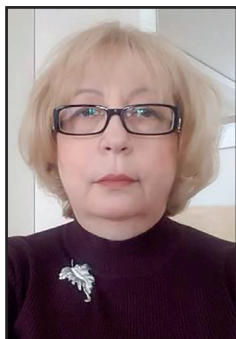




# Public Passenger Transport Logistics in the Context of Digital Transformation of Transportation Services Organisation Systems



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## ABSTRACT

Transport route specification models are used to analyse the need for combined passenger transportation on popular routes in a large urban agglomeration. The problem of managing the travel chains of passengers using public transport (PT) is revealed with the focus on the complexity of applying the principle of multimodality on the route network used by population due to the mismatch of the schemes of transport and users' routes.

The study of the logistics of passenger transportation with PT introduces the concept of «public transport user (PTU)» which has a variable status relative to the flows of people, pedestrians, passengers, and transport vehicles. The description of the registers

of the main parameters of the routes under study serves to create their digital twins.

To manage the travel chains of PTUs, identify related sections of transport routes, it is proposed to highlight within the passenger flow the currents of the same profile which include PTUs that have common transport behaviour.

Models and algorithms of network proximity to transport infrastructure objects, visualisation of digital traces of PTUs and the results of comparing the used and the best route options according to the modelled parameters allow to identify behavioural profiles of PTUs, as well as regulators managing the travel chains.

**Keywords:** urban public transport, metro, combined transportation, currents of passenger flows, transport behaviour, complex routes, long routes.

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## INTRODUCTION

The high rates of development of transport in urban agglomerations towards increase in the length of the transport network, better connectivity of routes of various modes of passenger transport, as well as organisation of speed and high-speed rail routes provide growing transport accessibility and the overall quality of public transport (PT). Along with improvement of this important indicator of efficiency of PT, both passengers and transport organisations face certain difficulties.

For users, the processes of building and choosing an individual route are becoming more and more complex due to an increase in the number of alternative options for moving through the territory of a large urban agglomeration using various routes of one or more modes of transport. As the results of our research have shown, for example, in Moscow urban agglomeration, the share of simple routes (without transfers, using one mode of transport) in trips repeated within a month is about 35 %. With the increase in the distance from the place of residence of travellers to the place of their long stay (4–8 hours), the number of transfers to regular routes of passenger transportation is growing. On «long» routes lasting more than 50 minutes, on average, the active residents make 3 transfers, including transfers to various metro lines.

For carriers, the tasks of «improving quality of transport services for the population» and managing passenger transportation on such routes are becoming more complicated. Difficulties in solving them are due to the lack of transparency of the research results of the population's need for public transport services and passenger transportation on various segments of PT route network, of an integrated transport and logistics system of public transport, as well as of end-to-end technologies for studying traffic flows (of pedestrians, passengers and transport vehicles) required for synchronisation and «coordination of independent processes and participants» in a complex «multi-agent system» [1].

The *objective* of the study is to identify modern tools for analysis and management of passenger travel chains using public transport in urban agglomeration. The task is to describe the approaches to the study of the logistics of passenger transportation by PT, models for specification of connected segments of transport lines on popular, complex (combined) routes used by population within the territorial boundaries of the megalopolis.

## LITERATURE REVIEW

Many publications are devoted to analysis and assessment of the demand for passenger transportation in relation to specific types of urban PT, separately to urban land PT, metro and railway transport operating within the urban agglomeration (in city–suburb area). Publications assessing the overall need for public transport services based on sociological and marketing research data dominate. A separate block of scientific papers deals with construction and selection of the optimal route by the user of the mobile application.

The successful international practices of integrating off-street and street transport within the framework of a single system of integrated transport services for the population (SITSP) determine the need to develop solutions related to management of passenger travel chains, logistics of transportation by all types of public transport in the urban agglomeration. Such management becomes possible, as the authors note, based on «logistics integration and cooperation, the principles of multimodality», due to creation of a «centre for urban public transport management to ensure effective coordination of passenger transportation» [2]. The authors proposed «algorithms for constructing optimal routes and statistical analysis of passenger flow», intended «not for a single person, but for the entire population of the city», adapted to the «real transport network with real timetables» of land transport [3].

It should be noted that this algorithm as most of other algorithms published in accessible sources, use volumetric indicators of passenger flows regarding transport routes, certain segments of transport lines obtained through the tools of registering the flow of people at the entrance to the transport system (station), exit from the station, at the places of transfer [4]. They did not consider individual groups of passengers with common transport behaviour. Moreover, the algorithms for optimising the work of public transport were based on average statistical values of the number of trips and generalised characteristics of PT passengers. Accordingly, the total passenger traffic was studied without identifying specific currents consisting of passengers with similar profile.

