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Approaches to Determining the Regular Transit Route Duplication Level

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ABSTRACT

Issues of duplication of regular transit routes are of particular importance in the field of transport services provided to population and organisation of passenger transportation from the perspective of ensuring compliance with passengers needs for transportation and of the effects of route duplication on the technical, operational, and economic indicators of performance of these routes and the integral route network.

In Russia duplication of regular routes within route networks emerged in the late 1990s – early 2000s in urban transit, other transit modes, and in interconnected transit. In the last decade, these routes have been increasingly subject to revision by local governments and executive bodies of federal constituent entities of the Russian Federation while solving transport planning problems and improving quality of transport services for the population.

Evaluation of route duplication, as a rule, is carried out based on the route factor and the route duplication factor, the latter allows pairwise assessment of routes by the length of their overlapping segments.

The objective of this article is to show incorrectness of the widespread technique and to present another approach that provides, in the author's opinion, the correct interpretation of the method for determining the route duplication rate. Achieving this objective is based on methods of theoretical research in the field of organising passenger transportation.

In development of this logic, the author proposed a new method for determining the route duplication factor using route adjacency factor, which considers directions and volumes of passenger origin-destination flows. Comparison of existing and proposed approaches is given using simple examples. The results of calculations have confirmed the different nature of factors and the absence of a direct relationship between the needs of passengers for transportation by public transport and the length of adjacent sections of routes. The conclusion is made about probable expediency of using the second (author's) approach based on the route adjacency factor, which provides a correct solution to the stated transport planning problem. Besides, the possibility of using a new approach when performing diagnostics or designing route networks of different transport modes is shown both in relation to route matching and regarding their clusters and the entire route network.

<u>*Keywords:*</u> *transport, duplication, origin-destination flow, route, route network, passenger, public passenger transport.*

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For the original Russian text of the article please see p. 210.

INTRODUCTION

The problem of duplication of regular transportation routes (hereinafter referred to as routes) has earlier emerged or exists now in many world cities and regions. The causes of its emergence and the level of impact on the quality of transport services provided to population were quite different because of the historical features of development of transport systems. A case study of the situation following deregulation of urban bus route services in Great Britain can be mentioned as a particular example resulted in expansion of duplication of most commercially profitable routes [1]. The problem is also regarded within the framework of general approach to improving of route networks while providing transport services to population, working out development strategies for public passenger urban, commuter, intercity transportation (e.g., in the form of the principle of least duplication of routes [2]), making decisions on limiting duplication of existing routes, particularly of different transport modes, to ensure fair competition [3], to avoid considerable density of overlapping (regarding length of duplicated route segments) while planning [4], to use route overlapping level among five core principles of route network quality assessment [5].

In Russia the route duplication problem manifested clearly in the late 20th–early 21st centuries due to downsizing of transport enterprises and intensive, almost spontaneous, development of commercial passenger transportation. Development of direct passenger transportation schemes became socially and economically advantageous. On the one hand, this development vector provided the population with better conditions for territorial accessibility of public passenger transport, a decrease in the level of interchange and of financial costs of passengers for travel. On the other hand, it led to an increase in the load on urban street and road network (hereinafter – SRN) by route vehicles and to a growth in the costs of carriers regarding drivers wages and transport operations, and limited the possibility of using vehicles of large and extra large capacity on routes. This situation at the beginning of the 2000s was hardly considered at the official level as a problem for a number of political, financial, legal and other reasons. In the last decade, the executive authorities have begun to show increasing interest in the issue of reducing duplication of routes, indicating the need to carry out the relevant work within the framework of municipal contracts [6–10, etc.]. But the dual nature of the phenomenon under consideration remains still undisclosed.

Objective and methods of research

The *objective* of the study is to show incorrectness of the widespread approach to determining the route duplication factor and to present another approach that provides a correct interpretation of the method for determining this factor.

Achieving this objective is based on the *methods* of theoretical research in the field of organising passenger transportation.

