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Simulation of Transfer Probability in the City Route Network: Case Study of Lviv, Ukraine

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Abstract

The correct organization of transfers in the public transport system allows to reduce the congestion of the route network while maintaining a sufficient level of service quality for users of transport services. When modelling the probability of transfer, it is advisable to separate the probability of a public transport user choosing a trip with a transfer and the probability of making a transfer at a certain stop of the public transport system. The first probability largely depends on the socio-economic characteristics of the passenger and the time parameters of the trip. The probability of transfer at a certain stop is affected by the information provision of the stop and the number of routes. The general configuration of the route network determines the "basic need for a transfer in the network" - the ratio of the number of pairs of transport zones between which there is no direct public transport route to the total number of pairs of transport zones. The simulation carried out in the PTV Visum software environment for Lviv city made it possible to assess the impact of the tariff system on the change in the number of transfers and to determine critical stops and routes of the network. The inclusion of data on the structure of the city's population in the model makes it possible to use mathematical functions of the probability of transfer on the socio-economic characteristics of the passenger (age, gender, income level) when calculating the forecast number of transfers on the network.

Keywords

transfer, public transport network, transport modelling, survey, user characteristics

1 Introduction

The problem of taking into account the probability of a passenger transfer at a city public transport stop is important when forecasting the demand for passenger transportation in the city transport system. Transfer costs are an element of the structure of travel time that affects the assessment of the quality of the urban transport environment (Nielsen et al., 2021). When using a fare payment system based on the principle of a single fare, the user of transport services often has a negative perception of a transfer, even if it reduces the distance or duration of travel, because it increases the cost of the trip. The fixed fare system allows you to eliminate the influence of the cost factor on passengers' perception of transfers. With such a system of fare payment, the time factors and the convenience of the transfer become decisive factors. Modelling the probability of transfer in the route network will allow us to assess the potential transport demand between individual city transport zones and to determine critical nodes and sections of the network (Cats, 2011; Naumov, 2019).

The purpose of the research is to assess the probability of transfers in the city route network, taking into account the socio-economic characteristics of the passenger and the parameters of the stop. In connection with the set goal, the following tasks are defined:

- conduct theoretical studies of factors affecting the probability of a transfer at a city transport stop;
- analyse the results of population surveys and determine the parameters affecting the probability of a transfer by a passenger;
- create a model of the route network of Lviv in the PTV Visum software (PTV Planung Transport Verkehr GmbH) environment and determine the modelling parameters;
- conduct modelling of the probability of transfers

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at stops and determine critical stops and routes of the network;
- form conclusions based on the results of modelling.

2 Literature review

The convenience of transferring passengers is one of the important components of the quality of transportation by public transport. Transfers are often perceived negatively by users of transport services (Garcia-Martinez et al., 2018; Wardman et al., 2001). An increase in the duration or cost of the trip, an increase in traffic fatigue contribute to, and a lack of information are the reasons for such a perception of a transfer. Schakenbos et al. (2016) structure the parameters of transfers, which affect their perception by passengers, into groups (Table 1). Chowdhury and Ceder (2016) identify psychological, operational and political factors influencing a passenger's willingness to transfer. Political factors characterize the influence of the activities of government or management offices on the formation and development of integrated transport systems. Psychological factors include the socioeconomic characteristics of users of transport services. A study by Kouwenhoven et al. (2014) deals with the influence of such characteristics on the perception of the total trip's duration. The authors estimated the change in travel time for different groups of passengers depending on changes in travel time, travel cost, and travel time reliability. Operational factors include the parameters of the trip: length, travel time, walking distance when transferring, duration and conditions of waiting for a transfer. Guo and Wilson (2011), in particular, researched the influence of such factors. Research by Abramović (2017) conducted in Zagreb (Croatia) identifies three parameters, change of which affects the passenger assessment of the quality of service at a transfer hub: reduction of the duration of the transfer, integration into the public transport system according to the schedule and tariff system, and available (educated) staff for interaction with passengers. Passengers' perception of a transfer is also influenced by the conditions of the transfer (Palmer et al., 2011): quality information before and during the trip regarding the duration of the trip, fares, possible delays; comfortable connection between various public transport services. Dispatch management of the coordination of transfers is important in this aspect. Both too short and too long transfer times are negatively perceived by passengers (Chowdhury and Ceder, 2013; Nesheli and Ceder, 2014). A study by Ceder et al. (2013a) found that for transfers lasting up to 5 min, the exact waiting time is not particularly important for the passenger. For longer transfers, a significant correlation was observed between the passenger's knowledge of the exact waiting time and the positive perception of the transfer. For transfers between city public transport and suburban railway, the optimal transfer time is 8 minutes (Schakenbos et al., 2016). Ceder et al. (2013b) investigates the impact of traffic correction of public transport vehicles on routes to improve the timing of the arrival of these vehicles at transfer stops. The results of the authors' experimental modelling confirm that online real-time tactics in the real world contribute to the number of successful transfers and shorten the duration of a passenger's trip. Yap et al. (2019) propose a clustering technique to identify significant transfer hubs of the route network in order to simplify the process of synchronization of public transport transfers. Applied to the route network of Hague (Netherlands), the technique made it possible to determine that 70% of all transfers occur at 0.9% of transfer locations. Nielsen et al. (2021) investigate the impact of transfer conditions on the attractiveness of public transport in the Greater Copenhagen Region. According to the authors' research, the ease of orientation and the presence of shops near a stop influence the attractiveness of a certain route. The range of changes in the transfer penalty used by the authors in modelling is from 5.4 min compared to bus in-vehicle time to 12.1 min.

