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# Application of principal component and hierarchical cluster analysis in classifying defects of trolleybuses

***Abstract**. The failure rate of vehicles is a relevant task, which is strictly connected with the reliability of transportation systems. Methods of data analysis allow us to find similarity and differences between failure rates of several parts of trolleybuses. This paper deals with the statistic of failure of trolleybuses from the municipal transport company of Gdynia (Poland).*

***Streszczenie.** Częstotliwość występowania awarii pojazdów jest ważnym zagadnieniem związanym z niezawodnością systemów transportowych. Metody wielowymiarowej analizy porównawczej umożliwiają znalezienie wspólnych cech I różnic pomiędzy częstotliwością występowania uszkodzeń poszczególnych podzespołów trolejbusów. W artykule przedstawiono awaryjność niezawodności trolejbusów eksploatowanych w Gdyni (**Zastosowanie analizy głównych składowych i analizy skupień w klasyfikacji uszkodzeń trolejbusów**)*

**Keywords**: trolleybuses, traction drives, failure rate, PCA, cluster analysis
**Słowa kluczowe**: trolejbusy, napędy trakcyjne, awaryjność, analiza głównych składowych, analiza skupień

## Trolleybus system in Gdynia

The trolleybus system in Gdynia exists for 70 years and during this time it became an important part of the city [2]. The first line was opened on the 18th of September 1943 and connected the city center with the Chylonia municipality. Over time, trolleybuses began to run on new lines leading to Orłowo, Sopot, Mały Kack, Cisowa, Oksywie Dolne. The greatest development in the history of trolleybus transport in Gdynia was in the years 1958-1971. Then the trolleybus lines were built to Oksywie Górne and then to the shipyard. After a period of prosperity came a time of crisis, the operation of several lines was suspended. However, since the year 1979, improvements slowly began. Trolleybuses were restored to the former lines, and new sections of the network were built. The first one was opened in 1985 along the Czerwonych Kosynierów street (now Morska street) to the new Sibelius Cisowa terminus, then in 1989 another one was extended from Mały Kack trolleybus traction on Karwiny. In 1996 a new line to Pustki Cisowskie was opened. The next two routes to Dąbrowa and Kacze Buki were opened in 2005-6 with the financial support from the European Union.

## Trolleybus transport

The trolleybus is a mode of public transport which combines attributes of tramways and buses. From the mechanical and passenger point of view it is similar to a bus, because trolleybuses uses public streets and the most modern trolleybuses are built on the diesel bus chassis. But, in contrast to the diesel bus, trolleybuses are run by electrical energy received from overhead cathenary – similar to trams. Trolleybus catenaries consists of two parallel wires with DC voltage 600 or 750 V. Usually trolleybuses are equipped with one traction motor with a power of 100 – 250 kW, in some long (18 m – 24 m) vehicles there are two motors. Trolleybus traction propulsion systems can be divided into three groups [3, 4]:

### *First Generation propulsion systems*

This is the oldest type of trolleybus drive, where a DC traction motoris used. The speed of the vehicle is moderated by a resistor where the values of resistance are changed by contactors. The very high losses of energy are the main disadvantage of this solution, but due to its very simple construction, it is still in use in plenty of vehicles.

### *Second generation propulsion systems*

The 70's and 80's of the XX century brought the rapid development of high power semiconductors. It made possible the elimination of the resistor and the implementation of lossless speed regulation. The impulse drive with a DC traction motor was constructed. The main part of it is the DC/DC converter, called "chopper", which changes the supply voltage theoretically without losses.

### *Third generation propulsion systems*

The application of the DC/DC chopper enables to significantly increase the energy efficiency of traction drives, but there still existed another problem: high production and maintenance costs of DC motors caused by low popularity of this kind of motors in other branches of industry. Therefore, attempts were made to the use the popular three phase asynchronous AC motors. This goal was achieved by using a DC/AC traction inverter, which converts DC voltage into AC voltage supplied to the asynchronous traction motor.

### *Auxiliary devices*

An important task is supplying auxiliary devices (non-traction), like lighting, opening and closing of doors, air condition etc. In diesel buses these devices are supplied from an alternator which is run by the diesel engine. In trolleybuses a converter is used to supply non-traction equipment, which changes input 600 – 750 VDC voltage into lower voltage: 24 VDC and, optionally, 400 VAC. In case of older vehicles a rotation converter built from a DC 600 – 750 V motor rotating a 24 V DC generator is used. In modern trolleybuses a static converter consisting of a DC/AC inverter, transformer and output rectifier is used.

