pedestrian flow; correspondence; modelling; attraction function

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OPERATION PEDESTRIAN FLOW IN CITIES

Summary. The key factors affecting formation of pedestrian flows and the methods of modelling pedestrian behaviour have been considered. It has been found that the basis for modelling is valid information about pedestrian movement in the network. Based on this, using the attraction model for calculation of correspondences has been suggested. The attraction function used has been found to depend to a different extent on the distance of movement on foot.

ФУНКЦИОНИРОВАНИЕ ПЕШЕХОДНЫХ ПОТОКОВ В ГОРОДАХ

Аннотация. Рассмотрены основные факторы влияния на формирование пешеходных потоков и методы моделирования поведения пешеходов. При этом установлено, что основой для моделирования является точная информация о перемещении пешеходов по сети. Исходя из этого, предложено использовать гравитационную модель расчета корреспонденций. Установлено, что используемая функция тяготения зависит от длины пешего движения в разной степени.

1. INTRODUCTION

People most often move around a city on foot. Hence, apart from studying and modelling transport flows, pedestrian flows demand special attention. This task is challenging because it is difficult to describe pedestrian behaviour, in contrast to behaviour of drivers who move in a vehicle in the transport network. Therefore, a topical problem for cities is organizing urban pedestrian movement ways with account of their purposes and population categories.

2. LITERATURE REVIEW

Movement of people is one of their key vital functions. In the majority of cases, it depends on their place of employment and residence. For proper organisation of pedestrian flows, the regularities of their formation should be considered.

2.1. Analysis of factors affecting the formation of pedestrian flows

Literature has distinguished four groups of factors affecting the formation of pedestrian flows (fig. 1) [1-4]:

1) Town-planning;
2) Road layout;
3) Social;
4) Economic.