Table 1 Transfer parameters

Information	Map of routes, schedules, interactive boards at bus stops
Safety	Poor lighting, safeness of district
Reliability	Frequency of movement, accurate adherence to schedules
Accessories of the stop	Availability of rain protection, seats, escalators
Method of transfer	Using disembarkation stop or walking to another stop, the availability of integrated ticketing systems
Comfort of transportation	Availability of accessible seats in the vehicle to which the transfer is carried out

3 Presentation of basic material

When simulating the transfer process, two indicators are the most important: the probability of a public transport user choosing a trip with a transfer and the probability of making a transfer at a concrete public transport stop. The availability of information about the value of the first indicator allows for an increase in the accuracy of modelling the passenger flow in the network as a whole or on individual routes. The second indicator enables an evaluation of the route network. This makes it possible to determine critical places of the network (places where passenger traffic will accumulate and for which it is worth considering the possibility of changing/harmonizing route schedules to improve the quality of passenger service). The first stage of passenger choice can occur at the stage of travel planning. There may be two alternative public transport stops within walking distance of the passenger from which they can reach their destination. Only a direct route passes through one of the stops, and both a direct route and routes with a transfer pass through the other. The passenger can choose which stop to choose. The probability of choosing a passenger is a function of the following parameters:

$$p_{pas} = f\left(s,l,\eta,i\right) \quad (1)$$

where:
s - socio-economic characteristics of the passenger;
l - distance to stop;
η - frequency of public transport at the stop;
i - information provision of the stop (in particular, the presence of an electronic scoreboard).

If a passenger is waiting to board at a bus stop with available alternative options for travel, the following options for the passenger's behaviour are possible:

- the passenger expects only a direct route;
- the passenger uses the vehicle that arrived first (regardless of whether it is a direct route or with a transfer).

The probability of one or another behaviour will also depend on the socio-economic characteristics of the passenger, the duration of the selected travel option, the occupancy of the vehicle that has arrived at the stop, and the wait duration at the stop. Route network parameters will affect the probability of transferring at a concrete public transport stop and the "baseline probability of a transfer in the network". The authors understand the concept of "basic probability of transfer in the network" as the ratio of the number of pairs of transport zones between which there is no direct public transport route to the total number of transport zones of the territory under consideration. That is, it is the probability of making a trip for which there is no non-stop route option when travelling by public transport. Three levels of transfers can be distinguished in the city route network:

- level A: transfers between city routes at the public transport stops;
- level B: transfers between urban and suburban routes at public transport stops;
- level C: transfers to/from intercity routes at external transport hubs.

Within the framework of this work, a study of level A and B transfers was conducted. Theoretically, a transfer is possible at any public transport stop. However, in practice, the probability of a transfer increases significantly if a new route appears at the stop, which was not at the previous stop on the passenger's path. Also, the total number of routes passing through a stop is a significant factor that can influence the probability of a transfer. The probability of performing a transfer can be modelled using Bayesian logistic regression. This issue is partially covered by the authors in the work of Zhuk et al. (2022). It is necessary to conduct sociological surveys to form models for determining the probability of a transfer by a passenger. It is necessary to analyse the route network for models of the probability of making a transfer at a stop.