RESULTS

Route duplication assessment indicators

The solution to the problem of reducing route duplication in works dedicated to transport planning is usually based on the use of a route factor or route duplication factor.

The route factor is one of the main characteristics of the urban route networks, which reflects the weighted average number of routes per one conditional SRN segment, serviced by public passenger transport [11; 12, etc.]:

$$K_r = \frac{\sum L_r}{L_{RN}}, \qquad (1)$$

where $\sum L_r$ is the sum of route lengths, km;

L_{RN} – length of the route network (length of SRN, serviced by public passenger transport routes), km.

The route factor is suitable for an averaged assessment of the state of the route network based on duplication (density) of route segments, is generalised and does not allow comparing the characteristics of routes with each other. There is also a slightly different interpretation of this factor, when the denominator indicates the length of the entire SRN [13].

The route duplication factor allows performing route pairwise comparison according to the length of their overlapping segments. Most commonly it is presented as follows [14]:

$$K_d = \frac{L_{drs}}{L_R} 100\%, \qquad (2)$$

where L_{drs} is the length of all duplicated segments of a route, selected as the base one, relative to another (for example, the projected route relative to the existing one), km;

L_R is the total length of the route chosen from two considered routes as the base, km.

Routes with a duplication rate of more than 60–95 % (different authors define this boundary differently) [14–16, etc.] are recognised as completely duplicated, and hence one or more of them are proposed to be cancelled. For existing routes, redistribution of the released passenger traffic to the remaining routes is provided.

The factor (2) can be further developed with the help of other factors, clarifying the characteristics of route duplication, for example:

a) Network route duplication factor, which allows to determine the proportion of duplicated segments of the route network:

$$K_{ND} = \frac{\sum L_{dn}}{L_{RN}} \cdot 100\%, \quad (3)$$

where $\sum L_{\text{dn}}$ is total length of duplicated segments of route network, km;

L_{RN} is length of the route network, km.

b) Weighted average share of duplication in the length of routes:

$$\nu_D = \frac{\sum L_{drs}}{\sum L_R} \cdot 100\%, \quad (4)$$

where $\sum L_{\text{drs}}$ is the sum of lengths of duplicated segments of each route, km;

$\sum L_{\text{R}}$ is the sum of lengths of routes, km.

The peculiarity of the presented factors is that duplication is assessed topologically: based on the length of the route segments. They make it possible to determine the level of provision of SRN with routes, are related to some extent to the loading of SRN with public transport (through the parameters of the routes), but they do not reflect the effect of duplication on the needs of passengers for transportation. This feature emphasises their secondary nature, since they do not so much determine but depend on availability of routes shaped based on transportation demand. So, they are closer to the issues of traffic management than to the issues of passenger transportation. Curiously, this approach has also become internationally widespread [17–19, etc.] [1].

In the field of public transit services and organisation of passenger transportation, the problem of route duplication is different and concerns:

- The need to ensure an acceptable level of distribution of public transit vehicles per stopping points, which have a significant impact on the carrying capacity of routes.
- The search for opportunities for using on the routes of vehicles of a higher class than that of operated rolling stock, while ensuring efficiency of their use (passenger load factor).
- Changes in the level of competition between individual routes or carriers.

The solution to these issues should be considered not based on comparing the lengths of route segments but based on comparing directions and volumes of passenger origin-destination flows between pairs of stopping points, since the structure and characteristics of public transport services are mainly determined by the nature of people's needs for movement. Accordingly, in the problem of evaluating route duplication, the main attention should be paid not to the links of the route network (segments, sections), but to its nodes which are stopping points.