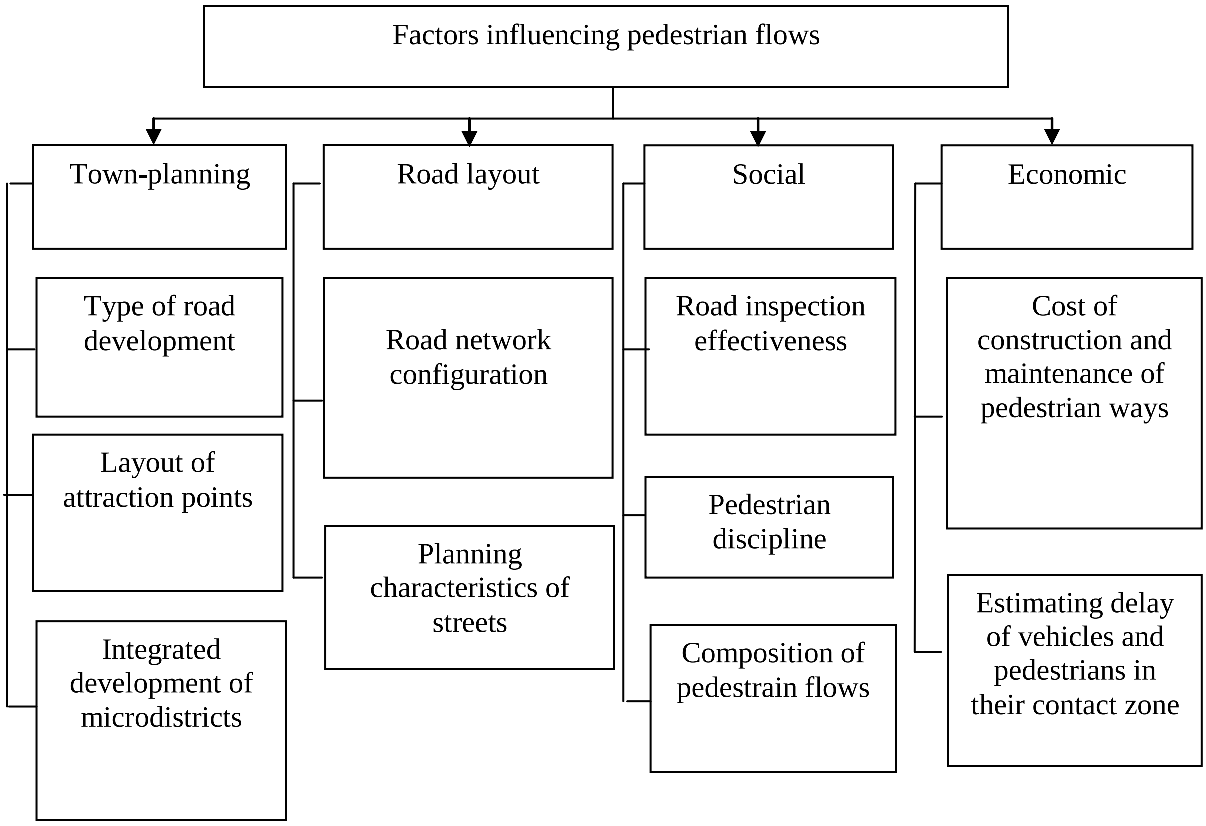

Fig. 1. Factors influencing pedestrian flows
Рис. 1. Факторы влияния на пешеходные потоки

Town-planning factors include the planning features of traffic connections, layout of attraction points and generation of pedestrian flows, and road layout types [1, 4].

Road layout factors include the road network configuration, the intensity of pedestrian and vehicle traffic, the speed of vehicles, street control conditions and street layout characteristics [1, 2].

The social factors include the age composition of pedestrian flows, the target of movement on foot, the level of traffic awareness of traffic participants – drivers and pedestrians, road inspection effectiveness, and transport adaptation of pedestrians [3].

The economic factors include capital and service outlay for construction and maintenance of technical means of organizing and supporting pedestrian traffic, the movement distance, and the delay of vehicles and pedestrians in the zones of their contact [1].

Papers [5, 6] discuss formation of pedestrian flows under the influence of the following factors: architectural space expressiveness (expanse, openness, height, dynamic characteristics of building architectural forms, the embedded symbolic meanings, and images) and psycho-physiological features.

The behaviour of pedestrians is a challenging process; hence, when planning facilities with high pedestrian traffic density and limited space for optimization of pedestrian flows, guaranteeing avoidance of discomfort and reducing delays, as well as for enhancing traffic safety, simulation modelling is advised. It is also required for solving the following problems [7]:

– pedestrian interaction with different kinds of transport;
– holding events involving big audiences;
– mass evacuation of people from places of their concentration; and
– checking functioning of pass entry systems.

Thereat, all the models can be classified as per the following features [7-9]:

– macroscopic or microscopic model;
– discrete or continuous model;
– deterministic or stochastic model;
– model based on rules or based on forces; and
– high or low accuracy.

The fundamentals of the theory of pedestrian flows, which have been developed, have become the underpinning for developing the following current models [7-9]:

1. Model of gravitating forces. According to this model, each pedestrian and obstacle carry a positive charge. The negative charge is concentrated in the place where the pedestrians are heading. The pedestrians are heading to their goal and avoid collisions. Two forces affect each pedestrian. The first is the magnetic force. It depends on the value of the pedestrian's electric charge and the distance between the pedestrian and the goal of movement. The other force acts on pedestrians to avoid collision with other pedestrians or obstacles by means of acceleration.

2. Model of social forces. Here, factors affecting a pedestrian are expressed as different forces. The model of social forces uses Newtonian dynamics for describing movement of pedestrians. It demonstrates several models of natural behaviour of pedestrians during movement:

- pedestrians choose the shortest route;
- pedestrians move with their own individual speed, with account of the situation, gender, restrictions and other features; and
- pedestrians move at a definite distance from each other.

3. Cellular automata. One of the most promising methodologies for modelling crowd movement is the so-called cellular automata approach. According to it, the model contains simple elements linked by local interaction with several 'neighbours', their number being limited by a definite small constant. Traffic is modelled as movement of people between cells according to definite rules.

Recent studies in physics and applied mathematics have shown that, in spite of the simple description of elements and the rules of their interaction, the dynamics of a cellular automaton can contain any natural phenomena: self-organisation, chaos, and complex behaviour of the entire system [8]. Hence, a significant advantage of using a cellular automaton for modelling crowd movement is that simple rules used to evaluate the behaviour of an individual pedestrian can yield an adequate description of a crowd as a complex object.

4. The gas kinetics model. In this model, pedestrians are represented as molecules in liquefied gas. The exact speed and position of pedestrians-molecules is unknown, though the static distribution of particles is a known value.

