time of a trip between districts "i" and "j" becomes the problem of transport communication between these districts. Correspondence time at the PUPT consists of the following components: walk time to the stopping point, the waiting time at the stopping point, the travel time by transport, the time for transfer (if necessary), and the time for walking to the destination point. The walking time to and from the stopping point is calculated for each center of the transport area and points to perpendiculars on the road network, taking into account non-linear coefficient of moving between transport areas. The waiting time of the PUPT and transfers are taken into account in the speed of movement along the RSN graph (speed of the PUPT message).

The volume of traffic on the PUPT will be 70% of the total trips volume. The trip matrix along the PUPT in total for labor and cultural/household trips is given in Table 3.

In accordance with trips thus obtained, a chart of the PUPT passenger flow can be built, as shown in Figure 5. Values of passenger flows by areas are presented in Table 4. Values gradation is indicated by color: minimum values—red and maximum values—green. Main passenger flows pass through the city center, as this route is the shortest for many trips. It is likely that future BRT routes will run from residential areas to the city center.

At the second iteration, 14 areas of the potential BRT network graph exceeded the passenger flow threshold value; at the next iteration, the speed of travel in these areas was assumed as 25 km/h. Detailed data presented at Tables 5 and 6. Visualization presented at Figure 6.

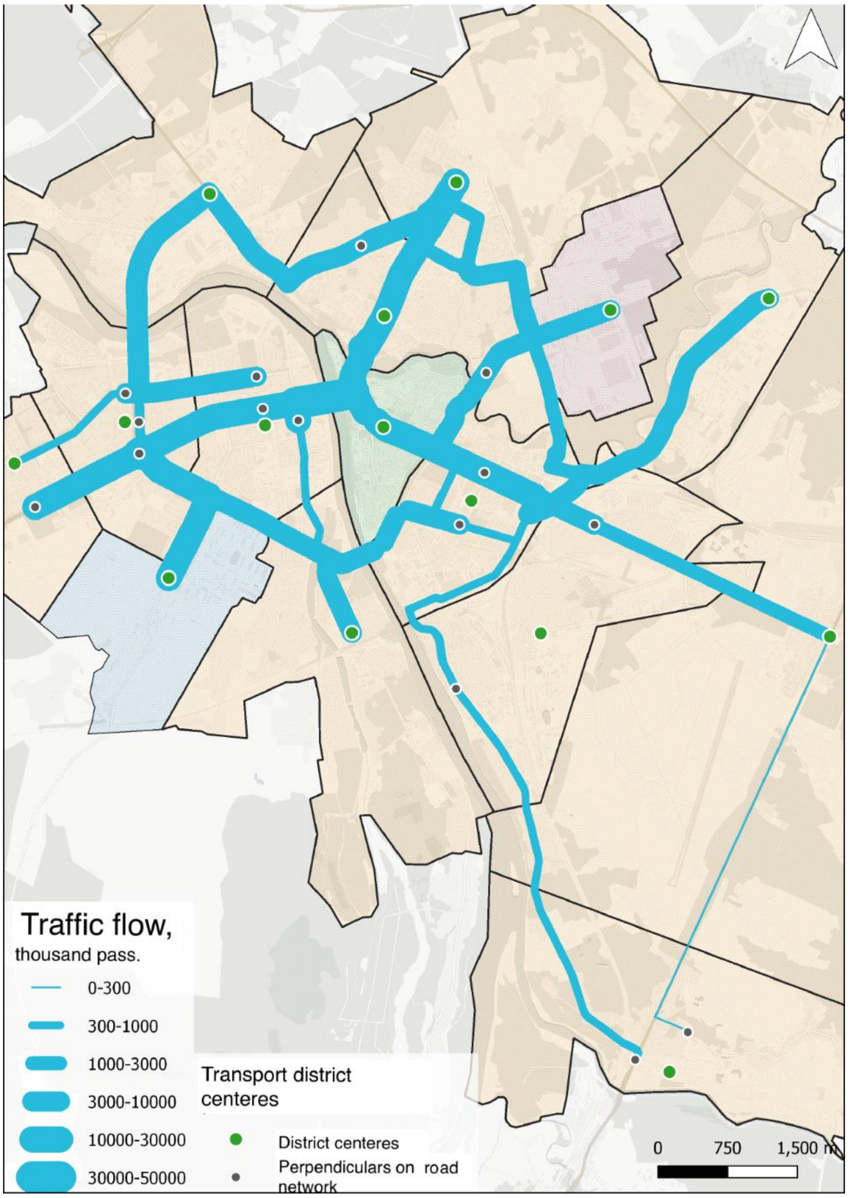

Figure 5. Chart of the passenger flow over the existing PUPT.

Table 3. Trips of population using PUPT.