3.1 Study area

The research was conducted in Lviv (Ukraine). Lviv is a city with a population of more than 753,820 people and a population density of 4.408 people/km^2 (based on data from Main Statistical Office in Lviv region, data as of 2021). Lviv's route network includes 8 tram and 10 trolley bus routes, large passenger capacity buses operate on 18 routes, and medium passenger capacity buses operate on 31 routes. There are also 71 suburban bus routes integrated into the city route network (EasyWay). Electric transport routes are shorter than bus routes: the average length of a tram route is 7.16 km (range of change from 5.3 to 9.2 km), the average length of a trolleybus route is 8.2 km (from 6.1 to 11.7 km), bus route – 15.85 km (from 8.49 to 25.3 km). Considering the curvilinear loop pattern of the street network of Lviv, 33% of all public transport routes are radial, another 40% are diametrical, and only 27% routes do not pass through the centre. The average detour factor of bus routes is 1.6, that of electric transport routes is – 1.4.

3.2 Data collection and analysis

An online survey was conducted (together with the Transport Department of the Lviv City Council) to collect data on the population's behaviour when they travel using public transport. The survey was conducted from February - November 2022. A total of 5.224 responses were received, which allows for an error of 3% with a 95% probability. The first part of the questionnaire consisted of questions about the socioeconomic characteristics of the respondent. The summarized data are presented in Table 2.

The second part of the questionnaire contained questions about the characteristics of the interviewees' movements using public transport. In general, 35% of the entire sample of respondents make a transfer when performing their urban trips by public transport. The results of the assessment of the differences in the probability of transfer for respondents with different socio-economic characteristics and for different time parameters of trips are presented in Table 3.

A more detailed analysis allows us to draw the following conclusions:

- Women use connecting routes more often than men: 37.1% versus 33.2%. The probability of performing a transfer increases with age for both men and women. For women this dependence is linear (t-test: t = 11.12, t_{cv} = 2.57); for men it is parabolic with a sharper jump after 50 years (Fig. 1):
  Understanding the effect of age may be important, given trends toward an older population. According to UN forecasts, in 2030 the share of the population over 60 years of age in the world will be 16.2%, and in 2050 – 21.5% (United Nations, 2022).
- With increasing income, the probability of a trip with a transfer decreases for men and women. For women, this trend is sharper: the probability of transplants changes from 0.42 to 0.22; for men, the range of change is from 0.38 to 0.23 (Fig. 2):

Fig. 3 shows the change in the probability of making a trip with a transfer depending on the period when the passenger starts their journey. The greatest probability of choosing such a trip is in the morning (before 7:00 a.m.), related to the small number of public transport routes already in operation.

There is a clear relationship between the duration of waiting for boarding at the public transport stop and the probability of choosing a trip with a transfer (Fig. 4). (The meaning of t-test: t = 12.77, t_{cv} = 2.57.)

The probability of making a trip with a transfer also increases exponentially when the duration of the trip increases (Fig. 5). The reverse statement will also be correct: the presence of a transfer usually lengthens the trip's duration. The value of the variable in the regression equations on the graphs varies from 1 to 7 (Fig. 1), from 1 to 6 (Fig. 4), and from 1 to 10 (Fig. 5). Each number corresponds to a corresponding range of values. The existing conditions for the organization of urban transportation

Table 2 Characteristics of the sample of interviewees

Indicator	Number of respondents	Part of the sample, %
Gender:		
male	2503	52
female	2721	48
Age:		
up to 17 years old	283	5.4
17–23 years old	1423	27.2
24–29 years old	1079	20.7
30–39 years old	1437	27.5
40–49 years old	648	12.4
50–59 years old	252	4.8
more than 60 years old	102	2.0
Professional status:		
pupil	210	4.0
student	953	18.2
part-time employment	296	5.7
full-time employment	3285	62.9
unemployed	330	6.3
retired	150	2.9
Income, EUR/month*:		
<125	384	7.3
125–250	991	19
250–375	1005	19.2
375–500	667	12.8
500–750	356	6.8
750–1000	142	2.7
>1000	407	7.8
don't work	891	17.1
refused to answer	382	7.3

* NBU exchange rate on February 14, 2023: 1 EUR = 39.75 UAH

Table 3 Differences between transfer probabilities

Indicator	The mean of the probability of transfer for different indicator's range										SD
	1	2	3	4	5	6	7	8	9	10	
Age	0.28	0.30	0.34	0.34	0.38	0.46	0.48				0.08
Income level	0.38	0.42	0.40	0.37	0.30	0.30	0.24				0.07
Waiting time	0.23	0.26	0.34	0.42	0.45	0.58					0.13
Travel time	0.10	0.12	0.18	0.20	0.24	0.32	0.40	0.47	0.60	0.76	0.22