5. Models using the theory of queues for describing the movement of pedestrians with the use of probability functions.

6. Calculation models. A big share of parameters is calculated once based on experimental data. Tables showing the dependence of these parameters on the number of pedestrians and the size of the room are compiled. In the following, these data are used for describing passenger flows.

These models are practical for planning facilities with high pedestrian traffic density and limited space for optimizing pedestrian flows, guaranteeing avoidance of discomfort and reducing delays, as well as for enhancing traffic safety. At the same time, the pedestrian flow formed moves along traffic connections to form correspondences.

2.2. Analysis of studies in determining correspondences

Assessing the quality of functioning of a transport system is intimately linked to the structure of correspondences between all spatial urban elements. Calculating correspondences is one of the central problems in all studies providing for more or less significant changes in the distribution of flows in the transport network. A correspondence matrix contains important information, which characterizes the distribution of pedestrian and vehicle flows in the road network system. These matrices are used widely in urban transport planning and for addressing road traffic organisation problems [10].

According to the basic attraction model, the correspondence matrix is obtained based on the physical law of attraction of bodies. Actually, the calculation method consists in proportional distribution of departure capacities from transport areas based on the value of one transport factor. The conventional and most common attraction model is built around the following hypothesis [11]:

$$b_{ij} = k \cdot HO_i \cdot HP_j \cdot f(\phi_{ij}), \tag{1}$$

where b_{ij} are potential correspondences between areas, which can be obtained according to perfect analogy with the law of attraction; HO_i is volume of dispatch of passengers from area *i* over the calculation period; HP_j is volume of arrival of passengers to area *j* over the calculation period; $f(\phi_{ij})$ is attraction function representing the distance or time and monetary expenditures for travelling from area *i* to area *j*; k is calibration coefficient.

With this method of modelling, formalizing the attraction function merits special attention [12].

The classical attraction function is found based on the hypothesis of feedback between the correspondence value and the distance between areas:

$$\phi_{ij} = l_{ij}^{-n}, \tag{2}$$

where l_{ij} is distance between *i*-th and *j*-th areas; n is exponent.

The attraction function is often defined as the overall assessment by inhabitants of the conditions of communication between transport areas as a function of time expenditures for movement required by employment links. This introduces vagueness to the physical representation of this parameter and its dimensionality. Due to this, researchers have been defining the attraction function qualitatively by determining principle relationships and providing dimensionality conditions in further calculations through a concrete approach to using a relationship. The physical meaning of the attraction function reflects its stochastic formulation, which interprets it as the probability of that the number of inhabitants of area *i* HO_i shall select with probability ϕ_{ij} movement to area *j* with arrival capacity HP_j.

Attraction functions of the exponential group in general form are represented as follows:

$$\phi_{ij} = \exp(-\beta \cdot k_{ij}), \tag{3}$$

where k_{ij} is indicator characterising the degree of ‘attraction’ between the *i*-th and *j*-th transport areas; β is empirical coefficient.

Attraction functions based on the regularities of settlement of urban population merit special attention. Thus, in [9], based on the hypothesis of the normal law of settlement of the inhabitants of a town, the following kind of attraction function has been offered:

$$\phi_{ij} = \frac{1}{\sigma \cdot \sqrt{2 \cdot \pi}} \cdot e^{-t^2/(2 \cdot \sigma^2)}, \tag{4}$$

where σ is parameter of the distribution law defined by the three sigma rule.

These models are practical for calculating matrices of passenger and transport correspondences when travelling occurs over big distances, which is not characteristic for pedestrian movement.

Depending on the goal of movement and method of further transportation, the time of movement on foot is limited to 20-30 minutes [13]. Hence, the following problems should be addressed and solved:

1) Giving a characteristic of the models of movement of people depending on the type of space where they are found;
2) Conducting field studies in a typical microdistrict;
3) Calculating correspondences and comparing them against experimental data; and
4) Determining attraction functions for movement on foot.

3. REVIEW OF PREVIOUSLY OBTAINED RESULTS

Properly modelled pedestrian spaces, and their layout and character affect changes and origination of new forms of behaviour in a modern urban environment [5].

Thus, according to the classification adopted in town planning, the following types of spaces are distinguished (fig. 2):

1) open;
2) semi-open;
3) closed.