	Labor Commuting Trips for Transport Departure Districts, Thousand													Total
	1	2	3	4	5	6	8	9	10	11	12	13	14	
1	152	885	2374	1654	325	40	935	277	1370	994	311	103	359	9779
2	137	553	3223	1196	528	17	700	112	268	278	144	32	121	7309
3	426	3745	1931	3234	1606	34	2021	448	1208	988	478	143	431	16,693
4	322	1593	3761	548	585	19	1037	428	1290	909	387	147	348	11,374
5	84	774	2269	807	243	8	215	38	689	561	71	7	50	5816
6	1	2	3	1	1	128	9	3	3	2	10	30	22	215
7	300	1295	3844	2012	253	87	813	99	1790	728	274	128	738	12,361
8	226	332	1044	913	95	60	243	407	1028	648	342	162	286	5786
9	174	201	766	661	329	16	276	355	394	416	324	64	50	4026
10	243	578	1676	1173	569	39	481	331	1358	1159	103	99	320	8129
11	78	212	503	352	117	76	250	201	1016	74	125	59	266	3329
12	24	33	91	77	10	96	117	133	109	43	25	83	58	899
13	47	167	520	268	28	83	216	98	196	111	68	44	57	1903
14	19	102	203	95	20	8	88	38	83	28	32	15	15	746
15	253	222	899	921	191	1	838	120	1225	1081	191	23	126	6091
													Total	94,456

Table 4. Passenger flows in areas, first iteration.

Passenger Flow in the Area, Thousand Pass																			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
20,998	19,103	27,711	14,428	19,312	0	8056	0	13,359	3928	2937	2337	5274	991	8321	12,612	11,981	16,975	28,393	15,612
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
15,612	0	0	1045	0	1045	0	1045	10,550	6403	563	563	8056	6403	4235	2178	2178	13,876	17,342	0
41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
0	0	1597	0	1395	1597	2992	2992	17,046	2057	4677	4512	14,225	20,713	795	6144	310	13,835	13,525	8071
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
0	8071	6091	321	6111	7624	2951	498	2453	5878	5834	460	321	84	0	84	6672	2283	8884	9312
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
3760	2367	654	654	0	155	155	0	0	0	2820	2820	0	0	4484	17,736	0	1367	7218	654

