Volume 8 • Issue 4 • 2016

DE GRUYTER OPEN

received: 5 January, 2016
accepted: 10 October, 2016

pages: 59-66

Structure and dynamics of a public bike-sharing system. Case study of the public transport system in Białystok

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ABSTRACT
The article presents the results of a research project referring to the dynamics of the public bike-sharing system BiKeR (Białystok, Poland) in 2014-2015. Identification of the dynamics of the system permits modifications that lead to the enhancement of the efficiency and help to determine the reasons for the choice of a location for new bicycle stations. The basic methodology used for compiling data were the statistical methods with special emphasis on network analysis and graph theory.
Analysis of the data allowed us to identify the mechanisms of changes in the system affecting its dynamics, especially in the area of network topology changes in conjunction with the location of network nodes (stations). The research and analysis showed the specificity of PBS as a transport network. The PBS network, the process of analysis, the value of network metrics and their distribution differ significantly from other types of transport networks (including municipal). The results improve decision-making processes related to the creation and modification of a PBS network, especially in the field of process support, the choice of station location and the impact of these choices on the networks dynamics (as a prognostic utility).

KEY WORDS
public bike-sharing system (PBS), network dynamics, network analysis

DOI: 10.1515/emj-2016-0033

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Introduction

The study of transport networks has a long history. One of the features of this type of research is the interdisciplinarity. In recent years, we have seen a growing interest in this field of study due to the development and implementation of methods for network analysis, mainly, the Internet research. Traditional studies of transport networks took flows of people or cargos as their basis, and these flows were connected with the optimization of costs, maximization of flows and the determination of the shortest transport paths. The main direction of the research was statics network associated with the structure topology. The prevalence of methods of the social networks analysis (SNA) has led to an increased interest in the dynamics of processes in the network associated with changes in time and issues of evolution.

In the case of urban transport networks, the widest representation in the literature includes research of transportation by bus. Due to the relatively short period of existence of urban cycling systems, the study of their dynamics is understood as a variation of the system (organisation) in time and are at an early stage of development. This article is an attempt to fill this gap. The authors examine the changes, which were applied to the urban bike-sharing system BiKeR (Bialystok, Poland) in its first two seasons of operation. The results were compared with studies by other authors on other personal communication systems of both urban and global character (airline network). The comparison of research results was also aimed at identifying tools and research methods that can be applied to urban bike systems.

1. Literature review

In the literature, there are three (or rarely four) generations of PBS (Shaheen & Guzman, 2011). The standard first-generation system is called the White Bicycle system, which originated in Amsterdam in 1965. The system was free-of-charge, which led to numerous thefts and destruction. The implementation of the system was a failure; however, the PBS concept survived.

The introduction of city bikes in Copenhagen in 1995 is considered as the beginning of the second-generation systems. The system involved a fee and worked on a coin-deposit principle. Assumptions of this system have not changed in the next generations of PBS (distinctive design and colour of bicycles, special docking stations serving the basic operations on rent and return, paid rent). Experience in the operation of second-generation systems allowed gaining experience, which is used for systems of the third generation.

The introduction of BIXI in Montreal in 2009 (Faghih-Imani et al., 2014) should be considered as the beginning of the third-generation systems. BIXI offers new solutions and concepts for both technical and organisational sides, which became the basis for the third generation of PBS in Canada and the United States (Mahmoud et al., 2015; Ahillen et al., 2016). Basic features of this generation are the integration between transport and advertising functions, additional features of the docking station (user identification and payment service) and the use of advanced information technology (mobile phones, magnetic stripe cards, smartcards). Most currently operating PBS belong to the third generation. All PBS operating in Polish cities are also the third-generation systems (Klimkiewicz, 2013; Kłos-Adamkiewicz, 2014).