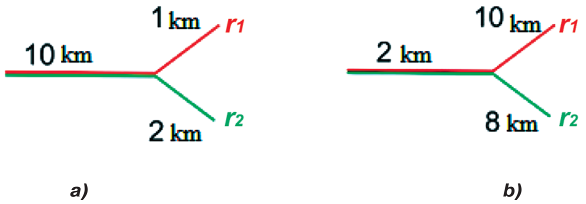
The analysis of literature sources showed that A. S. Kazhaev turned out to be close to this approach in his dissertation work [20], but the author failed to reveal the essence of the issue and limited himself to using the stopping points adjacency factor. Other works offer correct description of the problem, the correct direction of research regarding the importance of passenger origin-destination flows between stopping points, but they seem not to run up to the method of determining duplicate routes. It is possible to mention among sources in Russia the Methodological recommendations of the Ministry of Transport of Russia on development of a planning document for regular transportation [21]; among international sources, for example, recommendations developed for the city of Edmonton [22].

For the convenience of description and clarity of the differences between two approaches (respectively based on the length of routes (first approach) and on passengers' origin-destination flows (second approach)) we will further replace the concept of route duplication by route adjacency.

The definition of route adjacency within the second approach is developed as follows.

Let select within the entire set of routes R several routes $R_r \in R$ which have at least one segment connecting two or more common

[1] SEPTA. Southeastern Pennsylvania Transportation Authority. Frequently asked questions. [Electronic resource]: https://www.septa.org/service/bus/network/faq.html. Last accessed 29.11.2020.



Pic. 1. Variants of schemes of an elementary route network (compiled by the author).

stopping points $S_r \in S$ (where S is a set of stopping points).

All stopping points S according to their functional purpose are divided into stopping points of departure (origin) $O \in S$ and stopping points of arrival (destination) $D \in S$ of passengers. Each pair of stopping points O and D is characterised by a certain volume of passenger trips:

Q (o, d) | o ∈ O, d ∈ D,

where *o, d* are numbers of stopping points, respectively, of origin and destination of passengers.

Let denote by Q_a *(o, d)* ⊂ *Q (o, d)* the number of adjacent passengers' origin-destination trips that can be identified when travelling on any of the considered routes R_r between a pair of stopping points *o* and *d*. The number of passengers' trips that can be made only on specific routes out of considered R_r number of routes between a pair of stopping points *o* and *d* will be denoted as Q_R *(o, d)* ⊂ *Q* (*o, d*). Then the adjacency factor for two or more (*k*) routes R_r will get the form:

$$K_a = \frac{\sum_{r=1}^{k} Q_a(o,d)}{\sum_{r=1}^{k}\left(Q_a(o,d)+Q_R(o,d)\right)} \cdot 100\ \%. \qquad (5)$$

Examples

Example 1

For clarity of differences between approaches (between the existing first approach and the proposed second one) to estimation of duplication (adjacency) of routes, let us consider a game model of choosing the best option for each approach from two variants of route networks, characterised by opposite limiting states.

1. Determining duplication of routes according to the length of their segments.

Let's consider two elementary route networks *a* and *b*, consisting of two simple routes. One network (*a*) has an extended duplicated segment, and the other (*b*) has a short one. The characteristics of routes r_1 and r_2 are shown in Pic. 1. Duplication rate of more than 80 % is considered as a high route duplication level.

It is required:

• To calculate values of route factor; route duplication factor for r_1 and r_2; network route duplication factor; the weighted average share of duplication in the length of routes.

• To determine the presence of routes with a high level of duplication and the need to cancel one of them.

Let's determine the values of factors for the route network a:

1) Route factor is determined according to formula (1):

$$K_r = \frac{L_{r1}+L_{r2}}{L_{RN}} = \frac{11+12}{10+2+1} = 1{,}77.$$

2) Route duplication factor is determined by formula (2) for cases when route r_1 or r_2 is taken as the base route:

$$K_{Dr_1} = \frac{L_{dr}}{L_{r1}} \cdot 100\ \% = \frac{10}{11} \cdot 100\ \% \approx 92\ \%,$$

$$K_{Dr_2} = \frac{L_{dr}}{L_{r2}} \cdot 100\ \% = \frac{10}{12} \cdot 100\ \% \approx 83\ \%.$$

