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Benchmark of the traffic congestion in electrical transport by means of multi criteria decision analysis

***Abstract**. Congestion of the road traffic is an important aspect related to the issues of energy consumption in public transport. Due to the multiattribute nature, the expression of traffic congestion in a quantitative valueis difficult to achieve. The article presents a method of estimation of traffic congestion by means of a multiattribute decision analysis.*

***Streszczenie.** Kongestia ruchu drogowego jest istotnym elementem związanym z zagadnieniami energochłonności transportu miejskiego. Ze względu na wieloatrybutowy charakter, wyrażenie kongestii ruchu drogowego w sposób ilościowy jest trudne do realizacji. W artykule przedstawiono sposób określenia kongestii ruchu drogowego za pomącą wieloatrybutowej analizy decyzyjnej. (**Ocena kongestii ruchu drogowego w trakcji elektrycznej za pomocą wielokryterialnej analizy decyzyjnej**).*

Keywords: supply system, traction substation, trolleybuses, PCA, DEA
Słowa kluczowe: trolejbusy, układ zasilania, podstacje trakcyjne, analiza głównych składowych, metoda obwiedni danych

Introduction

One of the basic types of research and analysis executed in various branches of science is comparative analysis. In this type of research we have to do with many objects which are characterized by means of various parameters, often expressed in different physical units. The aim of multidimensional comparative analysis is to find dependencies between specific objects parameters and grouping them on the basis of similarities.

The term multidimensional comparative analysis covers a wide scope of statistical methods, which allow for grouping objects with regard to their features (e.g. cluster analysis), finding principal factors characterizing objects (factor analysis, principal components analysis), estimation of specific factors essentiality (hierarchic analytical processes), and accumulation of factors in order to estimate specific objects – creating complex indexes (DEA, TOPSIS) [2, 3, 9, 10]. These methods are applied mainly in economy and psychology research areas. The objective of this article is to indicate a possibility to apply multidimensional comparative analysis method also in the technical sciences area. The subject of analysis is a trolleybus network power supply system, for which a multidimensional analysis of electric-motion parameters has been conducted.

Nowadays there is a visible growth in the number of vehicles on public roads. The congestion becomes a significant problem of the cities, which also influences public transport. Therefore, the analysis of the road traffic intensity is an important issue. The main goal of the research was to develop the benchmark of the traffic congestion in electrical public transport.

In the first part of the paper Principal components analysis was used to select the main factors which characterize the supply system of urban transport. In the second part there were assigned values of congestion benchmarks by means of the Data envelopmentanalysis.

Trolleybus power supply system

Trolleybuses are trackless vehicles, thus what it entails is that a trolleybus traction network serves at the same time as the power supplying and the return one. It is composed of two parallel wires, as a standard hung at the height of 5,5 m over the street level. Usually the wire which is right to the travel direction (outer) is a wire of a lower potential (minus), and a left wire (inner) is a wire of a higher potential (plus).

A trolleybus traction network is powered from traction substations placed in 2 – 5 km distances. Traction substations are powered from a public 6 – 35 kV energy network. In substations this voltage is decreased and straightened. Rated voltage of traction network power supply is 600 or 750 V.

Analogically to the rail or tram traction the trolleybus traction network is divided into power supply sections. Each section is powered by a dual wire feeder from a traction substation. The tracks of the traction network for both travel directions are constantly connected with each other by means of diagonal equalizing links (so called equalizing bridges), located at every 300 – 500 metres.

A characteristic feature of a trolleybus power supply system is a considerable changeability of specific feeders loading. It is a consequence of an influence of traffic congestion on the running of trolleybuses, the effect of which loading of the trolleybus power supply system has a random and difficult to forecast character. In reference to the above statistical analysis methods constitute a perfect tool for the analysis of city traction power supply systems and allow for finding dependencies between numerous factors having impact on the power supply system operation [4, 5, 6].