Some authors (Shaheen et al., 2010) postulate the separation of the fourth generation of PBS. It contains all of the features particular to the third-generation systems, but also aims for the integration of cycling with other modes of public transport (especially car sharing). The basic method of integration is common in determining the locations of stations and stops for all modes of transport. It also increases the use of advanced technological solutions (solar systems and bicycles with electric drive in order to promote the principles of sustainable development).

Most publications consider transport networks as static systems. With such a perspective, the main objective is to determine the characteristics of the network structure based on the topology, geometry, morphology and transport flows (Ducruet & Lugo, 2013). Within the static perspective of research on transport networks, two directions of research dominate: at the global level, dealing with the network as a whole and on the local level of the network by separating individual groups of nodes (Lu & Shi, 2007).

Transport networks belong to the broad category of spatial networks because their structure is closely linked to sites connected to the physical infrastructure. The physical infrastructure is determined by the mode of transport. The nature and course of the transport processes affect the durability of the relationship between flows and infrastructure. Regardless of the type of transport, networks have a durable link with nodes in the form of terminals, ports, railway stations or bus stops and their locations. Flows between nodes are dependent on the specification of transport. In the case of urban transport (subway or bus) or rail link with elements of transport, through which the flows go (roads, bridges, railway lines), those links are strict in nature (Ibarra-Rojas et al., 2015). In some modes of transport (maritime, airlines) spatial location of flows is determined by the location of the nodes, whereas the flows between nodes can take place in almost any way (Lillo et al., 2016).

On the global level, most focus is given to the accessibility of a transport network. The planning of transport infrastructure is supported by topographic measures and their impact on the mobility in the city, the suburbs or the region. Transport networks without the physical structure of the route (maritime, airline) analyse systems of cities at different levels (Dobruszkes, 2006).

On a local level, the main objective of the research is to analyse the position of each node in the network and discern node groups (clusters) within the network. Since the analysis of the whole network is complicated in terms of computing (and less useful in terms of pragmatics) there are definitely more papers and articles related to the analysis of the local transport network perspective (Farahani et al., 2013).

The development of a transport network requires analysis and understanding of the complexity and dynamics of the processes that cause changes in the transport system. The literature defines two major research problems: how the spatial organisation of the transport system changes over time and what mechanisms modify the structure. A number of techniques have been found that allow the simulation, and describe the changes (Colizza et al., 2006). A popular tool for the analysis of the network dynamics is an Agent-Based Model (Xie & Levison, 2009). ABM assumes the existence of independent components (called agents) having relationships with each other and the environment. Interactions between agents are based on simple principles and cause complex changes in the networks on the global level. ABM is a good option as a method for the analysis of the dynamics of transport networks enabling the evaluation of the models and a large variety of theoretical approaches.

There are two main procedures for the analysis of dynamics. Generative methods explaining the formation of connections between nodes take the existence of nodes with no connections between them as the initial position, and in the development process of the system, the connections are formed (as a result of action, i.e. the principles of the lowest cost or the optimization of time of transport), (Newman, 2003). The degenerative method for analysis of the initial state considers the existence of the network, in which all nodes are connected to each other. Connections represent all possible variants of paths in the system, while process dynamics change their parameters (Yerra & Levison, 2005).

The literature review allowed us to identify the specificity of urban cycling systems distinguishing them from others. The summary of differences is reported in Table 1.

Tab. 1. Network characteristics of an urban bike transport system

Parameter	Traditional public transport systems (bus, Metro)	Public Bike-sharing systems
Means of transport	Group	Individual
The influence of the user on transport move	Negligible	Significant
Route selection	Conditioned by organization and transport network topology	Any (including the possibility of returning to the original station)
Availability (by day)	As timetable	Full
Availability (per year)	Full-year	Limited by climate (usually in the summer period)
Interaction with other modes of transport	Imposed by the transport manager	Shaped by the user
The degree of the impact on user behaviour	Significant	Limited
Main substitutes of urban transport systems	Private cars	Private bikes
Possibility of transport system modification	Limited, dependent on urban infrastructure	Smaller limitations, integration with infrastructure of pedestrian flows