The characteristics of passengers based on «type of activity and income» often used in marketing research, as the authors of [5] argue, are not directly related to the regularity of travel,



and therefore are of little use for identifying routes which are «popular» among the population. The proposal on the need to consider «personal characteristics», «habits» that affect, respectively, the rate of regularity and the transport behaviour of people, was reflected in the work [5].

Quan Liang, Jiancheng Weng, and other co-authors of their research proposed a «travel chain extraction method of individual public transport traveller» and a passenger travel analysis method based on a graph «of individual travel behaviour», which made it possible to get an idea of the «spatial position» of the research object and its real route necessary for further forecasting «the public transport passenger's behaviour choice» [6]. The proposed research technology was based on the information data of transactions of PT smart cards. The authors note that previously the applicability of the proposed characteristics of passengers, their «individual features were not studied adequately» [6].

Most scientific developments (methods, algorithms, models for analysing passenger traffic and optimising routes for groups of travellers) used the «travel time» criterion [7]. Some works were devoted to the study of the influence of the criterion «quality of service» («satisfaction with quality» rate) and the financial affordability of PT services («cost of travel along the route») on the choice of a route option by a traveller.

The work of R. R. Sidorchuk and D. M. Efimova proposed to evaluate the quality of the route through «satisfaction» at the «points of contact» of the passenger with the transport infrastructure [8], and not on the segments of traffic of various flows. The «respondent statuses» selected in this work, i.e., social groups of workers, specialists, students, pensioners, and temporarily unemployed persons, in our opinion, are of little use for determining popular, complex routes of PTUs.

A process approach to the specification of people/vehicles flows on the routes based on the data of automatic recording and image processing (machine vision) was described in [9]. However, its practical use refers more to organising traffic on the existing lines, determining the modes of traffic organised on the transportation route («operating mode profiles» [9]), and not to managing PT passenger travel chains.

An attempt to formalise the transport behaviour of people was an important step towards improving the methods and tools for studying the structured demand for public transport services. The results

of these studies were reflected in publications devoted to the urban zoning per transport mobility rates in relation to the socio-economic characteristics of the city's residential areas and transport infrastructure. In particular, the gravity model is an interesting development on specification of the places of origin of passenger flows and on the study of the need for combined transportation on the «long» routes of the population, in which the «intensity of connections» is determined on the basis of the «economic gap» value [10]. The results of these studies can be useful since they allow explaining and predicting the transport behaviour of the population on the territory of economic entities. At the same time, they do not make it possible to determine the regulators for managing the travel chains of the population using PT and to identify the segments of transport routes that are in demand by various behavioural groups of passengers.

## RESULTS

Unlike transport routes, for which roads/tracks, places for embarkment and disembarkation of passengers (starting and ending points, stops/stations) and the direction of movement of vehicles are defined, the routes of PTUs have integrated walking sections, on which the population uses the available urban street and road infrastructure. The pedestrian sections of PTUs indicate the lack of connectivity of transport routes in a certain location, as well as the absence of integrated stops and controlled pedestrian crossings included in the list of transport infrastructure objects.

Individuals initiate streams and merge into various streams of street and transport infrastructure. The need for transportation by PT arises for them on those segments of individual (user) routes where they use the services of urban passenger transport.

The probabilistic nature of movement of people across the territory of the city and adjacent settlements complicates the solution of the problem of managing the logistics of passenger transportation by PT. However, some of the trips and the demand for comprehensive public transport services are quite predictable. This applies to mass, regular trips and patterns of commuting of the population on certain days of the week, of months, and during some hours.

To connect the flows of people, pedestrians, passengers, transport vehicles, it is obviously necessary to highlight the key element: the initiator

of movement. We have introduced the term «public transport user» (PTU). We mean that he is a person as a part of society and a mobile population, who is at the same time: a pedestrian (participant in/part of movement of the flow of people, of the flow of pedestrians); a passenger (part of the passenger flow) at public transport infrastructure facilities; a driver (participant in/part of the transport flow) when using personal vehicles on segments of the individual route. This solution allowed us to link data about PTUs obtained from different sources, to create a knowledge base about their movements and transport behaviour (using key attributes of smart cards and mobile devices registered with cellular operators), to link and combine them into flows based on various criteria.