The subject of analysis

Trolleybus transport in Gdynia was first launched in 1943. Three traction substations “Grabówek”, “Dworzec” and “Redłowo” were built to power the first line. After the end of the Second World War there followed an intensive development of this means of transport. In 1948 – 49 there were put to start two traction substations “Sopot” and “Sopot II” designed to supply power to a suburban line Gdynia – Sopot, existing objects being also expanded. In the beginning of the 1970s the first shift-make substation “Cisowa” has been put in operation. 1980s brought the next period of trolleybus network intensive expansion, at the time of which there were built further two subtations “Chwaszczyńska” and “Północna” (to replace the makeshift substation “Cisowa”). In 2010 there began a modernization of the traction network power supply system, in the framework of which there were built five new traction substations: “Kielecka”, “Wielkopolska”, “Sopot Reja”, “Plac Konstytucji” and “Wendy”, as well as existing objects were modernized. This investment was to increase reliability of existing system and create a basis for further development of trolleybus transport in Gdynia – substations “Kielecka”, “Sopot”, “Sopot Reja”, “Redłowo” and “Wielkopolska” are predicted as to power new planned trolleybus routes.

The subject of analysis in the article hereby is 19 power supply sections forming Gdynia trolleybus network. The traction network is made with a 100 mm^2 Cu wire, and sections are powered from section substations with cable 625 mm^{2}Al feeders. The measurements have been made on five traction substations. Currently in Gdynia there are exploited only 12-metre trolleybuses and the majority of the stock (ca. 70%) is equipped with propulsion systems with energy-electric steering.

Principal components analysis

In numerous physical processes there exist correlations between initial variables [7. 8], which enables replacement of initial variables correlated each other by a lower number of variables at a slight loss of initial data variability scope. The principal components analysis is about transforming observable initial data into new, non-correlated and unobservable variables called principal components [1]. Variations from two following principal components, and what follows, their information resources are smaller and smaller. The sum of initial variables variations is equal to the sum of main factors variations, so this transformation does not cause the initial data loss. However in practice already the first few main factors contain majority of initial variables information resources, as a result of which a reduction in the number of factors describing a process is possible with a slight loss of initial data [1].

The idea of principal components method can be described as:

$$V = WX \tag{1}$$

where: X – initial data matrix, V – principal components matrix, W – own values matrix of covariances matrix of initial variables matrix X. The number of principal factors may be decreased by the usage of n first matrix vectors W

$$V' = W_n X \tag{2}$$

In order to determine the number n of principal components one may apply the criteria of:

- own value: principal components which own value is bigger than 1 undergo an analysis,
- a diagram of eigenvalues: it is a graphic method, the choice of the principal components number is made on the basis of a subjective estimation of a eigenvalues graph, i.e. the graph of specific components own values,
- the extent of explained variance: the value of components number n depends on the required level of initial variables variances explanation by principal factors,
- the criterion of principal components essentiality, in which there is verified a hypothesis about a thorough enough explanation of correlations between initial variables.

The analysis of measurement data

The aim of the analysis is to detach from the set of parameters principal components power supply sections, which describe electric-motion parameters of power sections [4, 5, 6].

The initial variables are:

- the average current of the power supply section I_{av},
- the maximum current of the power supply section I_{max},
- the length of the power supply section l,
- the time of travel on the power supply section t,
- a trolleybus traffic interval Δt,
- the average speed v_{av},
- the average number of trolleybuses on the power supply section n_t,
- the number of stops the power supply section n_z.

The measurements of the feeders' currents were performed by means of HIOKI 8807 recorder placed in the traction substation. This recorder was plugged to the shunt of the traction substation negative pole feeder. The records were made at 0,75 s intervals. Other factors values were indicated on the basis of timetables. The table 1 presents power supple sections data accepted for the analysis.