2. Object of the research – the BiKeR system

The bike-sharing system was established in Bialystok in 2014. The initiative to start the bike transport system came from the city authorities. In the beginning, the city held a contest to name the system. Residents chose the name of the project from among the following options: BIKESTOK, BICIKLO (Esperanto for a single track vehicle) BiKoMobil, BKMBike, BIKER (Bialystok Bicycles Communication). Before the system began to function, two tenders for the operator of the urban bicycle-sharing system were held. Only two companies competed in the first tender. The bids submitted by the two companies were not attractive. In the second tender, only one company, namely Next Bike, made an offer. Next Bike priced its offer at PLN 4.4 million. Although the offer was PLN 1.5 million higher than expected, it was selected.

In Bialystok, on 31 May 2014, the first BSS was launched. In the beginning, 30 stations were in operation with 300 bikes. The locations of stations were established by administrative decisions. The first season of BiKeR lasted until the end of November. Bicycles were hired 347 797 times and the system registered 26 330 users.

The second season began on 24 March 2015. The system was enlarged by additional 15 stations. The locations of the stations were selected by resident votes on the system's website. These stations were equipped with 150 bicycles. The third season began on 1 April 2016. Users could choose from 46 stations and 460 bicycles. In the future, the system is expected to expand by 15 new stations.

