Modeling demand for passenger transfers in the bounds of public transport network

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Abstract. The proposed model is based on the developed approach to perform the routing assignment stage in the classical four-stage urban planning procedure. Demand for trips is generated for each stop of a public transport system on the grounds of stochastic variable of the time interval between passengers arrival to the respective stop. After defining of the destination stop, the route for the passenger's trip is determined with the use of Dijkstra's algorithm within the frame of a public transport network which is presented as a graph model with stops for vertices and route segments for edges. Transfer nodes are defined in the model as such graph vertices which are common for at least two lines of the public transport system. The author presents a class library implemented with the use of the Python programming language. On the basis of this library, the model for simulations of demand for transfers within the given public transport system was developed. The proposed approach to the demand modeling and the developed software were used for simulations of demand for transfers within the bounds of the public transport system of Bochnia (Poland).

Keywords: Public Transportation, Transfer Demand, Trip Simulations.

1 Introduction

The passenger transfers optimization is one of the main directions to enhance the quality of public transport services. Modeling a demand for services of transfer nodes is quite a complex issue due to the stochastic nature of the transport process and the random nature of demand for trips in urban areas. However, this procedure is an essential stage for solving any problem related to optimization in transfer nodes, such as timetables scheduling for public transport lines, designing the public transport network or estimating the parameters of a given transfer node.

The main objective of transfer optimization usually is minimization of the passengers waiting time due to synchronization of public transport vehicles at the system interchanges. The existing literature considers the trade-off between passenger waiting time and operating costs [1], but multi-objective optimization approaches are also commonly used, e.g. a model for the multi-objective re-synchronizing of timetables [2]. According to the commonly used approach, the problem of the timetables' synchronization is being presented as an integer programming problem [3]. Recently, this problem was solved with respect to fluctuating demand in order to minimize both the expected total waiting time and the observed load discrepancy [4], in order to maximize passenger transfers and minimize bus bunching in the network [5], and with objective to achieve a maximal synchronization amongst the buses and metro [6]. Due to a big dimension of the problem, standard integer programming methods not always could be used for solving it in the real-world conditions. For this reason, to obtain some rational solution, different heuristic techniques are applied: the ant colony model in combination with fuzzy logic methods [7] or genetic-based algorithms [3].

For obtaining realistic models, randomness of public transport parameters should be considered. Stochastic disturbances appear due to the variation of vehicles intensity over time, traffic jams, weather condition, etc. The mentioned uncertainties lead to increasing the variability of the travel time and diminishing service reliability. Some published transfer models consider uncertainties of travel demand: authors of the paper [8] propose demand-oriented train timetabling models aiming to decrease passenger waiting times, authors of [9] assess the demand for an adaptive transit service on the example of Chicago region, in the paper [10], its authors have developed a predictive control scheme for a hybrid model with actuation via bus speeds, which can regularize headways and improve bus service quality, etc.

As it could be concluded from the discussed literature, the main tool for developing adequate demand model is computer simulations. Direct machine simulations are preferable, because they allow researchers to consider numerous stochastic parameters, which cannot be taken into account on the grounds of formal models. Nowadays, the commonly used tools for the transport demand simulations are PTV Visum and Aimsun, but open-source solutions [11, 12] recently become more popular due to their ability to be modified and adjusted.

The goal of this paper is to present an approach to model demand for transfers in the interchanging nodes of a public transport system based on computer simulations of the transportation process. In the framework of the described approach, a model of the public transport system is developed that allows describing the demand at the level of the system elements, which guarantees more adequate results of demand simulations in comparison with models based on the macrosystem approach.

The paper has the following structure: in the second section, the mathematical model of the public transport network is briefly described and the proposed approach to passenger transfers is presented; the third part depicts the class library developed by the author in order to simulate public transport systems; the forth section introduces a case study of transfer demand simulations for the public transport system of Bochnia city; the last part offers brief conclusions.

2 Mathematical Model for Simulations of Demand for Passenger Transfers

As far as passenger transfers are being determined in the frame of a public transport network containing public transport lines, the mathematical model aiming an implementation of these procedures should be defined in the bounds of the model of a public transport system.