Table 1. Electric-motion data of analyzed power supply sections

SectionNo.	Section name	I_{av} [A]	I_{max} [A]	l [m]	t [min]	Δt [min]	v_{av} [km/h]	n_t	n_z
1	Cisowa	150	825	1000	3	6	20	1	2
2	Gazownia	124	925	1400	3	5	28	1,2	3
3	Wiejska	142	1025	1300	3	5	26	1,2	3
4	Kcyńska	182	1050	1500	5	5	18	2	6
5	Pustki	74	428	2600	6	15	26	0,8	6
6	Leszczyńki	270	1367	1300	4	3	19,5	2,7	4
7	Grabowek	186	1500	900	3	3	18	2	3
8	Mleczarnia	211	1275	1200	3	3	24	2	3
9	Kołłątaja	236	1075	1300	6	4	13	3	5
10	10 lutego	94	854	900	3	7	18	0,9	4
11	Świętojańska	271	1400	1120	3	3	22,4	2	6
12	Wzgórze	149	1167	600	3	2	12	3	5
13	Redłowo	273	1433	2500	7	4	21,4	3,5	6
14	Kack	189	1300	1280	4	4	19,2	2	5
15	Wielkopolska	83	733	1120	4	12	16,8	0,7	5
16	Wajdeloty	120	1013	1700	4	4	25,5	2	4
17	Źródło Marii	149	1360	1700	4	4	25,5	2	6
18	Nowowiczlińska	174	1181	1500	5	5	18	2	4
19	Rdestowa	105	728	1300	3	5	26	1,2	3

The calculations were made in Statitica programme. The Fig no. 1 shows the diagram of relative value of clarified initial data variance in relation to the principal components number. In the picture no. 2 there is a rubble's diagram, where it is highlighted to what extent specific principal components clarify initial variables.

The first initial variable PC1 clarifies 43% of initial data, two first components PC1 and PC2 clarify 74% altogether, three components clarify 89%, and four components - 94%. Applying own value criterion (for the analysis one should assume the principal components, which own value in the correlation matrix V is bigger than 1) three principal components PC1, PC2 and PC3 were selected. The values of these principal components are presented in table 2. They also constitute linear correlation values between initial and principal variables. The fig. 3 depicts a graphic representation of the principal components values in the coordinates axes PC1 and PC2. The length of the vector symbolizing a specific initial variable shows the extent of its clarification by the component PC1 and PC2, and proximity to specific axes of coordinates system informs us whether a specific variable data is explained to a greater extent by PC1 or PC2 component.

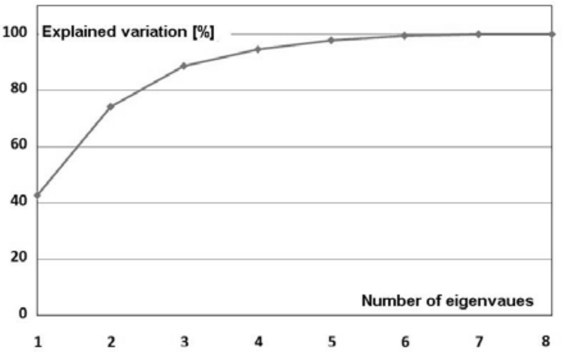


Fig. 1. The percentage of clarified initial variables variance in relation to the principal components number

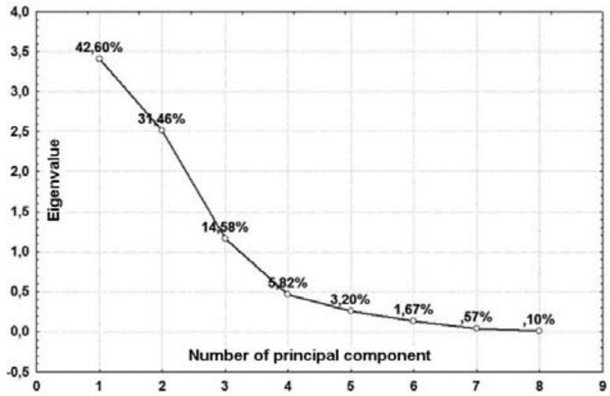


Fig. 2. A diagram of eigenvalues

In the table 2 initial variables clarified by specific principal components were highlighted in bold type. It is assumed that initial variable is clarified by specific principal component if the value of coefficient is bigger or equal to 0,7.