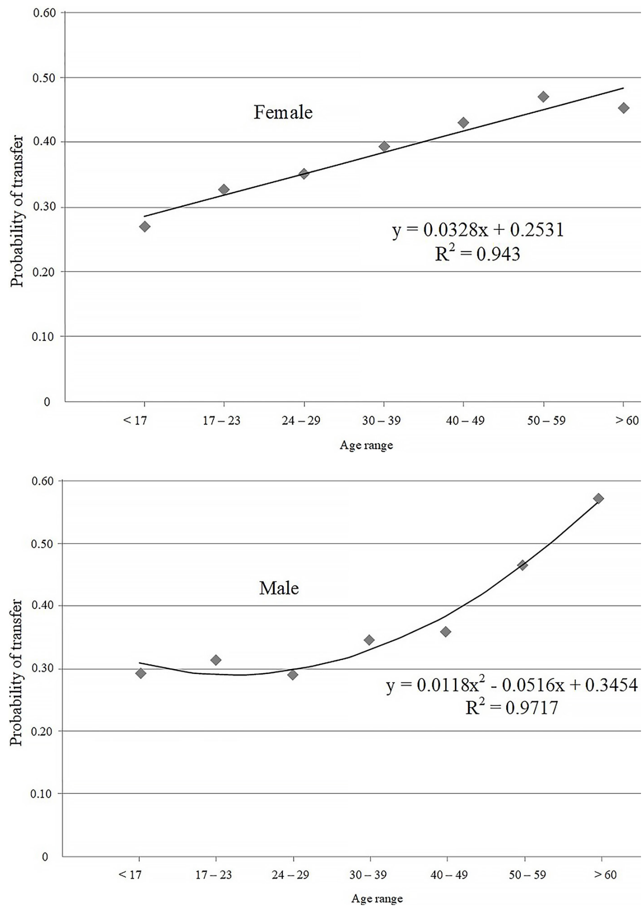

Fig. 1 Change in the probability of making a trip with a transfer depending on age

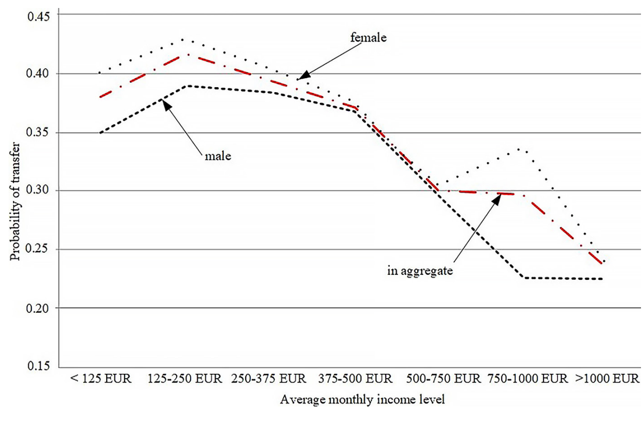

Fig. 2 Change in the probability of making a trip with a transfer depending on the level of income

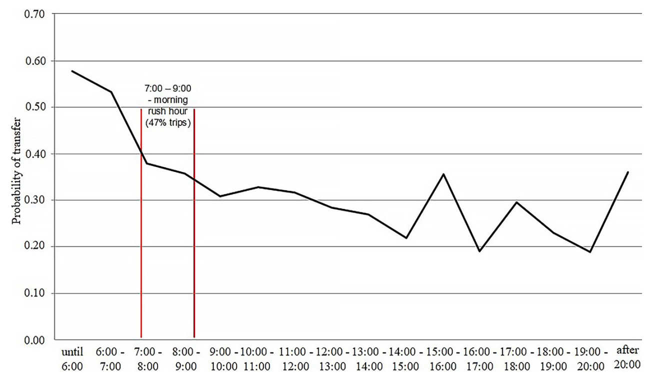

Fig. 3 Change in the probability of making a trip with a transfer depending on the period of the start of the trip

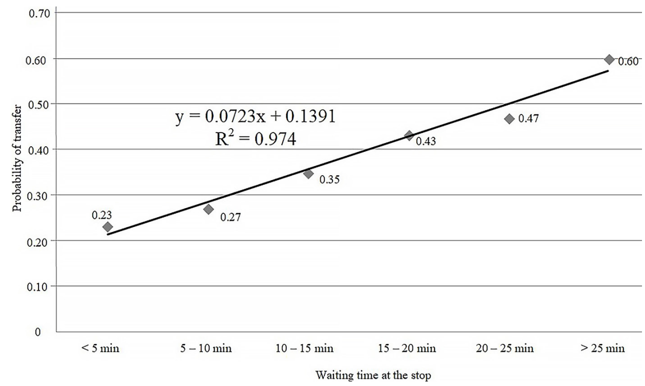

Fig. 4 Change in the probability of making a trip with a transfer depending on the duration of waiting for boarding at a stop