## Type of trolleybuses in Gdynia

Nowadays the Trolleybus Transport Company of Gdynia (PKT) owns 85 trolleybuses which are categorized in six main types. The summary of the all vehicles is presented in table 1. The trolleybus Saurer is a historical vehicle, so it will not be mentioned in further analysis. Also the trolleybus Mercedes-Benz O530N, due to its short time of operation, will be skipped.

### *Jelcz PR110 E / 120 ME (J)*

In the late 70's and 80's of the XX century attempts to build a trolley bus from the polish body Jelcz and electrical equipment of the scrapped trolleybuses Škoda 9 Tr began in Gdynia. They were finished and, therefore, in the years from 1980 to 1982, in Gdynia, 20 trolley economic way Jelcz 110th PR were built. Based on Gdynia experiences, KPNA Słupsk began production of PR 110 E trolleybuses. They are equipped with rheostatic contactor electrical equipment and a DC traction motor with powerof 110 kW. ME Jelcz 120 trolleybuses were to develop vehicles Jelcz PR 110 E which are different with their new styling along with a modified layout of the interior. Electrical equipment is the same as in the Jelcz PR 110 E. Nowadays these trolleybuses are planned to be withdrawn from service.

Table 1. List of the trolleybus fleet in PKT Gdynia

| Typ | Producer the electric equipment | Years of production | Generation of the traction drive | Type of the auxiliary supply converter | Number of vehicles |
|---|---|---|---|---|---|
| Saurer 4TIILM | BBC (Switzerland) | 1957 | 1 th | static | 1 |
| Jelcz PR 110 E / 120 ME (J) | Kapena Słupsk (Poland) | 1986-2000 | 1 th | rotating | 8 |
| Jelcz 121 MT | IEL Warszawa (Poland) | 1998 | 2 th | static | 1 |
| Solaris Trollino 12 T (SI) | IEL Warszawa (Poland) | 2001 | 2 th | static | 4 |
| Solaris Trollino 12 AC (SC) | Cegelec (Czech Republic) | 2002-2008 | 3 th | static | 16 |
| Solaris Trollino 12 M (SM) | Medcom Warszawa (Poland) | 2009- 2012 | 3 th | static | 27 |
| Mercedes-Benz O 405 N (M) | PKT Gdynia (Poland) | 2004-2009 | 1 th | rotating | 23 |
| Mercedes-Benz O 405 NE (ME) | Enika Łódź (Poland) | 2009- 2010 | 3 th | static | 5 |
| Mercedes-Benz O 530 N | Enika Łódź (Poland) | 2012 | 3 th | static | 1 |

*Jelcz M 121 MT (J)*

In 1999 the first low-floor trolleybus in Poland – Jelcz M 121 MT was put into operation. Also it was the first trolleybus in Gdynia equipped with impulse DC propulsion bade on IGBT transistors and the static auxiliary converter made by Electrotechnical Institute in Warsaw (IEL).

*Solaris Trollino 12 T (SI)*

These trolleybuses were based on modern low-floor bus chassis Solaris Urbino 12 It is equipped with the power electronics equipment from the IEL, the same line in Jelcz M 121 MT.

*Solaris Trollino 12 AC (SC)*

Solaris Trollino 12 AC trolleybuses were the first vehicles in PKT Gdynia with AC traction drive. The manufacturer of electrical equipment was Czech Cegelec.

*Solaris Trollino 12 M (SM)*

Theese trolleybuses are based on the same mechanical chassis like other Trollino trolleybuses, but polish electrical equipment from MEDCOM Warsaw was used. Moreover, trolleybuses Trollino 12 M are equipped with traction batteries, which allow autonomous running (without supply from an overhead catenary) in case of disturbance of the supply system.

*Mercedes-Benz O 405 N (M)*

The high cost of purchasing new trolleybuses forced PKT to search for an alternative way of rebuilding its vehicle fleet. In 2004 it bought second-hand bus chassis from Mercedes-Benz O 405 N in order to incorporate it on the trolleybus. The contactor rheostatic drive "recovered" from scrapped trolleybuses Jelcz with the rotating converter was installed.

*Mercedes-Benz O405NEnika (ME)*

These trolleybuses were a continuation of “homemade” vehicles Mercedes O405N. In order to reduce energy consumption the brand new propulsion system with AC traction motor and static converter was used. Similar to the vehicles Trollino 12 M, these trolleybuses where equipped with traction batteries for autonomous running.