In contrast to the method of «multi-modal planning and assessment» by Todd Litman [9], we propose to use a process, logistic approach to the study of transport routes and management of travel chains, passenger transportation by PT using digital technologies. In our opinion, it is fair to speak about «multimodality» and «multimodal passenger transportation by PT» only in case of complete connectivity of transport routes, coincidence of individual routes and public transport routes in urban agglomeration. In our case, we use the terms «combined» transportation of passengers, «combined» travel of people by public transport.

The classification of sections of transport routes is based on the patterns of transport behaviour of passengers (PTUs) and indicators of «popularity», «predictability» of choice, «insensitivity» to the route parameter. The information base for the analysis of a PTU's preferences is the data on the actually used routes, the conscious or unconscious choice of the route from a variety of alternative route options, which is repeated in the patterns of commuting.

We use a classic set of parameters to describe the combined route chosen by a PTU and to create digital twins of popular routes.

To describe transport routes:

$$M_t = \{N_{st}, T_t, F_{tr}, Q_t\},$$

where  $M_t$  is metamodel of transport routes;

$N_{st}$  – model of the register «Transport hubs, integrated PT stops»;

$T_t$  – model of the register «Time of movement along the segment of the transport route»;

$F_{tr}$  – model of the register «Cost of travel on a transport route»;

$Q_t$  – model of the register «Quality of public transport in LOS notation».

To describe PTU routes:

$$M_{ptu} = \{C_{comb}, T_{ptu}, F_{tr}, Q_{ptu}, U\},$$

where  $M_{ptu}$  – metamodel of the characteristics of the combined PTU route;

$C_{comb}$  – model of the register «Complexity of the combined PTU route»;

$T_{ptu}$  – model of the register «Travel time along the segment of PTU route»;

$F_{tr}$  – model of the register «Fare for a combined route of a certain type of PTU»;

$Q_{ptu}$  – model of the register «Quality of public transport on the combined PTU route»;

$U$  – model of the register «Particularly valuable characteristic of the combined route for PTU», includes latent characteristics ( $U_h$ ), determining the choice of the route.

The route parameter  $C_{comb}$  determines the number of transfers and their place in the route pattern. This parameter considers transition from pedestrian sections of the route to a segment travelled through a transport route, transfers from a transport route to another.

The parameters  $T, F, Q, U$  are determined for each section of PTU route and are combined when describing the complete route.

The similarity in the value attitudes of travellers in relation to the quality of PT on the route makes it possible to single out in the flow of users of public transport separate currents that unite latent groups of people with similar transport behaviour.

The following types of PTU behavioural profiles are suggested:

- behavioural profile «business» ( $W_H^B \rightarrow T$ ;
- behavioural profile «economical» ( $W_H^E \rightarrow F$ ;
- behavioural profile «demanding» ( $W_H^Q \rightarrow Q$ ;
- behavioural profile «rational» ( $W_H^O \rightarrow F/Q$ ;
- behavioural profile «special» ( $W_H^S \rightarrow U$ ;
- behavioural profile «indifferent»<sup>1</sup> ( $W_H^I$ ).

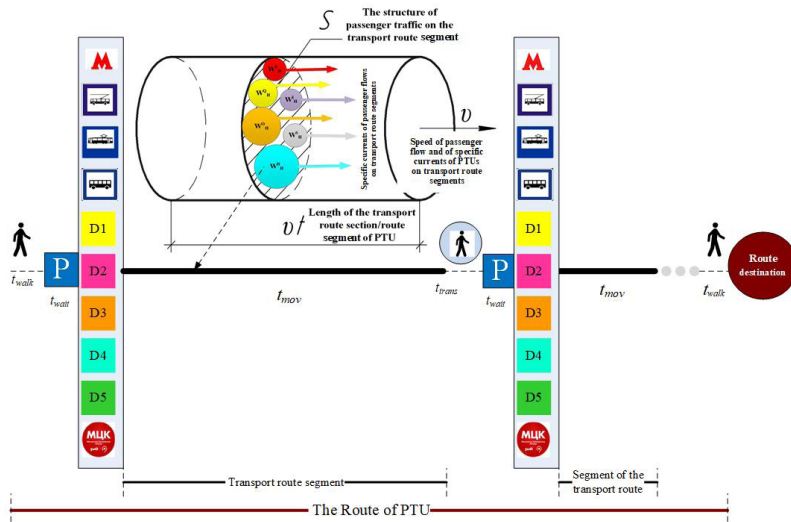
For the economic substantiation of decisions related to management of passenger flows, it is advisable to single out the types of PTU/passenger:

- H1 – PTU, pays the full travel fare on the segment (s) of the combined transport route;

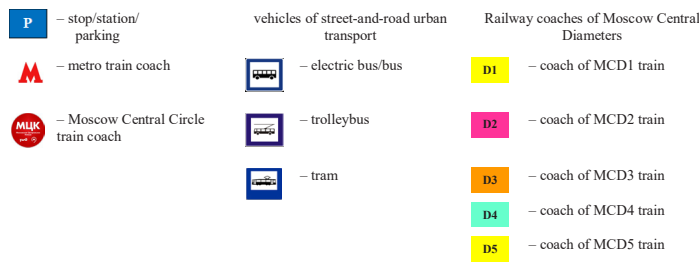
<sup>1</sup> PTUs having this profile use an irrational route due to: 1) lack of available information about the best alternative option; 2) unwillingness to look for the best option due to the difficulty of independently analysing and evaluating alternative options; 3) habits. 1–2 represent managed PTU behaviour; 3 – partially managed PTU behaviour.







**Designations:**  $t_{walk}$  – time of passage of the walking section of the route;  $t_{wait}$  – waiting time of the vehicle;  $t_{mov}$  – time of movement of the vehicle along the segment of the transport route;  $t_{trans}$  – time of transfer to another transport route.



**Pic. 1. Universal model of the structure of PTU route (developed by the authors).**

- H2 – PTU, has a social card with the right to travel free of charge by PT;
- H3 – PTU, enjoys fare discount (social card of a school pupil, of a student).

In this case, the structure of PTU route and passenger flow on the segments of transport routes used by a PTU can be represented as the diagram (Pic. 1).

Considering development and widespread adoption of digital technologies in transport sector, it becomes possible to register and identify the selected segment of the transport route not only with various types of PTUs, but also with their behavioural profiles.

The study of the structure of an individual route, of a chain of travels by public transport of a specific type of PTUs widely uses transactions from smart cards of a traveller. Some foreign transport systems possess the complete information about movement of a passenger of the given type (payer status) along the segments of transport routes, since a turnstile system records the entry of people to the PT facility, their transfer to other transport lines and exits. In Russian practices, the

number and type of passengers in the framework of the fare payment system is recorded only at the entrance to public transport facilities. The Scientific and Educational Centre «Digital High-Speed Transport Systems» of Russian University of Transport developed «models of network proximity in transport information systems» [11] allowing to visualise the trajectories of travels of people around the city (without linking the data to personal data) based on the information received from cellular operators. This allows us to «see» the process of formation of pedestrian flows, its transformation into a significant volume of passenger flow, as well as movement through city zones with possible linking to road and transport infrastructure facilities without «total tracking» of a specific person. «Distribution of entrances/exits in time» and «zoning of stations» [12] of metro (a frequently used mode of transport) makes possible, in this case, to identify popular, complex users' routes.

The decision to move along a specific route in most cases is made by PTU intuitively, based on experience or on the results of rapid assessment

of the route parameters that are significant for the user. And those parameters are not limited exclusively to time and cost of travel. Recently, the level of satisfaction with quality of PT has become significant. The last parameter is characterised by the well-known customer loyalty indices: «Service Quality Index – SQI (SERVQUAL methods), Customer Satisfaction Index – CSI, American (ACSI) and European (EPSI) indices» that are used for qualitative analysis of the streets, pedestrian zones, including intersections, as well as for classification of the conditions and nature of transport flows organised on the road network.

Obviously, the specific values of the elements of this parameter, which reflects the quality of all PT subsystems on user's individual routes, are of particular importance for PTU. In this regard, the model of the register «Quality of public transport on the combined PTU route» will include the following assessments:

$$Q = f(Q1, Q2, Q3, Q4, Q5, Q6, Q7),$$

where  $Q1$  is assessment of the quality of *the street and road infrastructure* on the pedestrian segment of PTU route *to the public transport infrastructure facility* and of the accessibility of the public transport system in terms of time and regularity of its operation.

The assessment of  $Q1$  is determined as:

$$Q1 = f(Q10, Q11, Q12),$$

where  $Q10$  is assessment of convenience of parking for personal vehicles, considering the risk of lack of parking spaces in a given time interval on the section of the combined PTU route;

$Q11$  is assessment of quality of roads intended for pedestrian traffic (including road surface, lighting), as well as schemes for intersections operations, operation of traffic lights used on the initial section of PTU route to the entry point to the object of PT facility;

$Q12$  is assessment of comfort on the initial segment of PTU route, of convenience of location of stops of land urban transport, railway station, metro station and of the availability of PT in terms of time and regularity of operation.