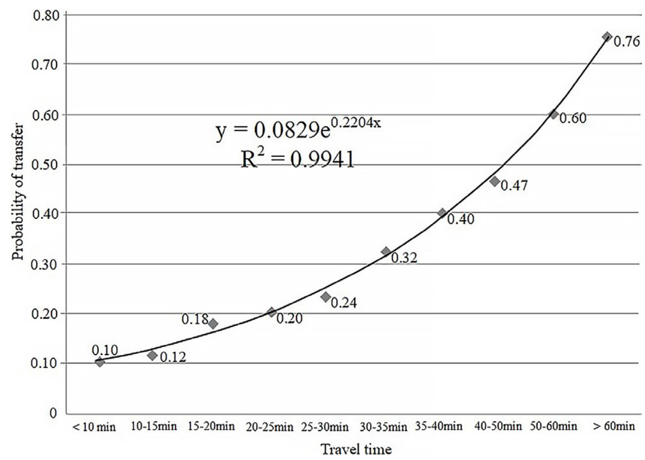

Fig. 5 Change in the probability of making a trip with a transfer depending on the total duration of the trip

in Lviv foresee an increase in the trip cost when making a transfer, which must be considered when modelling the passenger's choice of the option of their trip. Therefore, a question was added to the questionnaire: "Would you use the option of a trip with a transfer more often if there was no need to pay twice?" 51% of respondents answered in the affirmative, and another 39% in the affirmative in the case of savings in travel time of more than 15 minutes. These results are taken into account in further simulations. A study was conducted at 54 bus stops in Lviv, of which 18 bus stops are equipped with electronic displays (ED), to assess the impact of information provision at the bus stop on the probability of its selection by the passenger. The obtained data make it possible to assess the impact of the availability of information support at the stop on the average number of passengers boarding a public transport vehicle in Fig. 6 and Table 4.

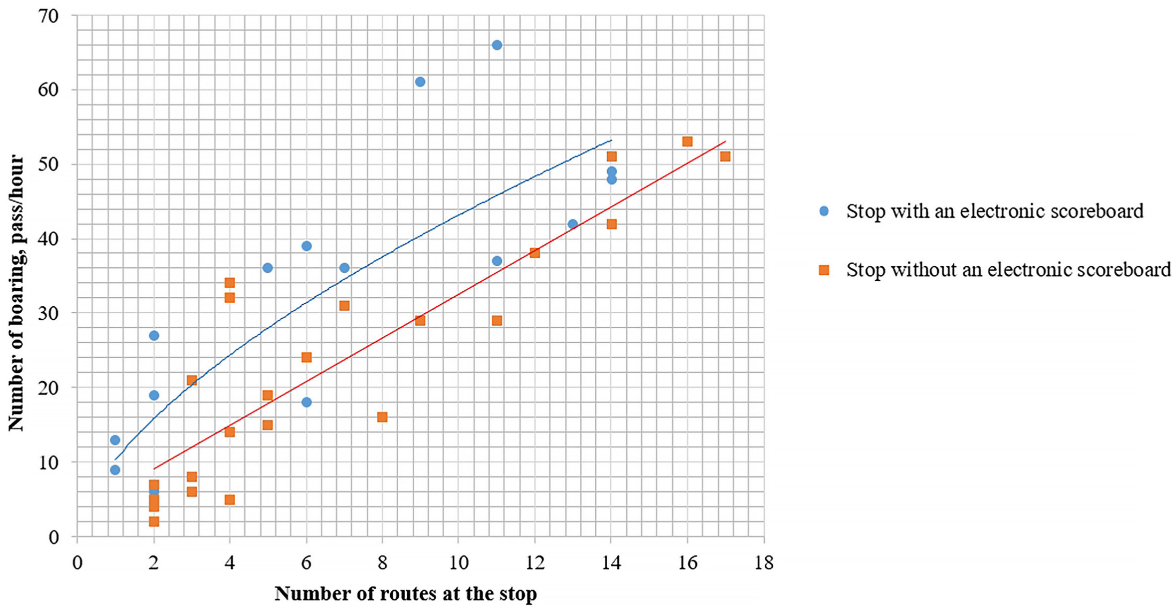

Fig. 6 The influence of the presence of an electronic display at the bus stop on the number of boarding passengers

Table 4 The influence of the presence of an electronic display at the bus stop on the number of boarding passengers