The first space type is characterised by the presence of extended undeveloped areas with a good view of adjacent territories. With such space, the natural pace of movement is maintained, and tension and stress reactions are absent. Open urban spaces are meant to be undeveloped areas in general, and include water and greenery systems, main avenues, embankments, pedestrian zones, squares, boulevards and other town planning elements, comprising a system of open spaces.

A semi-open space is characterised by alternating densely developed areas and open territories with periodic field of vision limitations. Under such conditions, pedestrian movement is characterised by frequent changes of accelerations and stops. This causes wariness in traffic participants and calls for choosing the safest routes.

The last, closed type, is characterised by densely developed territories, absence of big open spaces, with the field of vision being limited at all times. In such type of space, a person moves resolutely, chooses the shortest routes and strives to find a more comfortable area.

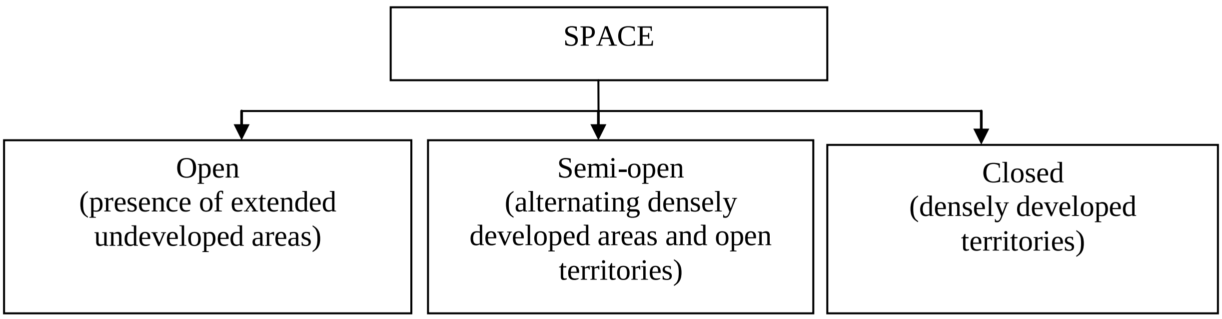

Fig. 2. Types of spaces
Рис. 2. Типы пространств

From the viewpoint of movements realised in transport, open spaces are those areas in parks, public gardens, squares, and boulevards, which pedestrians use to access car parkings and public transport stops. This territory should ensure movement with its characteristic features, namely: slow speed, abrupt change of heading and speed of movement, and frequent stops [2].

Semi-open spaces include public transport stops, car parkings, underground and ground pedestrian crossings, ground metro stations, whereas the closed spaces are underground metro stations.

Hence, depending on the type of space of formation of pedestrian flows, the following modelling methods were identified (fig. 3).

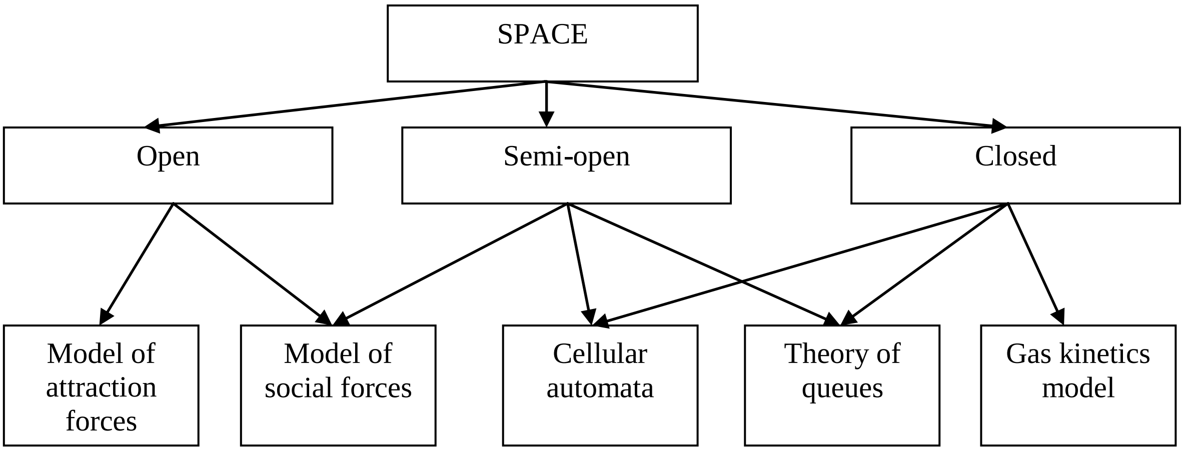

Fig. 3. Classification of spaces with account of pedestrian flow models
Рис. 3. Классификация пространств с учетом моделей пешеходных потоков

Analysis of spaces, pedestrian traffic models and factors affecting such traffic allows distinguishing topical problems of interaction of transport and pedestrian flows.

