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Model of urban public transport network for the analysis of punctuality

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Analysis and modelling

ABSTRACT

Purpose: The building of mathematic model, which enable description of urban public transport network is a purpose of the article. This model will make the estimation of public transport quality according to analysis of punctuality easier.
Design/methodology/approach: The methodology of building the mathematical model of public transport network consists in application of the graph theory. The mathematical instruments make the description of real network easier.
Findings: The mathematical model of public transport network on the proper level of aggregation may be effective instrument, which assists the decision process. It makes an estimation of chosen coefficients that describe public transport quality easier.
Research limitations/implications: The research has been conducted only in the range of punctuality estimation for the sake of time-consuming and expenses. This limit also concerns database. It requires detailed description of public transport network to exact presentation in mathematic model.
Originality/value: To make the calculations more efficient, the relative database has been built. It includes geometric parameters of the sections and junctions in network. It also covers all necessary detailed data of analysed public transport lines. The database is the ground for estimating punctuality in research area.
Keywords: Engineering design; Public transport; Mathematical model; Database; Software application; Punctuality

1. Introduction

The research and analysis, which are conducted in the field of the public transport require building the networks. The network may be divided into some elements. In the case of research of public transport network they are: bus stops and the sections between them. The properties of these elements influence estimation of public transport functionality. The analysis of public transport punctuality is a perfect way of verification of the thesis.

Punctuality is one of the most essential coefficients from among synthetic criterions of reliability. It is a feature, which is very important for passengers, because it directly influences subjective passenger's estimate of organizer of transportation. It is an important factor of quality of public transport. Therefore the correctly modeling of public transport network is essential problem.

2. Modeling of the urban public transport network

The graph theory may be found application in building the model of network [1, 2]. There are many factors, which are necessary to take into consideration during the building the urban public transport model. Therefore it is essentially to combine two elements [3]:

- the network in the technical sense, which is meant as the existing (or planned) road system,
- the network in the functional sense, which is described through route of bus line and localization of bus stops.

The urban public transport network is received by putting the elements of technical network on the elements of functional network.

2.1. Technical network

The network in the technical sense describes the chosen road system. The degree of precision of the network model depends on its application. For example, the junctions may be represented by: towns, communication regions, intersections, inlets and outlets of intersections. According to the graph theory, the road system of communication lines in research region is described as:

$$G_T = (N_T, L_T) \tag{1}$$

where:
G_T – the graph, which describes the structure of the network in the technical sense
N_T – the set of the junctions, which describes the road system in research region,
L_T – the set of the sections, which describes the road system in research region,

In accordance with this description, the technical network of the public transport may be written as:

$$S_T = \left(G_T, \left\{f_T^i\right\}, \left\{h_T^j\right\}\right) \tag{2}$$

where:
f_T^i - the set of technical factors of junctions in network S_T,
h_T^i - the set of technical factors of sections in network S_T.

2.2. Functional network

The network in the functional sense describes the chosen elements of communication lines. The junctions are represented by the bus stops, and the sections - by the connections between them. According to the graph theory, the structure of the lines on the research region is described as:

$$G_F^d = \left(N_F^d, L_F^d\right) \tag{3}$$

where:
G_F^d - the graph, which describes the structure of the line *d*,
N_F^d - the set of junctions that corresponds with bus stops for the bus line *d*,
L_F^d - the set of the sections between neighbouring bus stops for the bus line *d*.

The structure of functional network may be described by creating the multitude sum of the graphs:

$$G_F = \bigcup_{d \in D} G_F^d \tag{4}$$

$$G_F = \left(N_F = \bigcup_{d \in D} N_F^d, L_F = \bigcup_{d \in D} L_F^d\right) \tag{5}$$

where:
G_F – the graph, which describes the structure of the functional network in research area
N_F – the set of junctions that corresponds with bus stops for the all bus lines in research area
L_F – the set of the sections between neighbouring bus stops for all communication lines in research region

In accordance with this description, the functional network of the public transport may be written as:

$$S_F = \left(G_F, \left\{f_F^i\right\}, \left\{h_F^j\right\}\right) \tag{6}$$

where:
f_F^i - the set of functional factors of junctions in network S_F,
h_F^i - the set of functional factors of sections in network S_F.