$Q2$ , which is quality assessment *at the entrance to a public transport infrastructure facility* (railway station, metro station, ground public transport stop) is determined as follows:  $Q2 = f(Q21, Q22, Q23, Q24, Q25, Q26, Q27, Q28)$ ,

where  $Q21$  is assessment of the level of quality of work and arrangement of the entrance to the PT facility;

$Q22$  – assessment of the level of physical comfort (queuing to pass through the entry point to the PT facility, taking into account the risk of malfunction of doors external to the turnstiles);

$Q23$  – assessment of quality of the atmospheric environment in an enclosed space, regulated (could be managed) by transport organisations (pollution<sup>2</sup>, freshness<sup>3</sup> and air temperature, noise, lighting) at the entrance to the transport infrastructure facility;

$Q24$  – assessment of the level of safety for health and life (systems of protection against undesirable weather phenomena: precipitation, strong wind, heat/cold; means of identifying people with signs of infectious diseases, means of disinfection; systems for counteracting social offenses; security systems and the level of cleanliness of pedestrian areas in front of the entrance to the transport infrastructure object);

$Q25$  – assessment of the level of aesthetic comfort (design, unobtrusive and useful sound background and visualisation at the entrance to the PT infrastructure facility);

$Q26$  – assessment of the level of information comfort (navigation systems, personal offers for optimising individual routes using PT);

$Q27$  – assessment of the quality of public transport personnel at the entrance to the PT facility (availability, professionalism, politeness, efficiency in solving problematic issues);

$Q28$  – assessment of the quality level of payment systems used by PTU in the context of service methods (purchase of tickets through terminals, cash desks, use of the network of cellular operators, the Internet).

$Q3$ , which is the assessment of the quality level *at the public transport infrastructure facility* (in the lobby, on the escalator, on the platform, at a public transport stop), is determined as follows:

$$Q3 = f(Q31, Q32, Q33, Q34, Q35, Q36),$$

where  $Q31$  – assessment of the quality of the indoor environment, regulated by transport organisations (pollution, freshness, air temperature, noise, lighting) in the lobby, on the escalator, platform, at the land public transport stop;

<sup>2</sup> Assessment based on sense impression and measuring of the presence of foreign odours (including toxins, carcinogens, exhaust gases), gases, particulate matters (in the form of dust, soot, pollen, smoke, etc.), infection (in the form of fungus, viruses, bacteria) in an amount exceeding permissible norms.

<sup>3</sup> Assessment based on sense impression and measuring of the level of oxygen saturation necessary for breathing in an enclosed environment (the ratio of carbon dioxide and oxygen).



*Q32* – assessment of the level of safety of health and life (protection systems against undesirable weather phenomena: precipitation, strong wind, heat/cold; means of identifying people with signs of infectious diseases, means of disinfection; systems for counteracting social offenses; security systems and cleanliness of pedestrian areas at the facility transport infrastructure) on a platform, at a stop of land urban transport;

*Q33* – assessment of the level of aesthetic comfort (design, unobtrusive and useful sound background and visualisation at the PT infrastructure: in the lobby, on the escalator, on the platform, at the stop of land urban transport);

*Q34* – assessment of the level of physical comfort at a public transport infrastructure facility (in notation of level of service (LOS, i.e., [13]) it is considered «as a quality measure describing operational conditions within a traffic stream, generally in terms of such service measures as speed and travel time, freedom to manoeuvre, traffic interruptions, and comfort and convenience» [14]), which is adjusted taking into account the risk of slowing down the speed of movement and increasing the density of passenger traffic caused by repetition of cases of malfunction in operation of technical means;

*Q35* – assessment of the level of information comfort (information support systems for navigation on PT);

*Q36* – assessment of the quality level of public transport personnel in the lobby, at the station (their availability, professionalism, politeness, efficiency in resolving problematic issues) on the section of PTU route.