4. TREATMENT AND ANALYSIS OF RESEARCH RESULTS

A typical microdistrict was chosen for conducting experimental research. The district is delimited by thoroughfares of citywide and district significance, with city public transport routes (fig. 4).

Within these microdistrict limits, 101 pedestrian attractors have been identified. They include 53 residential buildings, nine educational establishments, five groceries and non-grocery goods shops with a floor area of over 30 m^2, and four car parks with an overall capacity of about 400 parking units.

The objective of conducting field surveys was to obtain correspondence matrices for pedestrian flows and compare the values obtained against those calculated using models (1) - (4). In so doing, the criterion of fitness of calculated and experimental values was taken to be the mean approximation error [14]

$$\varepsilon = \frac{1}{N}\sum_{i=1}^{n}\left|\frac{y_i^m - y_i^e}{y_i^e}\right| \cdot 100\%, \tag{10}$$

where N is number of observations, units; y_i^m, y_i^e is the dependent value calculated using the model and the actual one, respectively.

The result was such baseline data as volume of departure of pedestrians from each point, volume of arrival of pedestrians to each point, and distance between attraction points.

To calculate correspondences, the course of influence of attraction function (2) was analyzed for different exponents (figs. 5-8).

Fig. 4. Layout of residential microdistrict
Рис. 4. Схема жилого микрорайона

Residential buildings
Educational establishments
Garages and car parks
Pedestrian ways
Shops
Public transport stops
Metro stations
11 Pedestrian attraction units

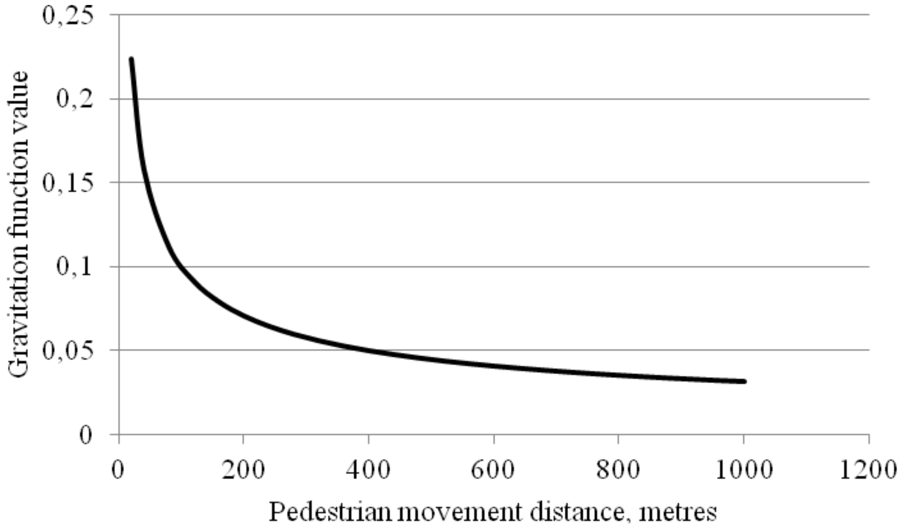

Fig. 5. Attraction function (2) vs. walking distance with exponent $n = 0.5$
Рис. 5. Зависимость функции тяготения (2) от расстояния пешего перемещения при показателе степени $n = 0.5$