2.3. The proper model of public transport network

In order to build the proper public transport network it is necessary to compilate the functional network and technical one according to specific rules. In this article the model of the bus network is presented.

It has been assumed that in the graph, which describes the public transport network, the technical junctions and the functional ones are also the junctions of the proper network:

$$N_A = N_T \cup N_F \tag{7}$$

In order to create a set of section for the bus network L_A the following symbols have been introduced:
- for the technical network:

- individual junctions as $n_i^T \in N_T$

- individual sections as $l_i^T = \left(n_{i_1}^T, n_{i_2}^T\right)$

where $l_i^T \in L_T$,
- for the functional network:

- the consecutive junctions on the line as $n_i^F \in N_F$

- the consecutive sections between the bus stops as $l_i^F = \left(n_i^F, n_{i+1}^F\right)$

where $l_i^F \in L_F$

Additionally it has been assumed, that every bus stop is located on the section between junctions (not at the intersection). Therefore the assignment $f_0 : N_F \rightarrow L_T$ may be defined. It describes localization of the bus stop n_i^F with relation to elements of road network l_j^F. Function $f_0\left(n_i^F, l_j^T\right)$ is of the following values:

- 0 - when the section $l_j^T \in L_T$ does not include the junction (bus stop) n_i^F,

- 1 - when the section $l_j^T \in L_T$ includes the junction (bus stop) n_i^F

The set of the section for the bus network L_A has been created according to the following rules:

1) $\exists_{l_j^T \in L} \forall_{n_i^F \in N_F} f_0(n_i^F, l_j^T) = 0 \Rightarrow l_j^T \in L_A$

It means that the set of the sections L_A covers all sections of the road network l_j^T, where there isn't any bus stop.

2) $\exists_{\substack{n_i^F \in N_F \\ n_{i+1}^F \in N_F \\ l_j^T \in L_T}} \left(f_0(n_i^F, l_j^T) = 1 \wedge f_0(n_{i+1}^F, l_j^T) = 1\right) \Rightarrow l_i^F \in L_A$

It means that the set of sections L_A covers all sections of functional network l_i^F, which connect neighbouring bus stops on the same section of the road l_j^T.

3)

$\exists_{\substack{n_{i-1}^F \in N_F \\ n_i^F \in N_F \\ l_j^T \in L_T}} \left(f_0(n_{i-1}^F, l_j^T) = 0 \wedge f_0(n_i^F, l_j^T) = 1\right) \Rightarrow \left(n_{j_1}^T, n_i^F\right) \in L_A$ -

It means that the set of sections L_A covers sections, which connect the initial junction $n_{j_1}^T$ of section l_j^T of the road network and first bus stop n_i^F on this section.

4)

$\exists_{\substack{n_i^F \in N_F \\ n_{i+1}^F \in N_F \\ l_j^T \in L_T}} \left(f_0(n_i^F, l_j^T) = 1 \wedge f_0(n_{i+1}^F, l_j^T) = 0\right) \Rightarrow \left(n_i^F, n_{j_2}^T\right) \in L_A$

It means that the set of the sections L_A covers the sections, which connect the last bus stop n_i^F on the section l_j^T of the road network and final junction $n_{j_1}^T$ of this section.

After building the structure of the graph $G_A = (N_A, L_A)$ it is necessary to describe functions, which are characteristic to the both types of junctions and connections between them. The bus network is described as:

$$S_A = \left(G_A, \{f_A^i\}, \{h_A^j\}\right) \quad (8)$$

where:

f_A^i - the set of functions of junctions for network S_A

h_A^j - the set of functions of sections for network S_A

Punctuality is one of the characteristic functions that helps to estimate public transport quality.

3. Estimation of punctuality

Punctuality is a compatibility with the bus schedule. Estimation of several coefficients, which directly or indirectly influence punctuality, is necessary to conducting complex punctuality analysis [12].

3.1. Deviation

Deviation is a difference between schedule departure time t_r for every course and real departure time t_e for every course at specific point on the route of bus line [11].

$$d = t_r - t_e \quad (9)$$

The positive value of deviation represents acceleration and the negative one – delay.