*Q4*, which is the assessment of the quality level *in the vehicle interior*, is determined as follows:

$Q4 = f(Q41, Q42, Q43, Q44, Q45, Q46)$ ,

where *Q41* is assessment of the quality level of physical comfort in the passenger compartment of a vehicle for a PTU of a certain type, taking into account the day of the week, time of day, position of a coach in metro and suburban railway trains (person/m<sup>2</sup>);

*Q42* – assessment of the quality level of the atmospheric environment in the vehicle interior (pollution, freshness and air temperature, noise, lighting);

*Q43* – assessment of the level of safety for health and life (systems for identifying people with signs of infectious diseases, warning

systems and counteraction to social offenses; cleanliness in the compartment);

*Q44* – assessment of the level of aesthetic comfort of the vehicle interior (design, unobtrusive, useful sound and visual accompaniment during the travel in the passenger compartment, «innovativeness» of technical and constructive solutions, visible for PTU);

*Q45* – assessment of the level of information comfort (quality of mobile communication: navigation systems; personal recommendations for prompt adjustment of an individual route, taking into account the delay in information about changes in the parameters of the single system of integrated transport services for the population on the planned segments of the combined PTU route);

*Q46* – assessment of the quality level of PT personnel (driver, check-taker, guard, conductor of land public transport) on the segment of PTU route.

*Q5*, which is the assessment of the quality level *of the interchange hub* (changing to another transport route, line of the route network), is determined as follows:

$Q5 = f(Q51, Q52, Q53, Q54, Q55)$ ,

where *Q51* is the assessment of the quality level of the interchange, regulated by transport organisations (pollution, freshness, air temperature, noise, lighting);

*Q52* – assessment of the level of safety of the interchange for health and life (systems of counteraction to social offenses; cleanliness of passages);

*Q53* – assessment of the level of aesthetic comfort of the interchange (design, unobtrusive and useful sound and visual accompaniment at the interchange hub);

*Q54* – assessment of the level of physical comfort<sup>4</sup> of the interchange (PT infrastructure object), taking into account the risk of slowing down speed of movement and increasing the density of passenger traffic caused by a malfunction in operation of technical means, imperfection of the system of organising and managing traffic;

*Q55* – assessment of the level of information comfort (navigation systems in PT).

*Q6*, which is the assessment of the quality level *at the exit from the public transport*

<sup>4</sup> The assessment includes an evaluation of the height of steps of stairs, the convenience of moving hand luggage and other oversized objects on wheels, assessment of operation of escalators.

infrastructure facility, is determined as follows:  $Q6 = f(Q61, Q62, Q63, Q64, Q65)$ ,

where  $Q61$  is the assessment of the quality level of the exit from the PT infrastructure facility regulated by transport organisations (pollution, freshness, air temperature, noise, lighting);

$Q62$  – assessment of the health and life safety level of the exit from the PT infrastructure facility (systems for counteracting social offenses; cleanliness of passages);

$Q63$  – assessment of the level of aesthetic comfort of the exit (design, unobtrusive and useful sound and visual accompaniment at the exit);

$Q64$  – assessment of the level of physical comfort at the exit from the PT infrastructure facility, taking into account the risk of slowing down speed of movement and increasing density of passenger traffic caused by a malfunction in operation of technical means, imperfection of the system of organising and managing traffic;

$Q65$  – assessment of the level of information comfort at the exit from the PT infrastructure facility (navigation systems on the final segment of PTU route).

$Q7$ , which is the assessment of the quality of street and road infrastructure on the pedestrian section of the route from PT infrastructure to PTU destination:

$Q7 = f(Q71, Q72)$ ,

where  $Q71$  is assessment of the quality of roads intended for pedestrian traffic (including road surface, lighting), as well as of schemes intersections, operation of traffic lights used on the final segment of PTU route to the destination;

$Q72$  – assessment of the level of convenience on the final section of PTU route of the stop point of land urban transport, railway station, metro station.

Besides the above qualitative indicators, it is necessary to consider  $Uh$  which is the register of special route parameters that are significant for a PTU of a certain type and behavioural profile, and that includes a latent, implicit requirement (condition) from the register «Quality of PT on a combined route».

The difference between our approach and assessment of the «quality» parameter of the route from the one proposed in the work of R. R. Sidorchuk and D. M. Efimova [8] refers to the object of qualitative assessment (section of movement of PTU flow), a set of quality indices and statuses, types, and behavioural profiles of

travellers. The structure of the route quality indices includes:

- Index of physical accessibility of a transport infrastructure facility at the initial and final sections of the route, where the city's street and road infrastructure is used.

- Index of life and health safety of PTU.

- Index reflecting the level of risk of slowing down traffic on a section of PTU route or of deterioration in the characteristics of a transport infrastructure object, obtained based on statistical measurements.

- Index of «unique characteristics» (U) from the register of characteristics especially significant for the behavioural profile of a PTU.