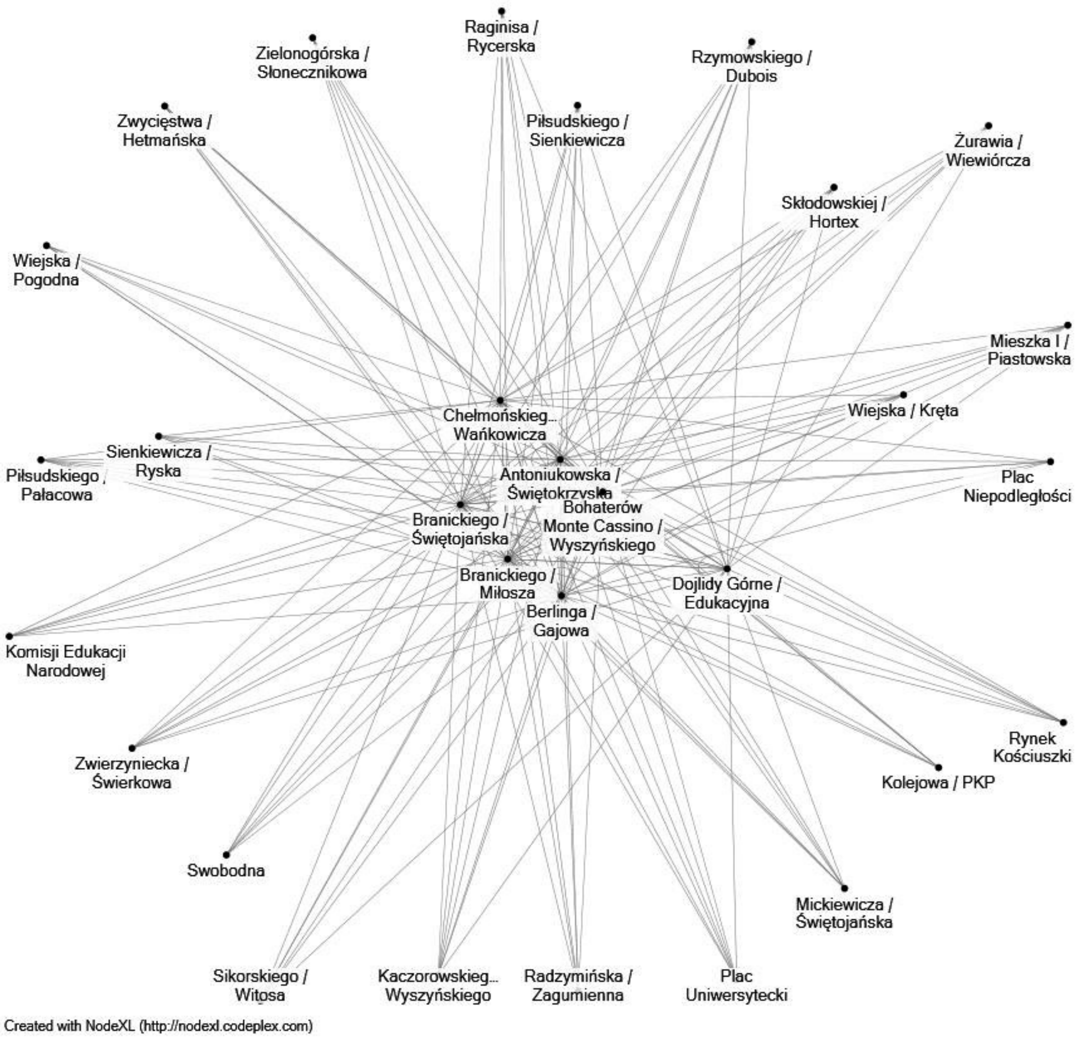

Fig. 1. Topology of the BiKeR system and flows between stations

Figure 1 shows the topology of the network BiKeR and the pattern of flows between stations. The empirical data confirm that this network has connections between two arbitrarily selected nodes (fully connected network topology or complete topology).

3. Research method

Multiple metrics have been developed for the analysis of the dynamics of networks at local and global levels (Rocha, 2016; Tarapata, 2013). The most popular metrics of the global level are:

- Betweenness centrality – the number of possible positions on the shortest path; in research practice, other variants of this measure are also used (e.g. closeness centrality or distance);
- Eccentricity – the number of connections (edges) required to achieve the furthest node in the network (graph);
- Shimbel index (Shimbel distance) – the sum of the lengths of the shortest paths connecting all nodes in the network.

Taking into account the specificities of urban bike network, which results from the analysis of comparative literature in the research part, the BiKeR system was examined mainly from a local perspective. A set of indicators for the analysis at the local level is focused on the issues of the neighbourhood node. Most measures are:

- Degree (or degree centrality) – the number of adjacent neighbouring nodes;
- Hub dependence – the share of the path having the greatest flow in the total flow of the network; it is a measure of the sensitivity of the connections;
- Average nearest neighbour degree characterized by the importance of the nodes adjacent to the analysed node;
- Clustering coefficient: the ratio between the observed nearest threes and the sum of all possible coming of threes; it is a measure of proximity and density.

The choice of a set of measures of the transport network is largely conditioned by the specificity of transport. The authors of the publication freely choose indicators depending on the purpose of research, so that the choice of indicators can vary considerably (e.g. for maritime (Wei-Bing et al., 2009), airlines (Wang et al., 2011) and the overall transport network (Sienkiewicz & Hołyst, 2005; Eagle et al., 2010). The dynamics of the bike system will be dealt with on a local level, the identification of this dynamic requires a selection of indicators grouped giving a deeper insight into this problem.

4. Results

Basic data concerning the operations of bike hire and return in Bialystok urban agglomeration for the respective seasons of 2014 and 2015 were obtained directly from the system BiKeR. Geographic data (location of stations) have been developed independently by the authors.

In this section, we present the results of statistical analysis of data on two levels of networks: local and global. At the local level, two features were considered: node-degree distribution and node clustering coefficient.

Figure 2 shows a graph of the validity of distribution network nodes of BiKeR, presented in a double logarithmic scale (note: individual points of the graph should be treated as multiple points). The distribution shows considerable differences in relation to similar ones calculated for other transport networks (can be compared with the distributions for the urban bus network (Chattterjee, 2005, Fig. 12) or airline network (Li et al., 2006, Fig. 2).