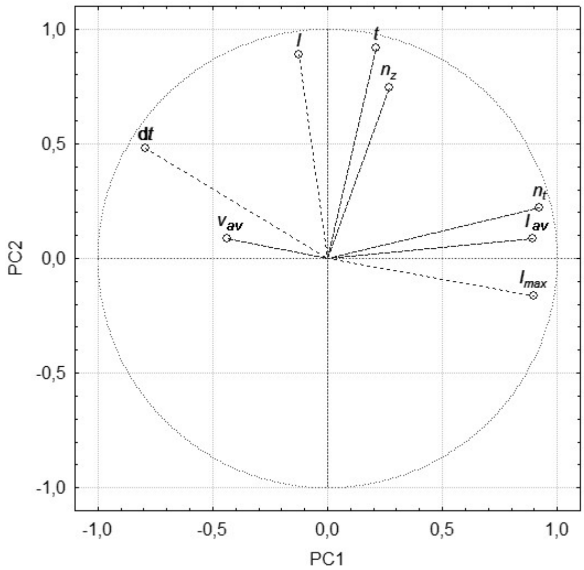
Table 2. The values of principal components coefficients

Initial variable	PC1	PC2	PC3
I_{av}	**0,89**	0,09	0,16
I_{max}	**0,90**	-0,16	0,22
l	-0,12	**0,89**	0,41
t	0,21	**0,92**	-0,12
Δt	**-0,79**	0,48	-0,25
v_{av}	-0,44	0,09	**0,88**
n_t	**0,92**	0,22	-0,02
n_z	0,27	**0,75**	-0,25

The principal component PC1 clarifies:
- the average current of the power supply section I_{av}
- the maximum current of the power supply section I_{max},
- a trolleybus traffic interval Δt,
- the average number of trolleybuses on the power supply section n_t.

The principal component PC2 clarifies:
- the length of the power supply section l,
- the time of travel on the power supply section t,
- the number of stops the power supply section n_z.

The principal component PC3 clarifies the average speed v_{av}.



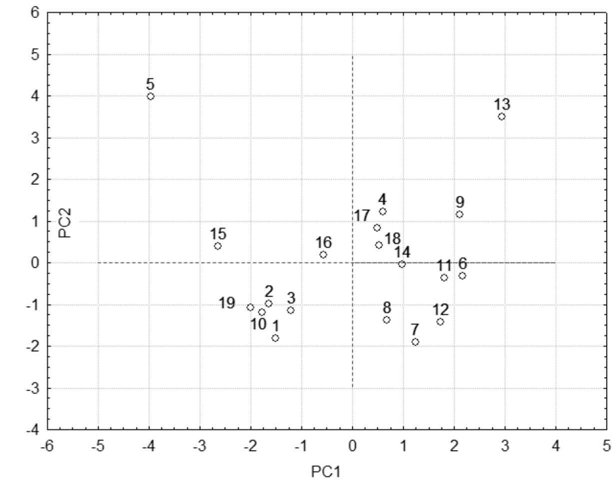
Pic.3. The configuration of points representing the principal components coefficients in the two first factor axes system

Basing on the conducted grouping of the initial variables one may state that:
- component PC1 contains information connected with the intensity of the trolleybus traffic: bigger PC1 value means greater traffic intensity,
- component PC2 contains information about geographic parameters of the power supply sections: bigger PC2 value means bigger power supply section size,
- component PC3 on the average trolleybus speed.

PC3 conveys information about only one initial variable, due to which it will be omitted in the further analysis. It should be noticed that variable Δt is negatively correlated with PC1 component, bigger trolleybus running interval means smaller traffic intensity.

Pic. 4 shows the diagram of points representing power supply sections in the two first factor axes system. The location of the points on the diagram attests to a value and relation between specific principal components values.