To study the routes used by PTU, it is necessary to proceed with a formal description of the admissible set of combined routes according to the key parameters described above. This description becomes possible based on the results of a pairwise comparison of the «actually used» and «best» option for a certain type and behavioural profile of a PTU.

Let's designate the compared options as  $i$  and  $i + 1$ , then the parameters of the routes will have the following designation:

$N_i, N_{i+1}$  – the number of transfers (complexity of the combined route), units;

$T_i, T_{i+1}$  – travel time along the combined route (min);

$F_i, F_{i+1}$  – total fare for the combined route (rub.);

$Q_i, Q_{i+1}$  – integrated assessment of the combined route quality;

$U_i, U_{i+1}$  – a special service on a combined route, feature valuable for a PTU.

The model for describing the set of PTU routes is as follows:

$$SO = \{[(N_i = N_{i+1}) \vee (N_i > N_{i+1}) \vee (N_i < N_{i+1})] \wedge$$

$$[(T_i = T_{i+1}) \vee (T_i > T_{i+1}) \vee (T_i < T_{i+1})] \wedge$$

$$[(F_i = F_{i+1}) \vee (F_i > F_{i+1}) \vee (F_i < F_{i+1})] \wedge$$

$$[(U_i = 0) \wedge (U_{i+1} = 1)] \vee [(U_i = 1) \wedge (U_{i+1} = 0)] \vee [(U_i = 0) \wedge (U_{i+1} = 0)] \vee$$

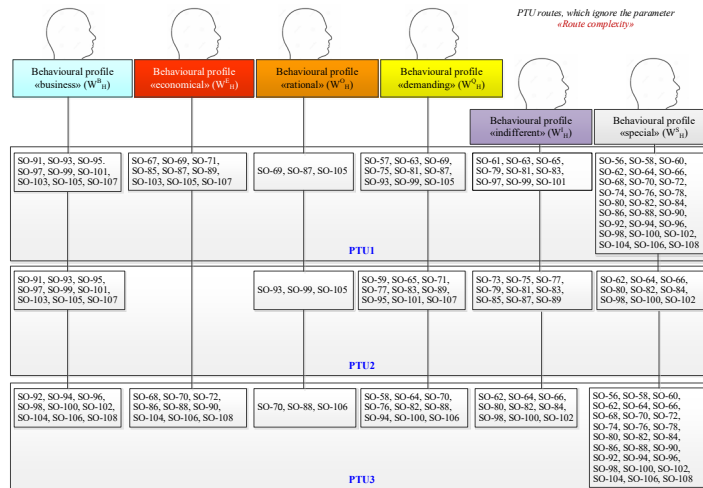
$$[(U_i = 1) \wedge (U_{i+1} = 1)]\}.$$

Comparative analysis of the characteristics of the used and alternative PTU routes allowed us to form a description of 162 choice patterns ( $SO_j$ ) in terms of predictability and sensitivity to certain parameters of the combined route for various behavioural profiles of PTU.

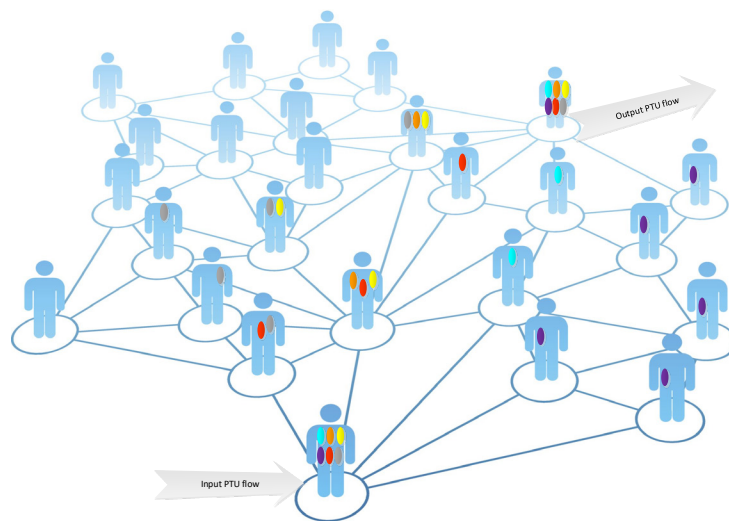
A fragment of the register of this description of PTU behavioural patterns is presented in Table 1.







Pic. 2. Identification of PTU behavioural profiles by route parameters (developed by the authors).



Pic. 3. Route network of PTUs (developed by the authors).

Based on the repetitive usage of the route and knowledge of the route parameters, it is possible to solve the problems of PTU typification and of identification of PTU behavioural profile. The model for identifying the behavioural profiles of PTU based on the used schemes (SO) is shown in Pic. 2.