In Figure 2, the phenomenon of heavy-tailed characteristics can be seen. The chart does not pre-

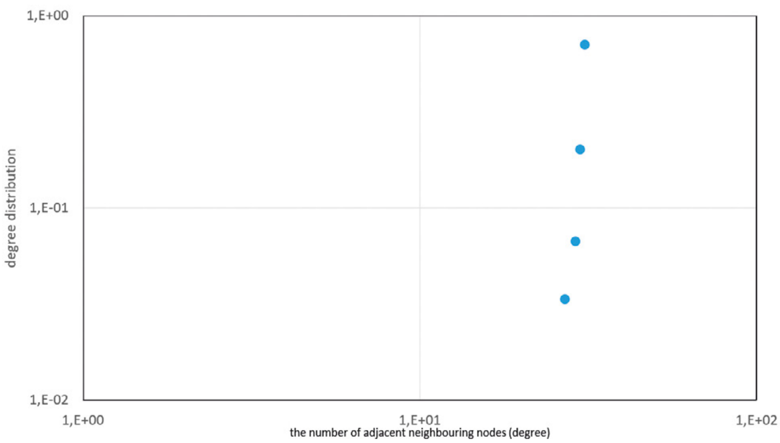

Fig. 2. Degree-distribution in the BiKeR network (double logarithmic scale)

serve the principle of power-law distribution[1]. In the discussions found in the literature, transport networks in the real world follow the principle of slower decaying distributions. Typical class networks have exponential or power law tails. The graph in Figure 2 is not compatible with any of these rules. A noticeable difference of a general nature is also a gap for the degree in the range from 0 to 10^1, not found in similar graphs for other modes of transport.

Figure 3 shows a variation factor of clustering in relation to the validity of nodes (the chart was also

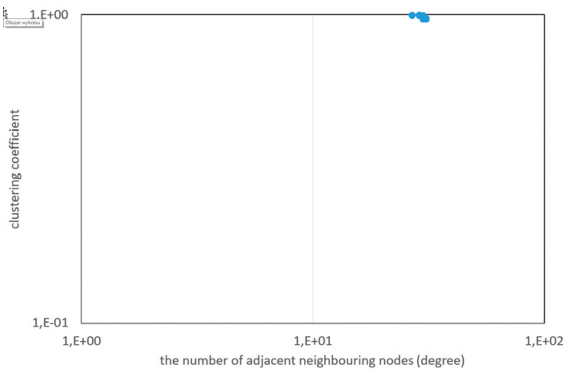

Fig. 3. Variation in clustering coefficient with the node degree in the BiKeR network (double logarithmic scale)

drawn up to a double logarithmic scale, and individual points are to be treated as multiple). There is no similarity between the graphs of these parameters prepared for other modes of transport (e.g. urban bus (Li, 2006, Fig. 15). The chart reflects the hierarchical structure of the network. The nodes with a high degree of validity serve as hubs focusing transport flows both on a local level and in general. The nodes of the lower level of importance formulate usual local clusters, concentrating flows of a local nature. Usually, transport networks existing in the real world have both types of nodes. In the BiKeR system, hub stations (nodes) dominate, which are central agents that focus the flows and interact with each other.

For the analysis of transport networks on the global level (topology), the most common indicators are node centrality and connectivity. Figure 4 shows the distributions of two indicators: betweenness and closeness centralities (the results can be compared with the same indicators for the urban bus network (Chatterjee, 2015, Fig. 12).