2.1 Model of a Public Transport Network

At the higher level, a public transport network $\mathbf{\Omega}$ could be presented as the set containing a set $\mathbf{\Lambda}$ of lines operating within the bounds of the system and a set $\mathbf{D}$ of passengers using the public transport system to satisfy their needs in trips.

$$\mathbf{\Omega} = \left\{ \mathbf{\Lambda}, \mathbf{D} \right\} . \tag{1}$$

As elements of the *i*-th public transport line λ_i, $\lambda_i \in \mathbf{\Lambda}$, the following objects should be mentioned: a set $\mathbf{L}_i$ of the route segments from which the *i*-th line is composed, a set $\mathbf{V}_i$ of vehicles operating on the *i*-th line:

$$\lambda_i = \left\{ \mathbf{L}_i, \mathbf{V}_i \right\},\ i = 1 ... N_\Lambda , \tag{2}$$

where N_Λ – number of lines in the public transport network.

Elements of the set $\mathbf{L}_i$ characterize the end points (respective stops at the beginning and at the end of the segment) and a weight (a length of the segment):

$$l_{ij} = \left\{ n_{ij}, m_{ij}, w_{ij} \right\},\ l_{ij} \in \mathbf{L}_i,\ j = 1 ... N_{L(i)} , \tag{3}$$

where l_{ij} – the *j*-th segment of the *i*-th line route; n_{ij} and m_{ij} – the beginning and the end stops of the *j*-th route segment, $n_{ij} \in \mathbf{N}_i$, $m_{ij} \in \mathbf{N}_i$; w_{ij} – weight of the *j*-th route segment [km]; $N_{L(i)}$ – number of the route segment for the *i*-th public transport line; $\mathbf{N}_i$ – a set of all bus stops for the *i*-th line.

A vehicle v_{ij} as an element of the set $\mathbf{V}_i$ ($v_{ij} \in \mathbf{V}_i$, $i = 1 ... N_{V(i)}$, where $N_{V(i)}$ is the number of vehicles servicing the *i*-th line) is first characterized by a capacity and the timetable on the *i*-th public transport line:

$$v_{ij} = \left\{ c_{ij}, s_{ij} \right\} , \tag{4}$$

where c_{ij} – capacity of the *j*-th vehicle [pas.]; s_{ij} – timetable of the *j*-th vehicle.

The proposed approach to present timetable items in the models of public transport systems is depicted in the paper [13].

2.2 Model of Demand for Public Transport Services

Demand for services of a public transport we propose to present as a set of elements that describe passengers intending to use the bus service. Each element of this set could be described on the grounds of a number of parameters:

$$\pi_i = \left\{ \eta_i, \mu_i, \mathbf{P}_i, \tau_i \right\},\ \pi_i \in \mathbf{D},\ i = 1 ... N_D , \tag{5}$$

where π_i – the *i*-th passenger; η_i and μ_i – origin and destination stops of the *i*-th passenger trip, $\eta_i \in \mathbf{N}$, $\mu_i \in \mathbf{N}$; $\mathbf{P}_i$ – a set of transfer stops where the *i*-th passenger changes lines within his trip; τ_i – moment of time when the *i*-th passenger appears at the bus stop η_i in order to perform a trip [min.]; N_D – the total number of passengers using the public transport system [pas.].

In order to simulate demand for travels, it is quite convenient to divide all the elements of the set $\mathbf{D}$ into groups according to the stops of the public transport network where the trips begin:

$$\mathbf{D} = \bigcup_{j=1}^{N_L+1} \mathbf{D}_j \, , \tag{6}$$

where $\mathbf{D}_j$ – a group of passengers travelling from the *j*-th stop of the bus line:

$$\mathbf{D}_j = \{\pi_i : \eta_i = j\} \, . \tag{7}$$

The time interval ξ_j between the moments of passengers' arrivals at the *j*-th stop is a random variable. Thus, for each group $\mathbf{D}_j$, the parameters τ_i for the set elements could be defined on the grounds of realization of the random variable ξ_j, which describes intervals between appearances of passengers at the *j*-th stop:

$$\tau_i = \begin{cases} \tilde{\xi}_j, \; i = 1, \; \eta_i = j, \\ \tau_{i-1} + \tilde{\xi}_j, \; i > 1, \; \eta_i = j, \end{cases} \tag{8}$$

where $\tilde{\xi}_j$ – realization of the random variable of an interval between the passengers' appearances at the *j*-th stop [min.].