Most detached from other points are the power supply sections no. 5 and 13, corresponding to sections Pustki and Redłowo. Redłowo is a section of the greatest values of PC1 and PC2 components. In Gdynia trolleybus network it is one of the longest and most loaded sections as far as traffic is concerned. On the opposite side of coordinate system in relation to PC2 axis there is located the point corresponding to Pustki section. This location can be clarified by similar geometric parameters of Pustki and Redłowo sections, yet diametrically lower traffic load of Pustki section in relation to Redłowo section. Among other sections one may distinguish three groups:
- the group including sections 1, 2, 3, 10, 19: Cisowa, Gazownia, Wiejska, 10 lutego, Rdestowa. They are characterized by both little geometric size and low traffic intensity;
- the group including sections 7, 8, 12: Grabówek, Mleczarnia, Wzgórze. These are short sections yet of high traffic intensity;
- the groupi ncluding sections 4, 6, 9, 11, 14, 17, 18: Kcyńska, Leszczynki, Kołłątaja, Świętojańska, Kack, Źródło Marii, Nowowiczlińska. They are characterized by average geometric size, but also high traffic intensity.



Pic. 4. The diagram of points representing power supply sections in the two first factor axes system

On the basis of the conducted analysis it can be claimed that the power supply sections 13 (Redłowo) and 9 (Kołłątaja) have too heavy traffic load and geographic parameters in relation to other trolleybus network sections. A reconfiguration of the way they are powered via dividing into smaller parts it is thus highly recommended. Inversely the sections of the group 1, 2, 3, 10, 19 (Cisowa, Gazownia, Wiejska, 10 lutego, Rdestowa) from a geographic and traffic wise point of view are loaded to a slight extent, thus it is possible to increase the frequency of running vehicles on them. One should notice, however, that the analysis does not take into consideration the values of voltage drops in the traction network, which appear to be a limitation to increasing the vehicles traffic in some cases.

Load flow of the supply system

From the first point of view of the methods of trolleybus supply system analysis the average I_{av} and maximum I_{max} values of the supply section current can be defined as a function of the electric-motion parameters. These parameters are: the number of trolleybuses crossing the supply section per one hour *n*, the length of the supply section *l* and the average number *N* of ~~the~~ vehicles on the supply section. It can be expressed as:

$$I_{\acute{s}r} = \frac{l \cdot n \cdot e}{U_{tn}} \tag{5}$$

$$I_{max} = I_{\acute{s}r} \cdot f(N) \tag{6}$$

where: *e* – the average energy consumption of one trolleybus per 1 km, f(*N*) – function of the peak factor. In real terms the load flow currents depend not only on electric-motion parameters but also are influenced by the congestion of ~~the~~ traffic. Consequently, the relation between the electrical load flow of the supply system and electric-motion parameters can be used as an indicator of the road traffic congestion.

Referring to the table 2, the motion parameters of the supply sections can be grouped into 3 principal components. Nevertheless, component PC3 is not directly related with the load flow of the supply system. The value of PC1 can be expressed by the trolleybus traffic interval Δ*t*, the value of PC2 can be expressed by the length of the power supply section *l*. These parameters were chosen because they can be easily and clearly set based on the timetables and parameters of the line.

In order to find relations between the electrical load flow of the supply system and motion parameters there was used the Data envelopment analysis.

Data envelopment analysis (DEA)

The DEA model is used to estimate and analyze efficiency of multiple units and multiple outputs, which can have very different units of measurement. A common measure for relative efficiency is:

$$\text{Efficieny} = \frac{\text{weighted sum of outpusts}}{\text{weighted sum of inputs}} \tag{7}$$

For each analyzed option the efficiency is defined as a ratio of the weighted sum of outputs to the weighted sum of inputs [13]. In the DEA model for a particular option in the data set of *n* options (*j*= 1,2,…,*n*) a h_o value is determined using a set of the best indicator weights u_r *and* v_i which h_o value of each option satisfies the restrictions. Each option is described by *r* values, $v_1 – v_r$ ale the inputs and $u_1 – u_r$ are the outputs:

$$\max h_o(u,v) = \frac{\sum_r u_r y_{ro}}{\sum_i v_i x_{io}} \tag{8}$$

$$s.t. \ \frac{\sum_r u_r y_{rj}}{\sum_i v_i x_{ij}} \le 1, \quad j = 1,2,\dots,n \tag{9}$$

$$u_r, v_i \ge 0, \ \text{ for all } i \text{ and } r \tag{10}$$

In other words, DEA is a linear programming model, where each entity selects a set of weights which are most favorable for itself to give a standardized efficiency score (between zero and one). The DEA model (8-10) allows to choose "the best" set of weights to use.