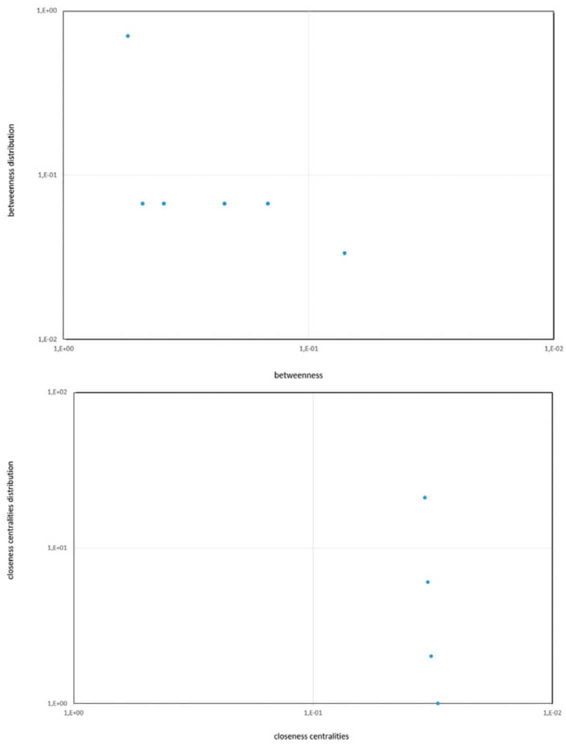

Fig. 4. Betweenness and closeness centralities for the BiKeR network (double logarithmic scale)

5. Discussion of the results

The studies analysed the properties of the urban bike network using statistical methods. The analyses revealed significant differences between the characteristics of a bike network and networks of other modes of transport. The bike networks show similarities to other transport networks. From the geographical perspective, they belong to urban (agglomeration) transport, which suggests a resemblance to bus networks. From the perspective of the infrastructure functionality, bike networks should have characteristics that are similar to networks of sea or air transport (fixed hub locations, the ability to change routes between hubs). The comparison of characteristics of the network and their distributions (degree distribution, clustering coefficient, betweenness and closeness centralities) showed significant differences between cycling networks and other types of transport networks. The main observed differences:

- Lack of hubs in bike networks with a small number of connections (low degree coefficient); bike networks are almost exclusively hub nodes that generate a connection not only with neighbouring nodes (stations) but also with more additional stations (greater distances); the characteristic of

1 In statistics, a power law is a functional relationship between two quantities, where a relative change in one quantity results in a proportional relative change in the other quantity, independent of the initial size of those quantities: one quantity varies as a power of another.

the bicycle network is the creation of complete networks, in which the nodes are interconnected;
- In bike networks, we do not observe the typical distributions characteristic of other networks; in transport networks, two types of distributions dominate: the exponential and Poisson distributions; distribution network indicators in bicycle transport are chaotic in nature;
- Nodes (stations) in the bike network tend to create a smaller number of strong clusters (steady state – low dynamics);
- The dynamics of the network bikes is degenerative; the choice of the location of a station is made by administrative decision or by voting (e.g. a plebiscite); new nodes form connections with all existing nodes.

Conclusions

The study by the authors allowed reviewing the current state of knowledge about bike networks, tools used for the analysis and the determination of the network characteristics. Despite a significant increase in the interest of the problems PBS face and a significant increase in publications on the subject, this research area requires a greater exploration. The research enables the development of a series of demands regarding the future research.

The dynamics of the systems are related to their variation in time. PBS are a new phenomenon in the context of transport networks, historical data about their functioning only dates back to a few years at the most (in the case of the BiKeR system, the maximum period of two years, i.e. from 2014 to 2015, can be considered, which is similar to the situation in other Polish cities). The initial stages of the development of PBS are also characterized by changes in the infrastructure (adding new stations), which cause temporary disturbances in the network and variations in the characteristics. At the initial stage of development, the PBS network has a small number of nodes (stations).

Network analysis tools (especially in the dynamically developing field of social network analysis) focus on the issues of topology (configuration) of the surveyed network. The strength of connections (flow volume) between nodes is usually a secondary issue. The conducted analysis, as well as the value and distributions of the network characteristics, indicate the need for tool identification for a deeper analysis of bike networks. It appears that in the case of PBS, it is necessary to use weighted indicators.

The analysis of transport networks is a prerequisite for their modifications and changes. The primary objective of the authors is to strive for the optimal configuration of transport networks. The results of the analysis should also be applied in field-level user support and serve for the improvement of the service. Previous work focused on the supply side (transport infrastructure); however, the demand side (users) requires a deeper and broader analysis.

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