Indicator	Information support at the stop	
	Stop with an ED	Stop without an ED
Function	$y = 10.259 \times x^{0.6238}$	$y = 2.9266 \times x + 3.2405$
Approximation probability coefficient	$R^2 = 0.69$	$R^2 = 0.81$
The range of changing the number of routes	1–18	1–18
The range of changes in the average number of passengers boarding in one vehicle	3–14	1–9
The range of the most likely number of passengers boarding in one vehicle	3–7	1–4
Results of t-test:	$t = 4.760$ $t_{cv} = 2.160$	$t = 9.528$ $t_{cv} = 2.073$

With the same number of routes passing through a stop, the likely number of boarding at a stop with an electronic display is greater, although the difference decreases as the number of routes increases. The number of boardings is also affected by other factors, the impact of which was not evaluated in this study.

3.3 Modelling in PTV Visum

The PTV Visum software environment (Academic license) was used to evaluate route network parameters and further modelling. The created model of the city of Lviv has 3.045 nodes (intersections) and 8.442 links (sections of roads) with a total length of 1.757 km. The route network consists of 62 urban routes (total length of 822 km) and 950 stops, of which 148 meet the condition of the appearance of a new route, therefore they are considered as potentially possible transfer nodes. Level B transfers (transfers only between urban route and suburban route) can be made at 32 stops, and both level A and level B transfers can be made at 70 stops (transfers between urban routes and between urban and suburban routes). The rest of the stops serve only level A transfers. If traffic schedules are observed, 9.075 trips/day are made in the network. The territory is divided into 89 transport zones. Based on the results of surveys and data on population mobility, an initial correspondence matrix was formed (967.000 trips/day). Of the 7.832 pairs of transport zones, 1.410 pairs have no non-stop public transport connections, so the basic need for a transfer in the network is 0.18.

A 4-stage model of transport demand was used to forecast the amount of passenger traffic at each of the public transport stops with the distribution of the number of passengers who board, disembark, transfer at the disembarkation stop and transfer at a nearby stop. The simulation of the assignment of trips takes place based on time intervals (headway-based assignment) in three stages: headway calculation, route search and route choice, route loading.

The determination of the intervals between the arrivals of the route at the stop is conducted according to the traffic schedules based on the value of the average waiting time of the passenger who came to the stop in a certain period in the time interval [a, b]:

$$\tau^{a,b} = \frac{1}{b-a}\sum_{i=0}^{n}\Delta_i$$
$$\Delta_0 = \left(x_i - a\right)^2 \qquad (2)$$
$$\Delta_n = \left(x_{n+1} - x_n\right)^2 - \left(x_{n+1} - b\right)^2$$
$$\Delta_i = \left(x_{i+1} - x_i\right)^2$$

The route search is made considering impedance:

$$IMP = PJT \cdot k_1 + NFP \cdot k_2 \qquad (3)$$

where:
PJT - perceived journey time;
NFP - fare (15 UAH = 0.38 EUR);
k_1, k_2 - the coefficients of the influence of the perceived journey time and fare of travel on impedance. The coefficient k_1 = 1, the coefficient k_2 is equal to the number of transfers made during the trip.

Perceived journey time includes all possible elements of the trip: start and final walking time, travel time in a vehicle, origin waiting time, transfer waiting time and number of transfers.

The start and final walking time in the model is calculated as the average value of all durations of pedestrian movement at a speed of 4 km/h from each point of the transport zone to the nearest public transport stop.

The origin waiting time is calculated:

$$OWT = \left(x_{i+1} - x_i\right)^2 \qquad (4)$$

where
x_i, x_{i+1} - departure time of the i and (i + 1) vehicle from the stop.

In case of unstable intervals between vehicles transfer waiting time is calculated:

$$TWT = \frac{1}{\sum_{j \in L}\lambda_j} \qquad (5)$$

where
λ_j- frequency of movement of the route j from the set L.

The route choice from a set of possible ones in the case of lack of information about a specific time of arrival makes using a formula:

$$\pi_i = \lambda_i \int_0^{\bar{h}} \prod \left(1 - \lambda_j \cdot w\right) dw \qquad (6)$$

where
$\bar{h} = \min\{h_i\}$ – the minimum interval from the available set;
λ_i – route frequency;
w – waiting time, min.