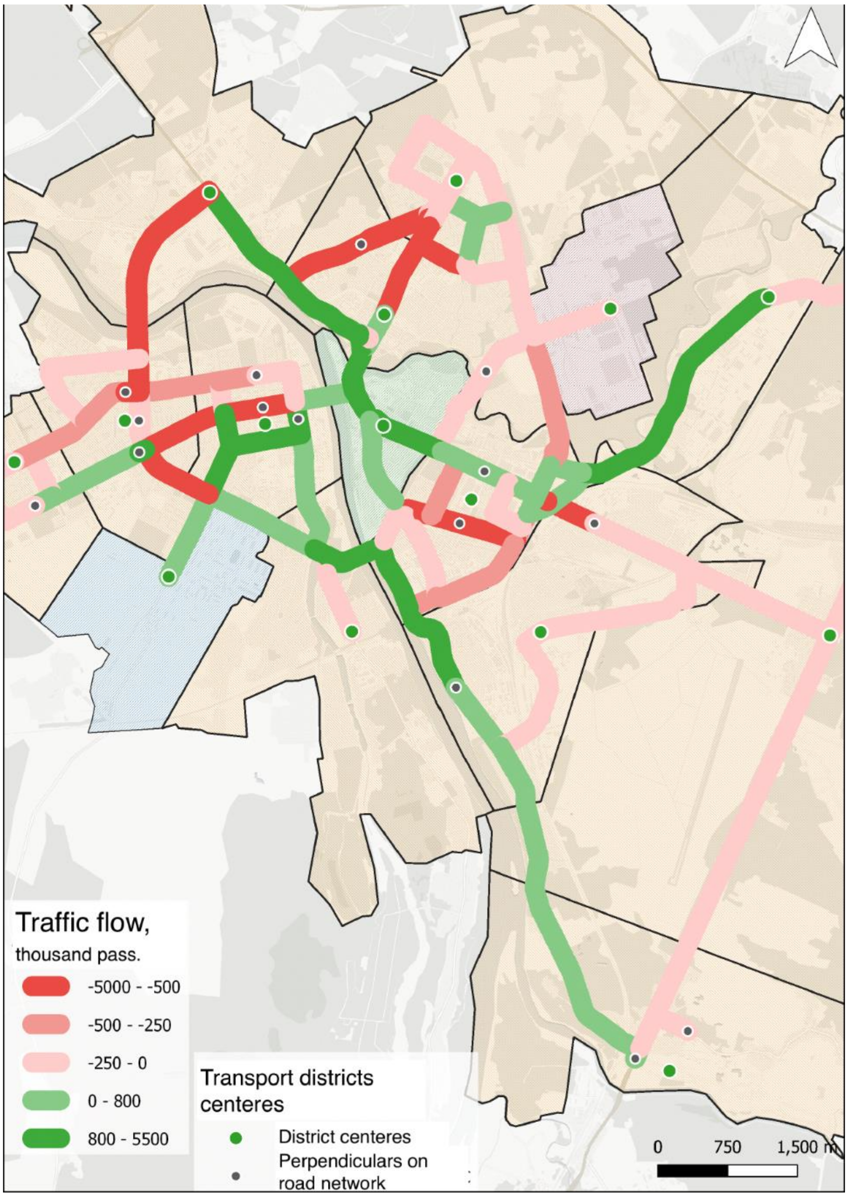

Figure 6. Chart of passenger flow changes at the second iteration.

Table 5. Passenger flow in areas, second iteration.

Passenger Flow in the Area, Thousand Pass																			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
20,998	19,103	27,711	14,428	19,312	0	8056	0	13,359	3928	2937	2337	5274	991	8321	12,612	11,981	16,975	28,393	15,612
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
15,612	0	0	1045	0	1045	0	1045	10,550	6403	563	563	8056	6403	4235	2178	2178	13,876	17,342	0
41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
0	0	1597	0	1395	1597	2992	2992	17,046	2057	4677	4512	14,225	20,713	795	6144	310	13,835	13,525	8071
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
0	8071	6091	321	6111	7624	2951	498	2453	5878	5834	460	321	84	0	84	6672	2283	8884	9312
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
3760	2367	654	654	0	155	155	0	0	0	2820	2820	0	0	4484	17,736	0	1367	7218	654

Table 6. Passenger flow changes in areas, second iteration.

1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
1182	2144	142	−2179	−2096	0	−331	0	2397	3082	2937	2337	5274	145	792	251	−3631	−4433	1666	17
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
17	0	0	−257	0	−257	0	−257	−1622	−799	−70	−70	−331	−799	1207	−850	−850	−894	−98	0
41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
0	0	323	0	−513	323	−190	−190	87	2057	−154	−229	832	897	795	−1046	−362	291	653	35
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
0	35	182	−478	647	1220	233	498	−265	−87	−684	−533	−478	−368	0	−368	−224	2283	1694	937
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
−77	1915	202	202	0	−64	−64	0	0	0	−127	−127	0	0	−1683	777	0	1367	1354	202

At the third iteration, the calculation of shortest routes was carried out for the same network as at the first iteration, since the areas of the shortest links used at the second iteration have not become effective enough to be included in the BRT network. Figure 7 shows the areas selected for BRT laying following the results of iterations 2 and 3.