The result of this identification of PTU allows to proceed with the next step focused on identifying specific currents (where the PTUs belong to the same behavioural profile) in the passenger flow on various segments of transport routes and determining the regulators that affect the demand for transport services on a specific section of popular routes.

Pic. 3 schematically shows the routes of movement of the flow of PTUs within the

boundaries of an urban agglomeration with labels of behavioural profiles on sections of walking and transport routes.

The chart shows the connected sections of PTU route network and regulators, which are easily determined by the pattern of PTU transport behaviour.

## CONCLUSIONS

Comprehensive studies of PTU travel chains and flows of people/pedestrians/passengers/transport vehicles on popular complex routes using «digital traces» of people travelling, algorithms of identifying relevant currents of passenger flows and of linking them to transport infrastructure facilities on sections of transport

**Table 1**

**Fragment of the register describing the patterns of PTU behaviour  
(compiled by the authors)**

Designation of a pattern of conditions for choosing PTU route	Characteristics of PTU behaviour and argumentation in favour of the choice of the combined route based on the results of pairwise comparison of alternative options
SO-1	unpredictable PTU behaviour and route choice
.....	.....
SO-6	predictable PTU behaviour, dependence of choice on availability of a unique service, insensitivity to PT quality on the route
.....	.....
SO-25	irrational PTU behaviour, insensitivity to fare and travel time
.....	.....
SO-38	predictable PTU behaviour, dependence of choice on travel time and availability of a unique service on the route
.....	.....
SO-50	predictable PTU behaviour, dependence of choice on travel time, SOst of travel and availability of a unique service
.....	.....
SO-57	predictable PTU behaviour, dependence of choice on the quality of PT on the route following its complication (increase in the number of transfers)
.....	.....
SO-63	predictable PTU behaviour, dependence of choice on quality of PT, admissibility of route complications, insensitivity to fare
.....	.....
SO-65	irrational PTU behaviour, insensitivity to route complexity, quality of PT on the route and cost of travel
.....	.....
SO-81	predictable PTU behaviour, dependence of choice on quality of PT on the route, insensitivity to route complexity, travel time and cost of travel
.....	.....
SO-88	predictable PTU behaviour, dependence of choice on cost of travel, quality of PT on the route and availability of a unique service, admissibility of route complications, insensitivity to travel time
.....	.....
SO-96	predictable PTU behaviour, dependence of choice on travel time and availability of a unique service, admissibility of route complications, insensitivity to quality of PT on the route
.....	.....
SO-101	predictable PTU behaviour, dependence of choice on travel time, admissibility of route complications, insensitivity to cost of travel and quality of PT on the route
.....	.....
SO-106	predictable, rational PTU behaviour, dependence of choice on travel time, fare, quality of PT and availability of a unique service, admissibility of route complications
.....	.....
SO-120	predictable PTU behaviour, dependence of the choice on complexity of the route and availability of a unique service, insensitivity to cost of travel and quality of PT on the route
.....	.....
SO-149	predictable PTU behaviour, dependence of choice on route complexity (number of transfers), travel time, insensitivity to quality of PT on the route
.....	.....
SO-159	predictable, rational PTU behaviour, dependence of choice on route complexity, travel time, cost of travel and quality of PT on the route
.....	.....
SO-162	predictable PTU behaviour, dependence of the choice on complexity of the route, travel time, cost of travel and availability of a unique service, insensitivity to quality of PT on the route

lines, based on a contactless method of determining parameters that are «ignored» by PTUs when building individual routes, create the necessary conditions not only for improving quality of transport services for the population,

but also for effective organisation of PT operations in dynamically growing urban agglomerations.

Depending on the degree of congestion of transport lines, the values of transit and carrying



capacity, as well as behavioural structure of passenger traffic within the sections of the transport infrastructure, the «fine tuning» of IT applications of MaaS ecosystem becomes an urgent task. Since the MaaS concept considers «mobility» «as a service», it should consider «the needs of all types of users, user groups should be introduced» [15]. For transport organisations, it is a tool for rational distribution of passenger traffic along PT routes by changing the waiting time and vehicle movement time on the line, LOS parameters, interchange parameters (through organising integrated stops for various transport routes, building new roads, lines, transport interchange hubs), ensuring an increase in the efficiency of the use of transport infrastructure and of transportation companies' operations. For PTU, this means a high-quality integrated public transport service with a higher level of consumer value.

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