**Failure rate of vehicles**

The failure rate of vehicles is a relevant task, which is strictly linked with the reliability of the transportation system [11, 12]. Vehicle failures cause financial losses related to the need to remove defects, not using the vehicle and the consequent disturbances in the transport system. Therefore, the observation and analysis of the reliability coefficients is necessary. Failure of trolleybuses can be divided in 6 groups [4, 12]:

1) group A – failures related with the traction propulsion:
   - DC/DC converter (2nd generation of traction drive),
   - DC/AC inverter (3rd generation of traction drive),
   - control resistor (1st generation of traction drive),
   - breaking resistor,
   - contactors,
2) group B – failures of low voltage (24 V) installation:
   - lighting,
   - ticket validating machines,
   - transparent,
   - passenger information system,
3) group C – failures of compressed air system:
   - breaks,
   - pneumatic suspension,
   - pneumatic installation,
   - air compressor,
   - freezing of pneumatic installation,
4) group D – failures related to mechanical parts of the vehicles:
   - wheels and tires,
   - mechanical systems,
   - v-belts,
5) group E – failures of traction motors,
6) group F – failures of elements of high voltage (600 – 750 V) installations:
   - cables,
   - current collectors.

**Methods of data analysis**

Pattern recognition methods allow us to find the relationships between data and can be applied to data collection. Two methods of data analysis were used: hierarchical cluster analysis and principal components analysis [1, 5].

**Hierarchical cluster analysis**

Cluster analysis is a multivariate technique which informs about similarity in the data set. Clustering is the task of assigning objects into groups – cluster. The objects in the same cluster are more similar to each other than to those in other clusters. The classification aims to reduce the dimensionality of a data set by finding similarities between classes [6].

Classification criterion is the Euclidean distance *D* between objects *x* and *y*, defined as:

$$D(x,y)=\left(\frac{\sum_{i=1}^{N}(x_i'-y_i')}{N}\right)^{\frac{1}{2}} \tag{1}$$

where: $N$ – number of dimension of objects, $x_i'$, $y_i'$ – standardized values of the object *x* and *y*.

Standardization is implemented according to the formula:

$$x_i'=\frac{x_i-x_{av}}{\sigma_x} \tag{2}$$

where: $x_{av}$ – average value of entity $x$, $\sigma$ – deviation of entity $x$.

Similar to the above, clusters are grouped into upper-clusters, which express similarity between groups. This operation is repeated until every object is grouped into one cluster. The result is a dendogram that illustrates the relationships between objects.

**Principal components analysis**

Principal components analysis (PCA) is a mathematical method which performs a reduction of data dimensionality and allows the visualization of underlying structure in experimental data [6, 7]. Indicators are grouped in a limited number of components and still are able to explain the majority of the variance in data. The first component covers as much of the variation in input data as possible. The next principal components are orthogonal. The idea of PCA can be expressed by the equation:

$$V = WX \tag{3}$$

where: $X$ – matrix of the input data, $V$ – matrix of the principal components, $W$ – matrix of eigenvectors of the covariance matrix $X$.

The dimensionality of input data can be reduced by using only the first *n* singular vectors of $W$:

$$V' = W_n X \tag{4}$$

The factor *n* depends on the required share of variance explained by the selected number of components.

Table 2. Average failure rates of vehicles

| Type of vehicle | Group of failures | | | | | |
|---|---|---|---|---|---|---|
| | A | B | C | D | E | F |
| J | 4,76 | 21,28 | 11,71 | 5,31 | 1,30 | 6,64 |
| M | 2,04 | 19,77 | 8,99 | 3,74 | 1,68 | 3,18 |
| ME | 2,63 | 15,44 | 6,18 | 1,01 | 0,00 | 3,85 |
| SI | 19,58 | 21,91 | 6,29 | 0,00 | 3,26 | 2,38 |
| SC | 1,95 | 7,31 | 1,23 | 0,22 | 0,04 | 2,13 |
| SM | 3,99 | 5,99 | 0,00 | 2,00 | 0,00 | 0,00 |

The PCA was applied to the data set of 85 trolleybuses. Three principal components were chosen. PC1 explains 40% of total variation in the data set, PC2 20 % of total variation and PC3 15%. The factor loadings are presented in table 3. In fig. 1 and 2 the graphic representation of the factors loading is presented.