3.2. Coefficient U – arduousness of unpunctuality

Arduousness of unpunctuality expresses excessive waiting time. It is a difference between delay for a chosen deviation and delay for an ideal punctuality [11]. The value of the coefficient U is estimated for individual cases of deviation [11] as:

$$U = \begin{cases} -1{,}3 \cdot d - 1{,}6 & d \le -2 \\ -0{,}5 \cdot d & -2 \le d \le 0 \\ 0{,}162 \cdot h \cdot d & 0 \le d \le 6 \\ 0{,}97 \cdot h & d \ge 6 \end{cases} \text{ for} \quad (10)$$

where:

d – deviation from bus schedule, which is defined in minutes („+" means acceleration, „-" means delay)

h – average interval between vehicles [min]

3.3. Coefficient Q – degree of punctuality

The fuzzy set is proposed to use as a measure of punctuality. It is described with the help of the affiliation function Q.

The value of coefficient Q may be estimated from [10]:

$$Q_i = \begin{cases} 0 & d_i \le d_1, d_i > 2 \\ \dfrac{d_i - d_1}{d_2 - d_1} & d_1 \le d_i \le d_2 \\ 2 - d_1 & 1 \le d_i \le 2 \\ 1 & d_2 \le d_i \le 1 \end{cases} \text{ for} \quad (11)$$

where:

d_i – value of deviation

$$d_1 = -\frac{2h + 150}{45} \qquad d_2 = -\frac{h + 75}{45}$$

h – average interval between arrivals.

4. Software application

To make the calculations more efficient, the relative database has been built. It enables to introduce the values, which are necessary to describe the problem and calculate the quality parameters of public transport. The database has been built in Delphi. The software enables to create applications [4, 5, 6]. The build-in SQL system makes simple transfer data from the database possible [7,8]. More information about building database and applications has been presented in publications [13, 14, 15].

The application consists of three basic forms, which include:

- technical characteristic functions of road network sections
- technical characteristic functions of road network junctions.

The examples of the technical parameters are:

- for the sections:
- number of section:
- number of road
- length and width of section
- for the junctions:
- number of intersection
- number of inlet and outlet

The application has been extended for additional form, which schematically presents the structure of the network [12]. The view of this form has been presented on the Figure 1:

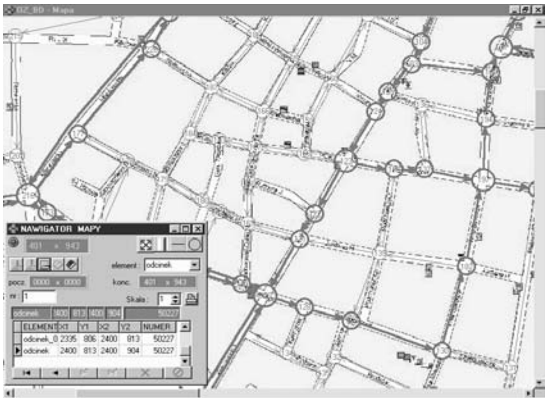

Fig. 1. The view of the form, which schematically presents the structure of the network.

The analysis of punctuality on the basis of deviation estimation has been presented on the Figure 2.

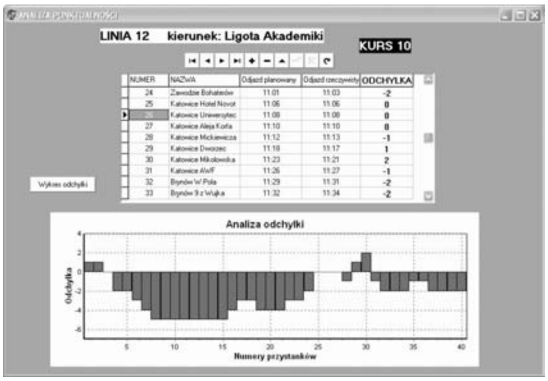

Fig. 2. The view of the form, which presents the analysis of punctuality.

5. Conclusions

Every action, which leads towards improvement of public transport quality should be preceded by analysis of many factors. The network model and the software application are effective instruments, which assist the decision process.

The connection of both types of networks (technical and functional) is essential to detailed analysis of public transport quality. It is particularly necessary during the analysis of punctuality and travel time, where the waist time on the bus stop, the awaiting time on the intersections and waist time on the route of bus line should also be taken into consideration.

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