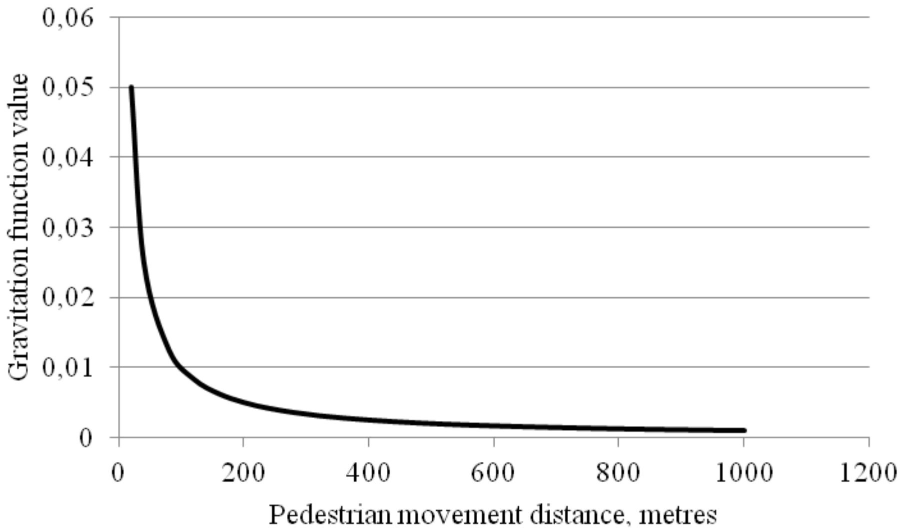

Fig. 6. Attraction function (2) vs. walking distance with exponent $n = 1.0$
Рис. 6. Зависимость функции тяготения (2) от расстояния пешего перемещения при показателе степени $n = 1.0$

The character of dependence of attraction functions on the pedestrian movement distance (figs. 5-8) shows that the acceptable exponent value is within $n = 0.5 \div 1.0$. Hence, theoretical correspondence values were calculated using attraction function (2) with exponents $n = 0.5; 0.6; 0.7; 0.8; 0.9; 1.0$. The goodness of fit test results are shown in Table 1.

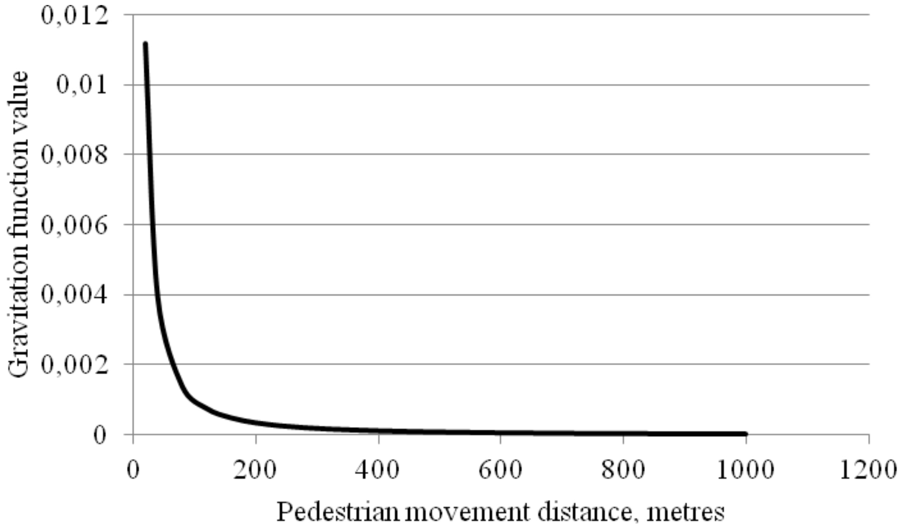

Fig. 7. Attraction function (2) vs. walking distance with exponent $n = 1.5$
Рис. 7. Зависимость функции тяготения (2) от расстояния пешего перемещения при показателе степени $n = 1.5$