3) Network route duplication factor is determined by formula (3):

$$K_{ND} = \frac{\sum L_{dn}}{L_{RN}} \cdot 100\ \% = \frac{10}{10+1+2} \cdot 100\ \% \approx 77\ \%.$$

4) Weighted average share of duplication in the length of routes is determined by formula (4):

$$\nu_D = \frac{L_{dr_1}+L_{dr_2}}{L_{r_1}+L_{r_2}} \cdot 100\ \% = \frac{10+10}{11+12} \cdot 100\ \% \approx 87\ \%.$$

The values for the route network *b* are calculated similarly:

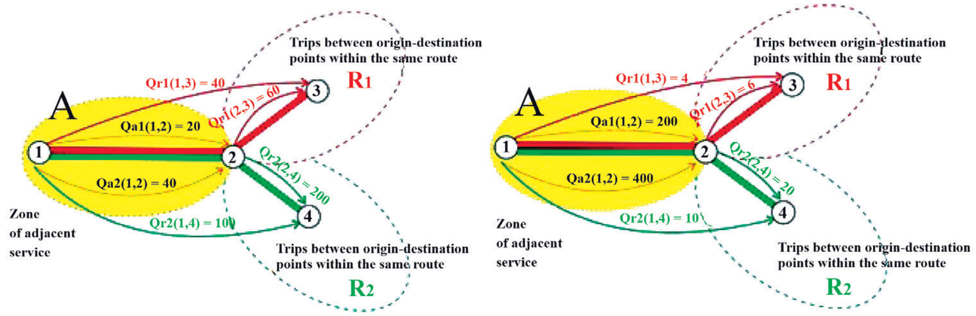
1) Route factor:

$$K_R = \frac{L_{r1}+L_{r2}}{L_{RN}} = \frac{12+10}{2+10+8} = 1{,}1.$$

2) Route duplication factor:

$$K_{Dr_1} = \frac{L_{dr}}{L_{r1}} \cdot 100\ \% = \frac{2}{12} \cdot 100\ \% \approx 17\ \%,$$

$$K_{Dr_2} = \frac{L_{dr}}{L_{r2}} \cdot 100\ \% = \frac{2}{10} \cdot 100\ \% = 20\ \%.$$



a) *b)*

Pic. 2. Variants of schemes of an elementary route network (compiled by the author).

3) Network route duplication factor:

$$K_{ND} = \frac{\sum L_{dn}}{L_{RN}} \cdot 100\ \% = \frac{2}{2+10+8} \cdot 100\ \% = 10\ \%.$$

4) Weighted average share of duplication in the length of routes:

$$\nu_D = \frac{L_{dr_1} + L_{dr_2}}{L_{r_1} + L_{r_2}} \cdot 100\ \% = \frac{2+2}{12+10} \cdot 100\ \% \approx 18\ \%.$$

Brief analysis of the results of calculations following the first approach

Comparison of the values of the route factor for two route networks shows a higher level of duplication on the route network *a*, since $K_{Ra} > K_{Rb}$ (1,77 > 1,1). But this result does not have sufficient validity to draw conclusions about cancellation of routes: it is clear that with option *a*, duplication is higher, but it is not clear whether and what exactly needs to be changed? For this reason, it is inappropriate to use the considered factor for solving such problems; it is acceptable only for network problems of a higher level. It is excluded from further consideration in the present example.

From a comparison of values obtained for remaining factors, it follows that route network *a* is characterised by a high level of duplication (between pairs of routes it is of 83 and 92 %; on the network it is of 77 %). Since the values for routes exceed 80 %, according to the conditions of the problem, one of them must be cancelled. The contender for cancellation is route r_1, as it has a higher factor value. In practice, the selection priorities may be different: maintaining a route with better technical and operational characteristics, a more reliable carrier, the highest passenger traffic, etc.

Route network *b* has performance values many times lower than 80 %, so its routes are not subject to consideration.

2. Determining adjacency of routes based on the volume of passenger origin-destination trips.

The initial data are the same variants of elementary route networks (*a* and *b*) shown in Pic. 1, but supplemented with the values of the volume of passenger origin-destination trips in accordance with Pic. 2. The length of the route sections is not considered in this case.