3.4 Modeling results

The assessment of the impact of a transfer on the probability of a passenger choosing the route of their trip is modelled for three variants of transfers:

1. the transfer time allowance when calculating the perceived waiting time is 5 minutes - passengers perceive the transfer as comfortable (Ceder et al., 2013a);
2. the transfer time allowance when calculating the perceived waiting time is 15 minutes – passengers perceive a transfer as appropriate only if the duration of travel when using a route with a transfer is at least 15 minutes shorter than a non-stop travel (results of conducted surveys);
3. the transfer time allowance when calculating the perceived waiting time is 30 minutes - taking into account double payment in transfer (30 minutes - the average duration of the trip by public transport in Lviv).

To perform the convergence check, we checked whether the volume of public transport changed by less than a threshold value (10%) during the last iteration. If not, the simulation returns to the Trip Distribution step.

Table 5 shows the simulated characteristics of the route network operation with three modelling options.

With the addition of 30 minutes to the transfer time,

Table 5 The impact of an increase in the cost of a transfer on the characteristics of the route network

Indicator	The value of the indicator when adding time for a transfer		
	5 min	15 min	30 min
Mean ride distance, km	9.1	9.6	9.9
Mean transfer wait time, min	13.3	13.4	14.2
Mean origin wait time, min	16.2	17.6	19.2
Mean transfer walk time, min	1.2	1.4	2.0
Total number of transfers	977353	826490	759381
Total number of passengers trips using public transport	911660	911660	911660
Number of passengers trips with one transfers	458673	417318	261640
Number of passengers trips with more than one transfers	55312	54735	45646

the total simulated probability of a transfer in the network is 0.34, which practically coincides with the survey results. If one saves more than 15 minutes using a route with a transfer, the total number of transfers in the network increases by 9%. The probability of a passenger making one transfer increases to 0.45 and two to 0.06 (the initial probability of such transfers is 0.05). In the case of organizing transfers with a comfortable duration for the passenger, the total number of transfers in the network increases by 29% relative to the initial value. The total simulated probability of a transfer in the network is 0.56. The average waiting time for boarding and transfers is also decreasing.

Modelling allows to determine pairs of transport zones with the many transfers, critical stops and routes of the city's route network (Fig. 7). Stops are considered critical if the number of transfers is more than twice the average value of the number of transfers in the network. The problem with Lviv is that most routes are radial or diametrical. Accordingly, most transfers are made in the central part of the city, which creates an additional load on the street network. 24 stops can be considered critical (13% of the total number of stops at which transfers are made). 64% of the total number of transfers in the network is performed at these stops. The information obtained allows for the formulation of recommendations for public transport management bodies and operators of transport services regarding the optimization of routes and schedules.

4 Conclusions

The organization of the transfer process is an important element that affects the passenger's assessment of the quality of the public transport trip. Modelling as an important component of modern transport planning allows to assess the level of transfers in the route network and identify