The analysis of the load flow by DEA

In the subject of analysis the inputs will be the motion parameters of the network: Δ*t* and *l*.The values of load flow I_{av} and I_{max} will be taken as the output parameters. The efficiency estimated by DEA implies how big is the load flow of each supply section in relation to the motion parameters. A bigger value of efficiency means bigger values of the supply section currents compared to motion parameters, consequently it means worse traffic conditions (stronger congestion). In the table 3 there are presented the results of the calculations, *h* means the values of efficiency.

Table 3. The inputs, outputs and the values of supply sectionsefficiency

No.	Section name	I_{av} [A]	I_{max} [A]	*l* [km]	Δ*t* [min]	*h*
1	Cisowa	150	825	1	6	1
2	Gazownia	124	925	1,4	5	0,64
3	Wiejska	142	1025	1,3	5	0,72
4	Kcyńska	182	1050	1,5	5	0,55
5	Pustki	74	428	2,6	15	0,17
6	Leszczyńki	270	1367	1,3	3	1
7	Grabowek	186	1500	0,9	3	1
8	Mleczarnia	211	1275	1,2	3	1
9	Kołłątaja	236	1075	1,3	4	0,83
10	10 lutego	94	854	0,9	7	0,55
11	Świętojańska	271	1400	1,1	3	1
12	Wzgórze	149	1167	0,6	2	1
13	Redłowo	273	1433	2,5	4	0,64
14	Kack	189	1300	1,3	4	0,68
15	Wielkopolska	83	733	1,1	12	0,38
16	Wajdeloty	120	1013	1,7	4	0,51
17	Źródło Marii	149	1360	1,7	4	0,48
18	Nowowiczl.	174	1181	1,5	5	0,65
19	Rdestowa	105	728	1,3	5	0,52

On the basis of a performed DEA analysis there can be found relationships between the intensity of the road traffic and the value of calculated efficiency. The highest values of efficiency *h* are visible for sections Cisowa, Mleczarnia, Grabówek, Leszczynki, Wzgórze, Świętojańska. This result can be easily explained on the basis of traffic observation. The sections Mleczarnia, Grabówek and Leszczynki are localized on the Morska street, which is one of the most important and most crowded streets in Gdynia. The sections Świętojańska and Wzgórze ale placed in the very center of the city with many stops and crossings. Also Cisowa section can be characterized as a section with high intensity of the trolleybus traffic as there is localized one of the biggest trolleybus stations. On the other hand the lowest value of efficiency is reached in Pustki section which is localized in the suburbs of the Gdynia.

Conclusions

The analysis conducted above proves the utility of multidimensional comparative analysis method in estimating urban traction power supply systems. By highlighting the principal factors it has been indicated that the element which has an influence on specific power supply sections load is vehicles traffic intensity. It has been shown that by using the findings of principal components analysis it is possible to estimate the strengths and weaknesses of urban traction power supply system.

By means of the Data envelopment analysis there was created a numerous benchmark of the traffic congestion in the electrical traction, which provides a quantitive assessment of a complicated phenomenon.

An impact of road traffic congestion and further, difficult to analyze factors causes the character of the urban traction power supply system random and hard to predict. As a result classic analytical methods are not effective in estimating energetic urban traction systems. Multi-attribute decision methods allow for the analysis of various, not connected with each other and difficult indicate elements having influence on power supply system operation. The subject of further analysis will be the usage of multidimensional comparative analysis method in creating an integrated indicator, which shows electric-energetic urban traction system condition . It is also being planned to implement multidimensional methods supporting decision-making in other areas of technical sciences [10, 11].

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