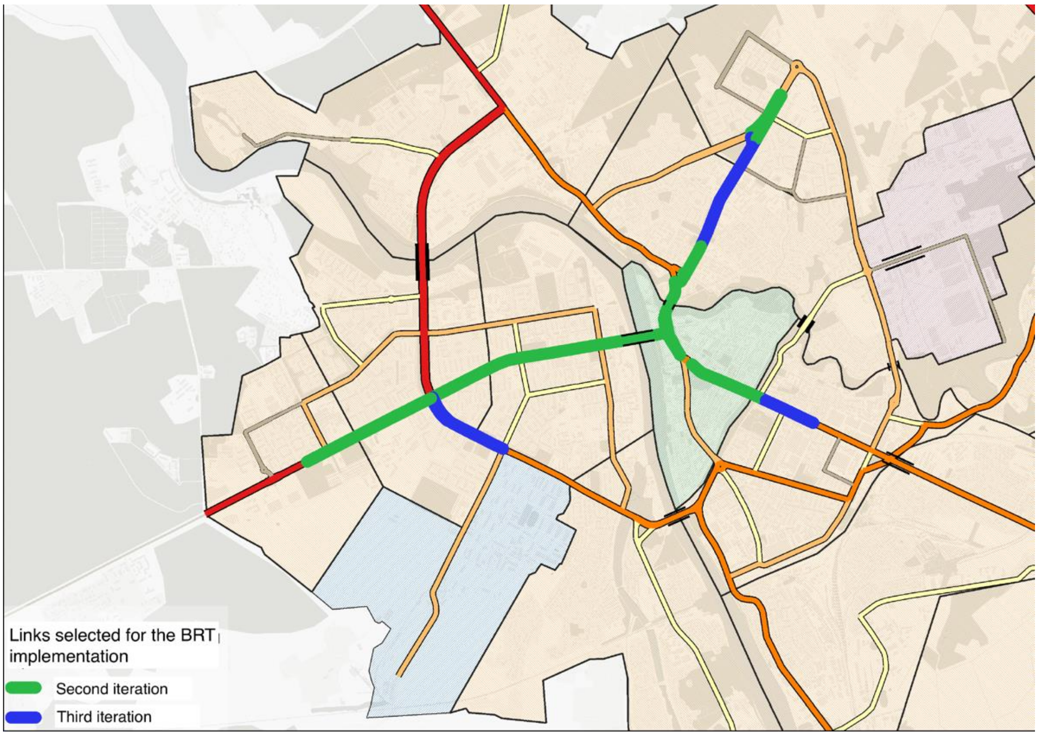

Figure 7. Areas selected for BRT organization.

At the fourth iteration, the BRT network has not increased and the algorithm operation was completed. Tables 7 and 8 present the passenger flow for network areas at iterations 3 and 4, respectively; Figure 8 visualizes the change in passenger flow between iterations 4 and 3. By adding new areas to the BRT network at iteration 3, the trip time through these areas reduced, which led to an increase in the probability of travel between the associated areas. In the chart it can be seen that the increase in travel speed in several areas led to significant changes in the attraction system. Passenger flow has increased both in BRT areas and in adjacent areas.