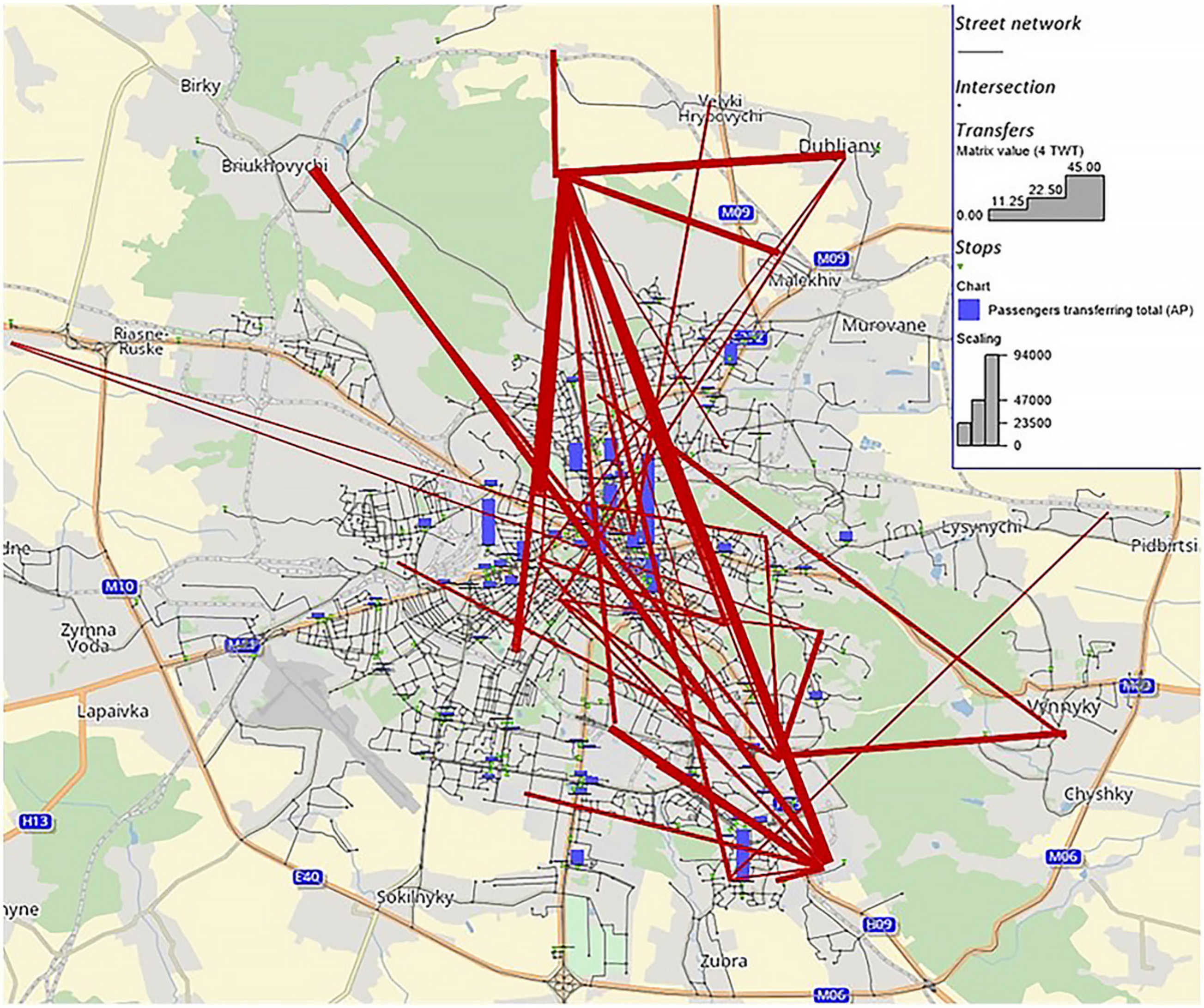

Fig. 7 Frequency of transfers when tripping between transport zones of the city

critical places that require the attention of planners and managers. The results of a survey of the population of Lviv city (5.224 completed questionnaires were processed) indicate the impact of the passenger's socio-economic characteristics and the characteristics of the trip on the probability of choosing a transfer option. In general, the probability of a trip with a transfer increases with age and decreases with the passenger's income. The influence of the time characteristics of the trip is also traced: the time of the start of the trip and the duration of its components (waiting, movement in the vehicle). When modelling transfers, it is advisable to separate the probability of passengers choosing a trip with a transfer and the probability of changing at a specific public transport stop. The probability of changing at a certain stop is influenced by the parameters of the route network: "basic need to transfer in the network" (the ratio of the number of pairs of transport zones between which there is no direct public transport route to the total number of pairs of transport zones of the territory under consideration), the appearance of a new route at a stop, which was not at the previous stop on the passenger's route, the total number of routes passing through the stop. Mathematical equations of the change in the probability of changing at stops with and without an electronic scoreboard were obtained for the range of changes in the number of routes passing through the stop, from 1 to 18. For example, with 5 routes, the probable number of boardings at a stop with a scoreboard is 28 people/hour against 18 (difference 36%), from 10 routes – 43 and 32 pas/h, respectively (difference 26%), from 15 routes – 56 and 47 pas/h (difference 16%). The simulation was carried out using the PTV Visum software environment for the Lviv route network for three variants of the transfer allowance. The basic need to transfer is 0.18. Considering the existing model of fare payment in Lviv, the total simulated probability of a transfer in the network is 0.34, which practically coincides with the survey results. When saving time of more than 15 minutes, in the case of using a route with a transfer, the probability of a passenger making one transfer increases to 0.45, and two transfers - to 0.06 (the initial probability of such transfers is 0.05). With a comfortable transfer duration and a tariff system, the total probability of transfers in the network increases to 0.56. 24 stops can be considered critical (13% of the total number of stops at which transfers are made). 64% of the total number of transfer in the network is performed at these stops. The obtained research results can be used by public transport management bodies and transport service operators to optimize routes. Considering the structure of the city's population and the predicted trends of its change during developing and implementing measures to optimize the route network will allow better satisfaction of passengers' requests and increase the level of satisfaction with the quality of transport services. Also, the obtained results can be beneficial for operation schedules at critical stops for a comfortable trip with a transfer. Further research can be directed at the formation of an algorithm for determining critical stops of the route network. Also, a possible direction of future work is a generalized assessment of the impact of the passenger's socio-economic characteristics and trip parameters on the probability of transfer, which will allow determining the relative degree of influence of these indicators on the overall result.

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