It is required to calculate the values of the route adjacency factor for each option.

Solution

1) Adjacency factor of routes for option *a* will be equal (for convenience, we will replace some of the parentheses with square brackets):

$$K_a^a = \frac{Q_{A1}(1,2) + Q_{A2}(1,2)}{\left[Q_{A1}(1,2) + Q_{A2}(1,2)\right] + \left[(Q_{R1}(1,3) + Q_{R1}(2,3)) + (Q_{R2}(1,4) + Q_{R2}(2,4))\right]} \cdot 100\ \% =$$

$$= \frac{20+40}{[20+40] + [(40+60)+(100+200)]} \cdot 100\ \% =$$

$$= \frac{60}{460} \cdot 100\ \% \approx 13\%.$$

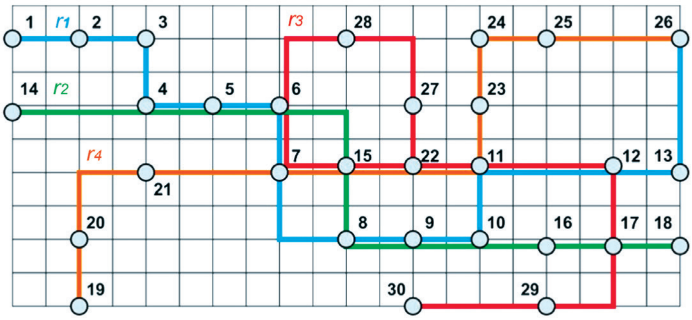
2) Adjacency factor of routes for option *b* will be:

$$K_a^b = \frac{200+400}{[200+400] + [(4+6)+(10+20)]} \cdot 100\% =$$

$$= \frac{600}{640} \cdot 100\ \% \approx 94\%.$$

Brief analysis of the results of calculations following the second approach

Route network a is characterised by a low level of demand by passengers for adjacent route nodes (13 %) and is inappropriate for consideration since it does not meet the stated condition: 13 % << 80 %. On the contrary, route network *b* is characterised by a high demand for adjacent nodes of routes by



Pic. 3. Route network chart (compiled by the author).

passengers and shows a high level of route adjacency (94 %), so it is possible to cancel route r_1, characterised by a smaller volume of passengers (the possibility of introducing separate trips on the remaining route in direction 2– 3).

Comparison of two approaches based on the obtained results

Comparison of the values of factors of duplication and adjacency of routes by length and by the volume of passenger origin-destination trips showed opposite results for route networks *a* and *b*. Using the first approach, a high level of route duplication is observed on route network *a*, and in the second approach, it is observed on route network *b*.

The results obtained confirm the different nature of factors and the absence of a direct relationship between the needs of passengers for transportation by public transport and the length of adjacent route segments. Accordingly, assessment of adjacency of routes according to formulas (1–4) does not allow to correctly determine the level of duplication of routes regarding transport services for the population and to make a right decision to change the route network based on those formulas. We will leave the issues of traffic management and traffic frequency outside the scope of this article.

The route adjacency factor, on the contrary, made it possible, according to formula (5), to obtain the desired correct level of route adjacency, which turned out to be characteristic only of route network *b*, and to identify the route to be cancelled. However, it is necessary to be careful when making a final decision. Despite consistency and the observed weight of the obtained value, it refers to a necessary but insufficient condition for cancelling any of the routes. Sufficiency can be ensured only on the basis of a full analysis of non-adjacent segments of routes, carrying capacity of the adjacent segment, social significance of routes under consideration and of stopping points on them, available and planned volumes of resource provision for operation of routes, assessment of feasibility of introducing supply routes (in the example, between stopping points 2–3–4) or combining adjacent routes into a single one with different modes of operation of vehicles along its length (main trips between terminal points 1–2, shorter trips between terminal points 1–3 and 1–4), assessment of other situations. The author witnessed a case when 100 % adjacent trolleybus and bus routes were forced to be kept due to insufficient carrying capacity of the trolleybus route and to ensure uninterrupted communication in cases of power outages. Therefore, it is only based on a multifaceted analysis that a final decision should be made to cancel or maintain any of adjacent routes. This condition also diminish the significance of the task of standardising and setting the maximum permissible values of the adjacency factor as a criterion for cancelling or maintaining adjacent routes, but does not exclude it.