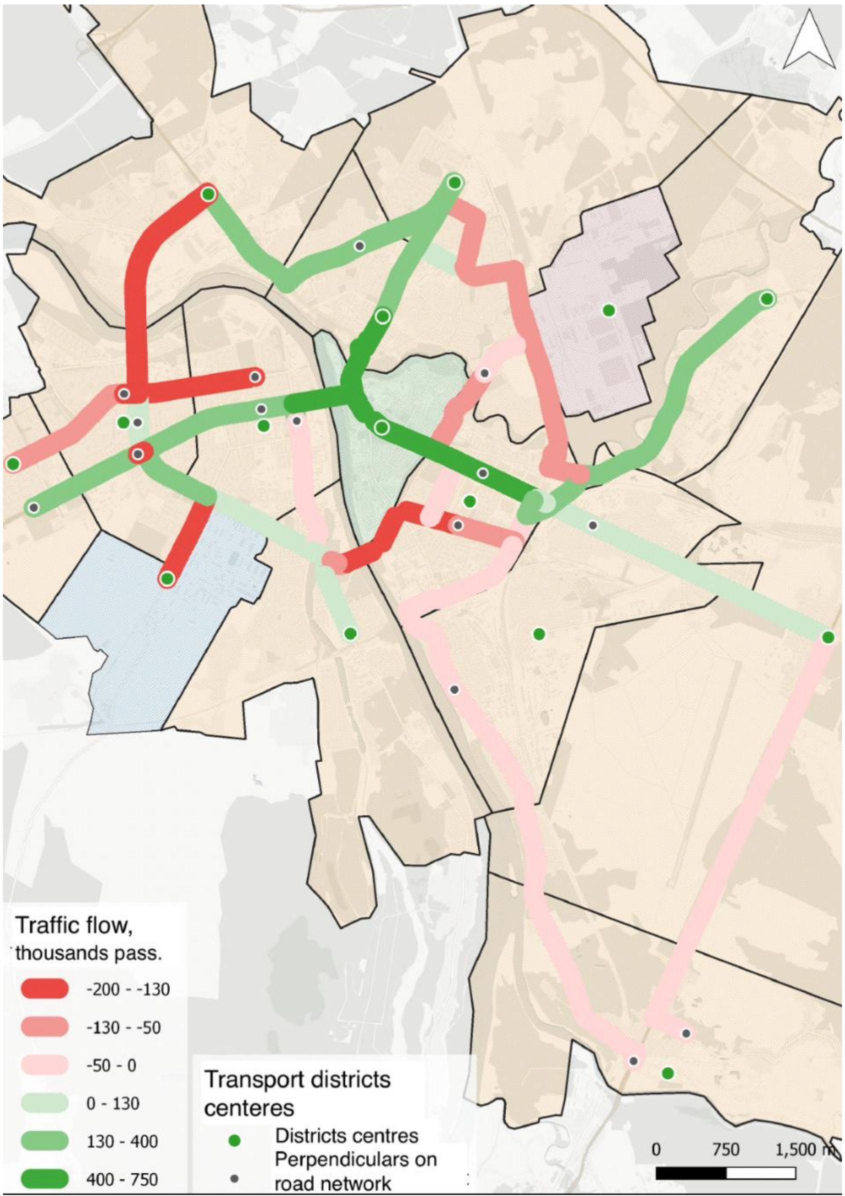

Figure 8. Change in passenger flow between iterations 4 and 3.

Table 7. Passenger flow in areas, third iteration.

Passenger Flow in the Area, Thousand Pass																			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
22,595	19,305	32,740	21,247	26,106	0	7568	0	11,493	762	0	0	0	762	7728	12,085	16,079	26,106	31,806	16,446
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
16,446	0	0	1061	0	1061	0	1061	10,065	6966	801	801	7568	6966	3206	3206	3206	15,261	17,792	0
41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
0	0	1351	0	1732	1351	3083	3083	19,305	0	4944	5039	15,972	22,595	0	7477	634	15,141	14,507	9685
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
0	9685	7272	748	6813	7953	2658	0	2658	5915	6843	1021	748	502	0	502	7201	0	7477	8490
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
3791	502	502	502	0	215	215	0	0	0	2695	2695	0	0	6005	19,305	0	0	6088	502

Table 8. Passenger flow in areas, forth iteration.