2.3 Obtaining Demand for Passenger Transfers

Demand for passenger transfers in the interchanging nodes could be defined on the grounds of the set $\mathbf{D}$ in the following way:

- for each π_i, the path from origin to destination stops is being defined; different criteria and methods for the path defining could be used here; the most simple approach here is to define the path with shortest distance within the bounds of the public transport network using Dijkstra's algorithm;
- for the obtained path, a set of transfer nodes $\mathbf{P}_i$, where a passenger changes public transport lines, is being determined: the intersection of the path stops set with the set of all the network interchanges should be defined, and for the obtained result the sequences of stops depending for the same line should be eliminated;
- for elements π_i with the non-empty set $\mathbf{P}_i$, the frequency of the transfer stops appearance is being calculated.

As a result, each transfer node of the public transport network will be characterized by the number of passengers, who change the line at this stop. For more advanced simulations, each transfer node could be characterized by a set of transferring passengers, which will allow researchers to investigate a structure of the transfer demand.

3 Software Implementation of the Demand Model

To model processes of the public transport systems functioning for solving scientific problems, the specialized library of base classes was developed. The classes' implementation was performed with the use of the Python programming language; it ensures compatibility of the developed software with the most popular environments for modeling of public transport systems (including Aimsun and PTV Visum). The developed code of the mentioned base classes is available in open access and could be downloaded at [14].

As the base classes, on the grounds of which simulation models of public transport systems should be implemented, the following classes are considered:

- *Net*: is used in order to develop the software implementation of a transport network model as an oriented weighted graph;
- *Node*: allows researchers to model points of the transport network as the graph nodes; the transport net points could be considered in a simulation model as software implementation of the public transport stops (transfer passenger nodes);
- *Link*: represents a software implementation of a link in a graph; the graph link could be used in simulation models for modeling segments of the road network or spans of the public transport lines;
- *Line*: could be used in order to model a public transport line; is defined for the software implementation of a road network as an object of the *Net* class;
- *Vehicle*: allows to model a vehicle as an element of the transport system model; is used for developing simulation models of the public transport lines;
- *Passenger*: is an abstraction for implementation of passengers as transport system elements; an object of this type is a unit used for description of demand for services of the public transport within the framework of a simulation model of the transport system.

To simulate parameters which describe the external factors influence on the transport system, in the proposed library the *Stochastic* class was developed. Implementation of the *Stochastic* class objects allows to model a random variable with the defined distribution and given numerical parameters.

The main class, on the base of which implementation of the transport system simulation model could be performed, is the *Net* class. An object of this type is presented in a simulation model in a single exemplar; it is used in order to form the road network model, to define the public transport lines, to generate demand for trips in the bounds of the transport network, and to run simulations of the transport system.

To run simulations, an object of the *Net* class should contain at least two objects of the *Node* type, at least one object of the *Link*, and at least one object of the *Line* class, but an empty set of the *Passenger* objects is allowed in the demand model.

In the process of simulation models implementation, the certain values are being assigned to the class fields of developed objects; to do this, the developed class methods and properties are used. Class methods are used in order to perform initialization procedures or to simulate the processes of the transport system operation. Class properties allow developers to calculate numeric characteristics of the simulated objects on the base of inner class values.

The procedures for simulations of passenger transfer nodes are implemented in the *Node* class. As far as the described library is available as an open code, additional functionality could be added to the proposed simulation tools.

4 Case Study: Modeling Demand for Passenger Transfers in Bochnia City

The described approach for transfer demand simulations was used on the example Bochnia (Lesser-Poland Voivodeship, Poland) public transport system. This case was chosen in order to illustrate the calculative abilities of the model and the respective software using a case which doesn't require many resources: Bochnia is a town of about 30 thousand inhabitants with 4 public transport lines. There are 43 bus stops at the public transport lines of the city where 8 bus stops are the interchanging nodes. More detailed characteristics of the public transport lines obtained from the official web-page www.bochnia.eu are presented in Table 1.