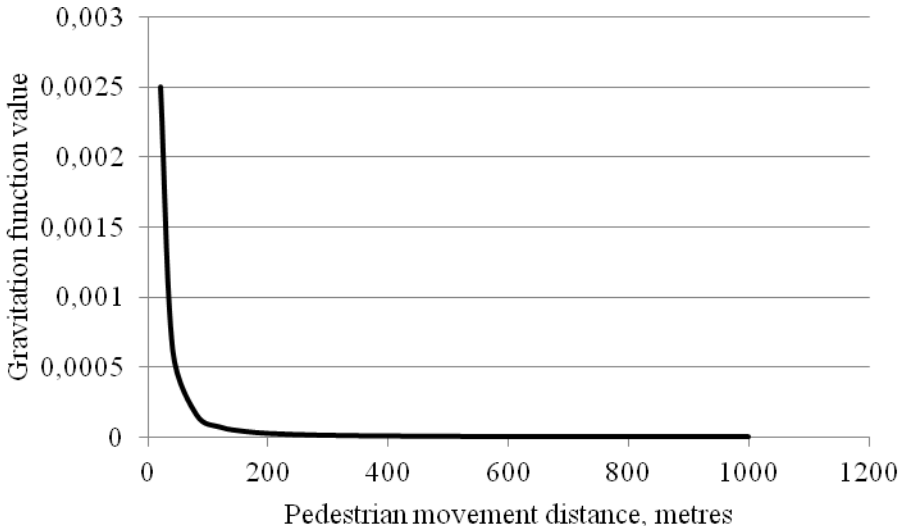

Fig. 8. Attraction function (2) vs. walking distance with exponent $n = 2.0$
Рис. 8. Зависимость функции тяготения (2) от расстояния пешего перемещения при показателе степени $n = 2.0$

Hence, the correspondences of pedestrian flows can be calculated using model (1) with attraction function (2) and exponent $n = 0.7$. The attraction function (2) vs. pedestrian movement distance graph with exponent $n = 0.7$ is shown in fig. 9.

Tab.1

Results of testing for goodness of fit of experimental and calculated values of correspondences of pedestrian flows

Type of attraction function model	**Mean approximation error,** ε, %
$\phi_{ij} = l_{ij}^{-0.5}$	23.48
$\phi_{ij} = l_{ij}^{-0.6}$	17.24
$\phi_{ij} = l_{ij}^{-0.7}$	9.63
$\phi_{ij} = l_{ij}^{-0.8}$	12.34
$\phi_{ij} = l_{ij}^{-0.9}$	18.61
$\phi_{ij} = l_{ij}^{-1.0}$	22.84

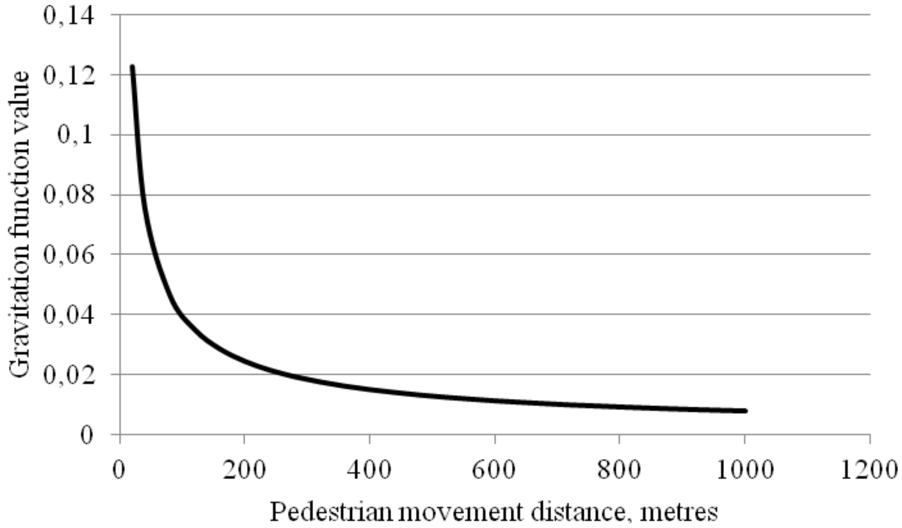

Fig. 9. Attraction function (2) vs. walking distance with exponent $n = 0.7$

Рис. 9. Зависимость функции тяготения (2) от расстояния пешего перемещения при показателе степени $n = 0.7$

5. CONCLUSIONS

Analysis of given factors that affect formation of pedestrian flows has shown that they fall into four main groups (urban development, road-planning, social and economic ones). Thereat, to optimize pedestrian flows, ensure guaranteed avoidance of discomfort and reduce delays, as well as to enhance traffic safety, simulation modelling is advised.

The key characteristic used for modelling is calculation of correspondences. Current research in calculating correspondences pertains only to transport and passenger flows when travel covers big distances as compared to movement on foot.

It has been found that route selection is influenced by a pedestrian’s walking distance, which is represented by the attraction function when calculating correspondences. Since the attraction function depends on the exponent value, this is indicative of that the influence of the movement distance can vary. With account of exponent variation within wide limits, application software was used to study its influence on the attraction function. It was found that an acceptable exponent value is within $n = 0.5 \div 1.0$. Further validation of experimental and calculation values of pedestrian flow correspondences has shown that the most acceptable exponent value is $n = 0.7$, with a deviation of 9.63 %.

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