## Results and discussion

There failure rates of 85 vehicles of PKT Gdynia were analyzed. The analysis covers the period of time between February 2011 and May 2012. In table 2 average failure rates (number of failures scaled to travelled distance) of each type of the trolleybus are presented.

Table 3. Loadings of input data

| Group of failures | PC1 | PC2 | PC3 |
|---|---|---|---|
| A | -0,27 | 0,09 | **0,91** |
| B | **-0,83** | 0,08 | -0,05 |
| C | **-0,85** | -0,01 | 0,15 |
| D | **-0,73** | -0,13 | -0,29 |
| E | -0,28 | **-0,74** | -0,12 |
| F | -0,30 | **0,75** | -0,28 |

PC1 explains three groups of failures: B, C, D. This is to be expected, because these devices belong to the "bus" part of trolleybuses – every analyzed trolleybus is produced on the bus chassis and devices from group B, C, D are related with the original bus body. The elements which belong to groups A, E, F are part of special electric equipment, which is designed and manufactured only for trolleybuses, so defects related with them are another group of failures. The difference between PC2 and PC3 can be explained by the different nature of the equipment. The technical problems related with group A explained by PC3 (traction propulsion system) mainly are caused by damages of power electronic devices, while failures of groups E and F (PC2) are linked witch faults of insulation and electric connectors

The sample score plot for PC1 vs PC2 is shown in fig. 3, PC1 vs PC3 are shown in fig. 4 and a number of observations can be made. First, looking at the location of points relative to the axis of PC1 the following order should be noted (from the right site to the left): SM, SC, ME (the central – right part of the graph) and mixed together points related with M, SI and SI (the left part of the graph). PC1 is negatively correlated with the fault rates of the groups B, C, D, so the higher values of PC1 mean a lower number of failures. Not surprisingly SM vehicles got the highest value of PC1, because they are brand new. Also trolleybuses SC are relatively new – they are 4 – 10 years old. The lower value of PC1 in case of ME trolleybuses is caused by the fact, that these vehicles were built on the chassis of 7 – 8 years old "second hand" buses, so the technical condition of the devices which come from the original bus body (B, C, D) is worse than in the case of the brand new trolleybuses. Other vehicles are significantly older (J, M and SI), so the points related with them are located on the left side of the graph. A relative big scatter of the points related to the trolleybuses SI, J and M in comparison to ME, SC and SM is noticeable. This suggests the high unreliability of them, i.e. the fault rates are different from one another.

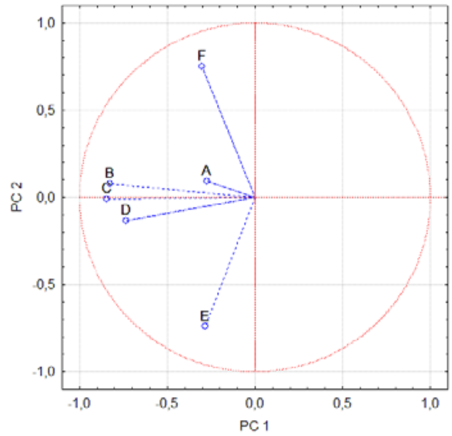


Fig. 1. Loading plots of PC 1 and PC 2

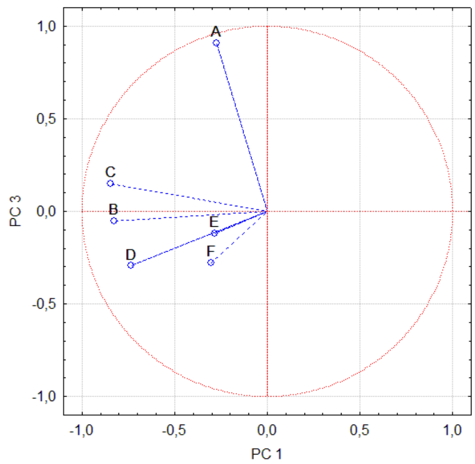


Fig. 2. Loading plots of PC1 and PC3

PC2 is positively correlated with the elements of group F and negatively with group E, so in the case of new vehicles, whose failure rate is not high, the values of PC2 is close to 0. In the case of older trolleybuses, values of PC2 can be higher or lower than zero. As a result of that, points which relatively represent trolleybuses (SM, SC, ME) are located close to the horizontal axis of the points of vehicles J, M or SI. It also can be noted, that average values of PC2 in case of vehicles ME and SC is bigger than in the case of SM, which shows the bigger failure rate of 600 V installation in SM vehicles and bigger reliability of traction motors in case of SC trolleybuses.