Passenger Flow in the Area, Thousand Pass																			
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
23,099	19,728	33,453	21,603	26,462	0	7418	0	11,850	740	0	0	0	740	7760	11,917	16,371	26,462	31,668	16,728
21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37	38	39	40
16,728	0	0	999	0	999	0	999	9890	6833	915	915	7418	6833	3339	3339	3339	15,641	17,956	0
41	42	43	44	45	46	47	48	49	50	51	52	53	54	55	56	57	58	59	60
0	0	1276	0	1738	1276	3014	3014	19,728	0	4911	4986	16,471	23,099	0	7278	585	15,587	15,002	10,205
61	62	63	64	65	66	67	68	69	70	71	72	73	74	75	76	77	78	79	80
0	10,205	7607	711	7168	8210	2556	0	2556	5915	6693	964	711	501	0	501	7038	0	7278	8500
81	82	83	84	85	86	87	88	89	90	91	92	93	94	95	96	97	98	99	100
3794	501	501	501	0	209	209	0	0	0	2751	2751	0	0	6082	19,728	0	0	5992	501

Figure 9 shows a graph of coefficient $\gamma 34$ changes by iterations. The graph shows how the share of labor commuting trips taking up to 34 min increased at the second iteration. However, at iteration 2 there was no rapid transit network yet. The coefficient increased due to the use of shortest links, which were added to the network as an alternative. Nevertheless, at the 3rd and 4th iterations, these were not included in the SRN reference graph for calculation because of low passenger flow therein. Values at iterations 3 and 4 show the rapid bus introduction effect. Moreover, an increase in the coefficient with an increase in the network length between iterations 3 and 4 is visible. At iteration 3, the coefficient was 0.91, which is 8% higher than 0.84 base value. At iteration 4, the coefficient was 0.93, which is 10% higher than the base value and 2% higher than at iteration 3.

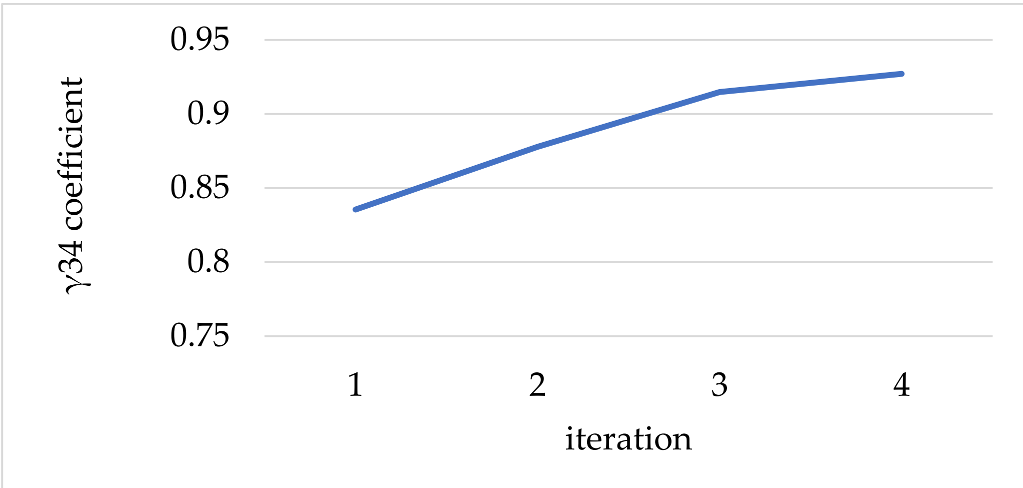

Figure 9. Change in the coefficient γ_{34} by iterations.

Thus, the hypothesis about the iterative increase in the network is confirmed. Passenger flow in areas that were included in the BRT system at iteration 3 has not reached the economically viable value of 14,000 thousand passengers/year at the second iteration. Due to the increase in travel speed in areas included in the BRT system after iteration 2, passenger flow increased in adjacent areas, which were included in the BRT system at iteration 3.

To define the economic viability of the proposed methodology, it is necessary to calculate the BRT network passing along the corridors selected in the previous section. As a result of the calculation, 3 service corridors were outlined. On their basis, 3 routes were formed as shown in Figure 10.