Example 2

For clarity, the first example was shown on an elementary route network of two routes. In real conditions, the structure of route networks is more complex, raising the question of applicability of considered approaches to assessing adjacency of a larger number of routes, including those with different adjacent segments. The applicability of the metrics at the network level needs to be confirmed. To do this, we will use a slightly more complex model to show the application of formulas (1, 3–5). The factor determined by the formula (2) does not apply to the network, therefore it is not subject to consideration in this example.

Table 1

Average daily distribution of passenger origin—destination trips (compiled by the author)

№№ ОП	Departure (origin) point																													
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23	24	25	26	27	28	29	30	Σ	
Destination points: 1		55	54	52	51	49	48	45	44	42	41	39	38													350					**908**
2	55		69	67	65	63	62	58	56	55	53	50	49													460					**1107**
3	54	69		86	83	81	78	74	72	70	68	64	62													580					**1318**
4	52	67	86		140	136	66	124	120	116	57	53	52	68	64	57	55	53								490					**1651**
5	51	65	83	140		164	80	150	146	142	69	65	63	78	78	69	67	65								590					**1826**
6	49	63	81	136	164		251	182	176	172	225	212	76	88	245	83	211	78				146				720			123	116	**3104**
7	48	62	78	66	80	96		87	84	82	158	75	73		87				77	79	84	84	79	77	75	1380					**2581**
8	45	58	74	124	150	182	87		258	250	121	114	111	108	129	121	118	114								1050					**2494**
9	44	56	72	120	146	176	84	258		302	147	138	134	123	147	147	143	138								1270					**2689**
10	42	55	70	116	142	172	82	250	302		155	146	142	122	146	155	150	146								1340					**2502**
11	41	53	68	57	69	223	158	121	147	155		274	113		246		154		94	97	103	279	116	113	109	2060	158	149	145	137	**4347**
12	39	50	64	53	65	210	75	114	138	146	279		61		14		18					17				580	17	16	17	16	**756**
13	38	49	62	52	63	76	73	111	134	142	113	61														1000					**1000**
14				68	78	88		108	123	122					250	222	216	210													**898**
15				64	78	94	87	129	147	146	249	15		250		73	228	69	69	71	75	257	75	73	71	670			148	139	**2018**
16				57	69	83		121	147	155				222	73		355	344													**699**
17				55	67	209		118	143	150	158	19		216	172	355		300				60					58	55	64	60	**597**
18				53	65	78		114	138	146				210	69	344	300														
19							77				94				69					69	65	57	54	53	51	480					**829**
20							79				97				71				69		59	52	49	48	46	440					**694**
21							84				103				75				65	59		43	41	39	38	360					**521**
22						153	84				284	18			215		63		57	52	43		78	76	74	700	82	78	71	67	**1226**
23							79				116				75				54	49	41	78		138	134	1260					**1532**
24							77				113				73				53	48	39	76	138		154	1450					**1604**
25							75				109				71				51	46	38	74	134	154		2000					**2000**
26	350	460	580	490	590	720	1380	1050	1270	1340	2060	580	1000		670				480	440	360	700	1260	1450	2000						
27						149					136	15			117		51					73						166	120	113	**399**
28						158					145	15			124		54					78							154	145	**299**
29						121					149	18			95		67					76					205	154		200	**200**
30						114					141	17			89		63					71					194	145	200		
Σ	**908**	**1107**	**1318**	**1651**	**1826**	**3102**	**2581**	**2494**	**2689**	**2502**	**4346**	**758**	**1000**	**898**	**2058**	**699**	**598**		**829**	**694**	**521**	**1226**	**1532**	**1604**	**2000**		**399**	**299**	**200**		**79638**

Let us consider a route network consisting of four routes (Pic. 3). The routes are traced on a regular SRN with a cell edge length of 0,25 km and have a length of: L_{r1} = 8 km, L_{r2} = 6 km, L_{r3} = 6,5 km, L_{r4} = 8 km. The length of the route network is 23 km. The total number of stopping points operating in one or several directions is 30 units. The average daily distribution of passengers' origin-destination trips on the route network is presented in Table 1.