In fig. 4 it can be noted, that the average values of PC3 in case of the vehicles J and M are lower than in the case of other vehicles, which may be explained by bigger failure rates of DC traction motors compared to AC traction motors.

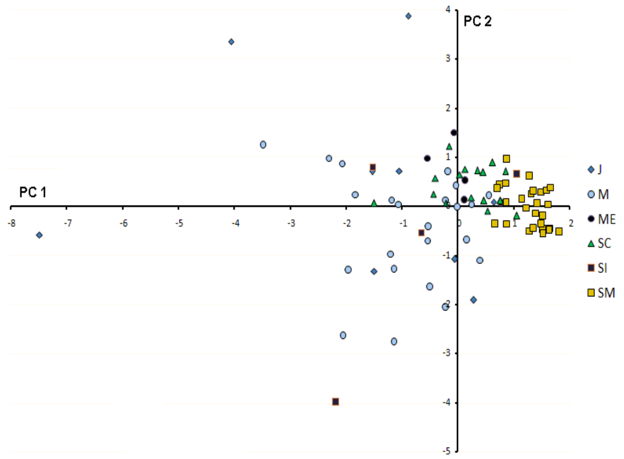

Fig. 3. Score plots for PC 1 and PC 2

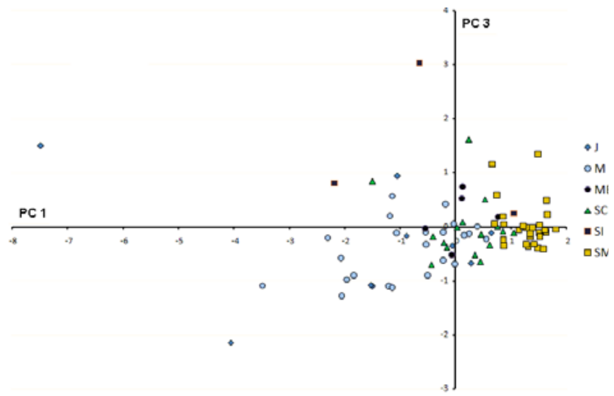

Fig. 4. Score plots for PC 1 and PC 3

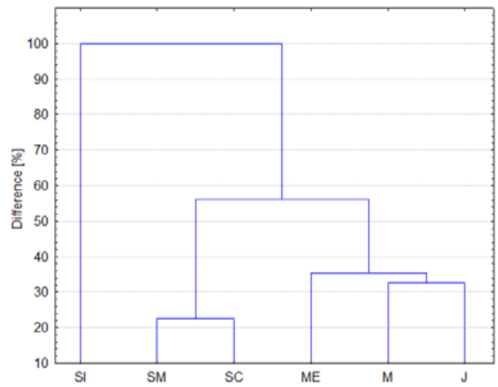

Fig. 5. Dendrogram of the hierarchical cluster analysis

The hierarchical clustering was applied to the average data of six types of vehicles. The results obtained by hierarchical cluster analysis are shown in fig. 5, where two well-defined clusters are visible: the first cluster contain the vehicles M, J and ME, while the second contains vehicles SC and SM. It should be noted, that vehicles are grouped according to the type of chassis. In the first cluster there are types of trolleybuses with old mechanical parts (M, J, ME), in the second there are newer types (SC and SM) based on the Solaris Trollino mechanical part. The smallest different is visible between the M and J vehicles, which can be explained by similar (rheostatic – connector) electric equipment vehicles of these types. Not surprisingly, the most separated from other cases are SI vehicles. These vehicles were short prototype series of vehicles. As a result of that, these trolleybuses, in comparison with other types, have relatively many manufacturing faults.

**Conclusions**

A Multi Criterial Decision Method has been accepted as a useful tool in many non-technical areas, such economy, society, and environment. In this paper is presented application of MCDM in field of technical sciences.

This paper was proved that the method of statistical analysis – PCA and cluster analysis – can be used as e useful tool for analyzing the condition of trolleybuses. By PCA the similarities between fault rates of several parts of vehicles were found. By hierarchical clustering it was shown that from a reliability point of view the "bus part" type of trolleybuses - mechanical part and low voltage installation – are the most important. This information will be helpful for technical maintenance of vehicles.

It is planned to use Multi Criterial Decision Method In another Fields of technical sciences [10, 11, 12].

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