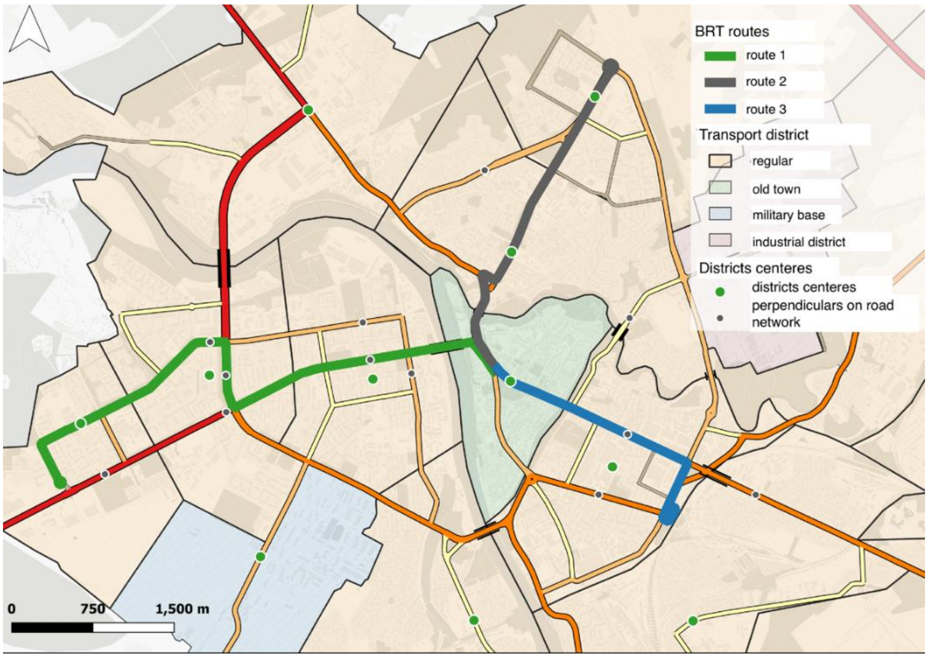

Figure 10. BRT routes scheme.

Operation parameters of the proposed routes are given in Table 9.

Table 9. Operation parameters of the proposed routes.

Indicator	Period	Route 1	Route 2	Route 3	Total
Run on the route, km	per day	3358	1281	879	5517
	per year	1,115,287	425,365	291,927	1,832,579
Vehicle operation hours, h	per day	134	51	35	220
	per year	44,509	16,940	11,626	73,075
Passenger traffic volume, pass.	per day	68,269	39,936	42,160	150,365
	per year	22,675,548	13,264,742	14,003,444	49,943,734

The cost of a 1 km run calculated in accordance with the Order of the RF Ministry of Transportation of 20.10.2021 No. 351 [34] amounted to RUB 106.86/km. Taking into account lease payments for vehicles, the cost of the first year of operation will be RUB 249.5 million. Capital expenditures include the construction of boarding platforms, a bus depot, control center equipment, terminals, and also measures to ensure PUPT priority passage and the installation of ticket vending machines, and a toll collection system. In total, estimated costs will amount to about RUB 2.1 billion as presented in Table 10.

Table 10. Capital expenditures by cost items.

Cost Item	Price, Thous. Rubles	Quantity	Cost, Thous. Rubles
Boarding platforms	2500	12	30,000
Bus depot construction	1,000,000	1	1,000,000
Control center equipment	100,000	1	100,000
Terminals equipment	5000	4	20,000
Measures to ensure PUPT priority passage	900,000	-	900,000
Ticket vending machine	1250	29	36,250
Toll system	2000	-	2000
Design works	3000	-	3000
Total	-	-	2,091,250

Toll for PUPT transportations in Pskov is RUB 27 in cash. The calculation of profit from each passenger has to take into account availability of discount tickets and transport cards, and since the ratio of passengers using different tickets is restricted information, we assume that for 1 passenger, the carrier will receive RUB 14 revenue on average. Based on the annual passenger flow, the profit from passenger transportation will amount to RUB 450 million. The profitability amounted to 1.8. Profitability level is the ratio of the system operation profit to the cost of operation.