Let's calculate the values of factors according to formulas (1, 3–5):

1) Route factor:

$$K_R = \frac{L_{r1} + L_{r2} + L_{r3} + L_{r4}}{L_{RN}} = \frac{8+6+6,5+8}{23} = 1,24,$$

i.e., on average, for every fourth section of the route network there are two routes, for other three sections there is a single route.

2) Network route duplication factor:

$$K_{ND} = \frac{\sum L_{dn}}{L_{RN}} \bullet 100\ \% = \frac{5}{23} \bullet 100\ \% \approx 22\ \%.$$

3) Weighted average share of duplication in the length of routes:

$$\nu_D = \frac{L_{dr_1} + L_{dr_2} + L_{dr_3} + L_{dr_4}}{L_{r_1} + L_{r_2} + L_{r_3} + L_{r_4}} \bullet 100\ \% =$$

$$= \frac{3,5+2+1,5+3}{8+6+6,5+8} \bullet 100\ \% \approx 35\ \%.$$

4) Factor of adjacency of routes will be (values in the numerator and denominator are pre-summed based on Table 1):

$$K_a = \frac{16621}{16621+63017} \bullet 100\ \% \approx 21\ \%.$$

In the given example, the values of the network route duplication factor and the route adjacency factor turned out to be close. Note that a certain relationship between them can really exist in polyfunctional cities, where distribution of the population's trips depends on the distance (time) of movement of people. However, this connection is not typical of all cities. To a lesser extent, it manifests itself in monofunctional settlements: industrial, resource-extracting, industrial, resort cities, etc.

Pairwise comparison of routes (six options were considered, calculations are not presented) showed that when determining the network route duplication factor, only three pairs of routes with values of the factor from 9 to 14 % were adjacent. When determining the route adjacency factor, five pairs of routes turned to be adjacent, the values of the adjacency factor ranged from 4 to 11,4 %. Thus, routes not adjacent in length and topology turned out to be partially adjacent in terms of passenger trips between stopping points. When comparing groups of three routes (four options), the values of the network route duplication factor ranged from 7 to 16 %, and the route adjacency factor was from 5,5 to 17,5 %.

As can be seen, in all the cases there are no routes with a high level of duplication. At the same time, the presented example gives an answer to the main question posed: formula (5), along with formulas (1, 3, 4), regarding its target turned out to be applicable to diagnose duplication of route clusters and the entire route network.

CONCLUSIONS

1. For the sphere of public transport services, it has been established that it is inexpedient to use route duplication factors based on comparing lengths of adjacent route sections, since such factors do not consider the needs of passengers for travelling, volumes and directions of trips, and the results may differ significantly from the logic of planning and organising public passenger transportation and lead to an incorrect result.

2. It is advisable to evaluate duplication (adjacency) of regular transport routes when diagnosing the current state and planning the development of route networks of cities based on the proposed route adjacency factor, which considers the direction and volume of passenger trips between network nodes (stopping points). The factor is useful for comparing pairs of routes, route clusters and entire route networks.

3. If the results reflect a high level of route adjacency, the final decision on maintaining, changing, or cancelling routes should be made only after a comprehensive analysis of other factors, not limited to the route adjacency factor.

4. It is shown that the use of the route factor for a detailed assessment of route duplication is inappropriate due to its lack of information and inadequacy for making decisions on maintaining or cancelling routes. This factor is only applicable for solving high-level network problems.

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