Table 1. Characteristics of the public transport networks of Bochnia.

Bus line ID	Route length [km]	Number of stops	Transfer stops
#1	8,1	16	sq. Pułaskiego, str. Karosek, str. Kazimierza W., str. 3 Maja, Dworzec PKP, str. św. Leonarda, str. Regis, str. Trudna
#3	9,9	22	sq. Pułaskiego, str. 3 Maja, Dworzec PKP, str. św. Leonarda, str. Regis, str. Trudna
#5a	6,6	16	str. Karosek, str. Regis
#9	17,7	38	sq. Pułaskiego, str. Kazimierza W., str. 3 Maja, Dworzec PKP, str. św. Leonarda, str. Regis, str. Trudna

Using the presented software, the model of the Bochnia's public transport network was worked out. For the obtained model, 100 runs of the demand simulation procedure were implemented, which yielded a sample for the transfers demand analysis. The obtained sample allows us to conclude that in average 53,4% of all the trips in Bochnia are performed with at least one change of a public transport line. According to simulation results, the share of transferring passengers is normally distributed random variable (Fig. 1), which was confirmed by chi-square Pearson's test.

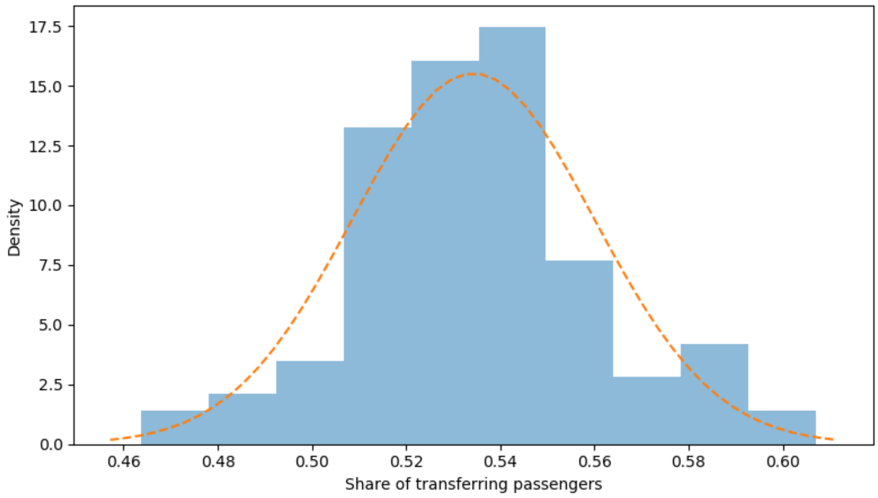

Fig. 1. Distribution of transferring passengers share in the total number of passengers

Due to the normal distribution of the transfers share, a sufficient number of observations was calculated for the significance level of 0,05: it appeared to be much less than the sample size; thus, it could be concluded that the transfer demand parameters evaluated on the grounds of the obtained sample should be considered as statistically significant with the confidence probability equal to 0,95. The calculated averages for the transfer demand parameters are shown in Table 2 (on the grounds of computer simulations, only 3 of 8 transfer stops have non-zero demand).

Table 2. Average parameters of transfers demand in Bochnia: simulation results

Demand parameter	Transfer node		
	sq. Pułaskiego	str. Kazimierza W.	str. Regis
Share of transfers in total passengers number	0,313	0,074	0,147
Share of transfers in total transfers number	0,585	0,138	0,276
Share of transferring passengers in the node	0,864	0,629	0,764

The obtained simulation results were checked on the grounds of the surveys with Bochnia public transport clients: the difference between obtained empirical and theoretical values does not exceed 10%.

5 Conclusions

The developed general mathematical model of a public transport system is a scalable tool which allows researchers to formulate a range of problems in the area of public transportation including the demand assessment tasks. The proposed software implementation of the model includes a number of methods providing simulations of the public transport operation processes.

The public transport simulations results obtained with the use of the developed tools allows researchers to estimate characteristics of demand on transfers in the public transport interchanges. This information is crucial initial data for solving a number of transportation management problems. However, it should be noted, that despite the high statistical significance of the obtained results, parameters of demand for passenger transfer must be re-checked by control surveys.

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