High profitability level is not typical of traditionally subsidized PUPT systems and depends on a number of factors. Routes pass along the main streets of the city connecting "bedroom" districts with the center. Within the model, BRT does not compete with other PUPT types, serving all public transport users travelling through BRT areas. Moreover, due to the fact that route 1 crosses the Olginsky Bridge connecting two banks of the Velikaya River and route 2 crosses the Sovetsky Bridge across the Pskova River, as well as due to the accepted hypothesis of commuting between transport areas by shortest links, this route system serves most of PUPT trips in the city. As a whole, this provides high passenger flow on relatively short routes, which in turn ensures high route efficiency.

The organization of BRT on the main highways of the city will reduce the capacity for road transport. On all 3 routes, the width of the carriageway at the narrowest points is 2 lanes in each direction. At the same time, on routes 1 and 2 it is limited by the width of the bridges. In the places where stopping points are located, it is possible to organize the local widening of the carriageway in order to maintain traffic capacity. It is also possible to create widening-accumulators for turning cars in order to separate flows and maintain the traffic capacity of UTS intersections.

At the same time, if we calculate the capacity of the lane not in units of transport, but in the number of passengers carried, then the capacity of the streets where BRT traffic is organized will increase significantly. Thus, one traffic lane in urban conditions passes 600–800 vehicles per hour [35]. On average, 1 to 2 people travel in one car, so it is 600–1600 passengers per hour. The PUPT can carry up to 8000 passengers per hour on a dedicated lane (80 articulated buses per hour with a capacity of 100 people). At the same time, any resident can use public transport, and only those with a driver's license can use the lane for cars. In addition to this, it can be said that reducing the intensity of road transport in the city center will improve road safety, reduce pollutant emissions, and reduce noise levels.

With the advent of the mainline public transport mode, the share of PUPT users in Pskov will increase insignificantly, due to the high current rates for using public transport and low motorization levels. However, this will help optimize route networks, schedules, and, as a result, increase the efficiency of using each vehicle, which will reduce specific costs and pollutant emissions per one passenger. When designing such a system, it is necessary to calculate the economic model of transportation, taking into account all the routes of the PUPT, and also compare it with the current model, evaluating the effects of creating BRT.

5. Conclusions

This article proposes a method for selecting areas for bus rapid transport routing. The economic efficiency criterion is the economically viable passenger flow selected for the city under consideration in a certain network area. Its value is based on the average passenger flow in existing BRT systems grouped by the population size of cities where they are located. This value can be adjusted in the course of calculations. The time spent in cities travelling from places of residence to places of work for 90% of laborers (one way) should not exceed certain values approved for cities with different population sizes. The change in this indicator is used to assess the impact of the new BRT on the city in general. The use of this method will improve the efficiency of newly implemented BRT systems in terms of capital and operating costs, the availability of inexpensive and reliable transport for everyone, and the reduction of anthropogenic impact on the environment.

The calculation of the BRT system for Pskov confirmed the hypothesis of passenger flow redistribution due to the changes in attraction of areas where BRT is introduced.

However, the model of passenger flows distribution over the network used in the calculations does not make it possible to assess the proposed system's effectiveness reliably. In further studies, for passenger flows distribution over the network, a multi-agent transport model will be used in which passenger flows over the network will be distributed according to algorithms taking into account more factors (selection of a transport mode, various user behavior sequences during the day, etc.) and also providing for the use of a more complex transport system graph. The effects of its implementation will take into account the changes in delays of the transport system users across the network in general, savings related to the reduced number of vehicles due to an increase in operational speed, as well as changes in the route network within the studied area. Thus, for the first time in the practice of creating BRT corridors, a numerical method for choosing the route of passage is proposed.

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