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Efficiency evaluation of urban transport using the DEA method

JEL Classification: *O18; R58; C10*

Keywords: *efficiency assessment; urban transport; data envelopment analysis; city management*

Abstract

Research background: An efficient and effectively functioning transport of a city is of great importance both for people who reside within it, as well as companies doing business there. It is an integral part of modern economy and society in the dimension of production and consumption. However, apart from having a positive impact, transport also carries many social costs including congestion, traffic accidents and a negative influence on the natural environment. Consequently, urban transport is an increasingly important area of city management.

Purpose of the article: The aim of this study is to assess the technological effectiveness of transport in selected Polish cities. The author created a ranking of cities and identified ways of improve efficiency.

Methods: The test procedure used the non-parametric method of Data Envelopment Analysis (DEA). The data for analysis was drawn from the Local Data Bank of the Central Statistical Office defining expenses in the transport section as well as data on the condition and use of transport infrastructure. Calculations were made using Frontier Analyst Application software dedicated to the DEA method. Performance results were determined using the BCC model. The analysis was con-ducted for 18 cities with district status from 150 to 500 thousands inhabitants.

Findings & Value added: The main result is the author's ranking of transport effectiveness in Polish cities. The analysis showed that urban transport is characterized by a rather low technological effectiveness. Full technological efficiency has been shown by five cities: Białystok, Sosonowiec, Bielsko-Biała, Olsztyn and Rzeszów. An average of the urban transport efficiency reached 51.1%. The lowest effectiveness was only 2.77%. This means that a substantial number of cities do not use optimal inputs. The DEA method enriches the methodology used by scientists to study transport effectiveness.

Introduction

Urban transport has become an significant domain of city management due to the pressure of spatial mobility residents (Pact of Amsterdam, 2016). On the other hand, transport contributes to extensive social damage through congestion, traffic accidents, noise, air pollution and climate change. According to data presented by the European Commission, this situation, over the next few decades, may become significantly worse in many European cities. Forecasts show that the intensity of freight transport in cities will increase by 40% by 2030 and rise by over 80% by 2050 when compared to 2005. At the same time, it is expected that passenger transport will also increase by approximately 34% by 2030 and by more than 50% by 2050 (in comparison to 2005) (White Paper, 2011). These projections indicate a need for cities to act in relation to this field. It requires changes in city management, which will make public transport one of its functional areas. Many European cities do not possess extensive experience and knowledge in integrating urban transport into the city's strategic goals and activities connected to their realization. One of the things which the European Union requires of its member countries is the need to develop a sustainable mobility strategy, including both passenger and freight transport (Hajduk, 2016, pp. 67–74). Unfortunately many cities, in their plans and activities regarding the field of transport, included only those tasks that relate to the movement of people, often without consideration for freight (Ministry of Infrastructure and Development, 2015).

City management concerning the field of urban transport could be viewed as management which is directed both to the inside (city hall management) and to the outside (city management as a whole) (Noworól, 2011, pp. 25–41). On the one hand, it involves the identification within the organizational structure of city hall, of those responsible for the coordination of the flow of people and goods (Hajduk, 2015). It becomes their task to formulate long-term goals in this area. On the other hand, it is the municipal government, in cooperation with other stakeholders including residents, forwarders, recipients, transport companies and public transport operators, who should emerge as the initiator of actions which aim to improve the flow of people and goods in the city. Nevertheless, it is the municipal government who should become the coordinator and initiator of all activities meaning to improve urban transport, for example, by including it into some area of city management.

While looking at city management connected to the field of urban transport, three dimensions must be considered: strategic, tactical and operational. The strategic perspective concerns the integration of urban transport goals into the city's long-term plans. Development of logistical strategy of the city which accounts for passenger and freight transport, as well as ICT systems, should become a standard practice. The tactical level involves planning and implementation of actions in the short-term and should relate to every kind of transport individually. The operational aspect relates to the realization of concrete projects in the field of urban transport. The thematic scope of those projects should be compatible with targets, formulated at the strategic and tactical levels and connected to urban transport.

The assumptions of sustainable development established in the 1990's have become a priority in the transport policy of the European Union. The need to change trends in transport is also visible in the Europe 2020 Strategy and documents resulting from this strategy (European Commission, 2010). Reducing the use of natural resources for the purposes of transport has become a priority within the transport policy of many countries (Ministry of Transport, Construction and Marine Economy, 2013).

In modern cities it is necessary to implement measures which aim to reduce private transport and replace it with public transport. Mobility is essential to maintain a high quality of life and competition within a society. Collective public transport should promote sustainable transport. It is necessary to use environmentally friendly means of transport, such as rail (tram, train), or electric vehicles, as well as those using the waterways and alternative fuels. Cycling and walking should be encouraged. At the same time, cities should develop car-pooling and car-sharing systems. Local government should use solutions which reduce the attractiveness of cars by limiting allowable parking time, raising rates for parking, implementing fees for driving into the city center and initiate the creation of eco-zones. It is also necessary to organize multimodal transfer junctions, provide easy access to bus stops, designate bus lanes, integrate tariffs and schedules, and construct park&ride, as well as bike&ride systems. There should be an increase in the use of intelligent transport systems within the fields of traffic management and travel. The following tasks are significant to achieve the goals stated above: (i) improvement of road safety and the safety of its participants; (ii) traffic monitoring; (iii) monitoring of vehicle speed; (iv) introduction of information services for travelers. Studies conducted in large cities have shown that ITS systems reduce expenditures for transport infrastructure by 30–35% and increase traffic capacity by up to 20% (European Commission, 2013). Investment into road improvements should mainly focus on the removal of excessive transit traffic by constructing bypasses and short connecting roads linking cities with large national arteries.

The aim of this article is to examine, through the use of Data Envelopment Analysis, the transport effectiveness of Polish cities. This method requires the definition of variables representing inputs on the one side and outputs on the other. The study used information from the Local Data Bank of the Central Statistical Office of Poland, defining expenses within the transport department (expenditures) and data on the condition and use of transport infrastructure (effects). The analysis was conducted for 18 cities with poviat status, meaning those having from 150 to 500 thousand inhabitants. The territorial units were then compared, and a ranking of the effectiveness of urban transport was prepared.

The elaboration consists of two parts: theoretical and empirical. General conditions of the DEA method were based on the study of literature. The main source of material which has been used in the article were scientific books of domestic and foreign authors as well as journal papers. The paper's empirical section dealt with efficiency assessment of urban transport. Source data comes from the Local Data Bank of the Central Statistical Office and refers to the year 2015. The research can lead to a better understanding transport in selected cities of Poland.

Literature review

In recent years, many institutions have created state of development rankings of countries, regions and industries (Balcerzak & Pietrzak, 2017). These mainly concern economic performance, investment attractiveness, the level of innovation and research potential (Pietrzak *et al.*, 2017; Cheba & Szopik-Depczyńska, 2017). Assessment is made on the basis of analysis of variables both quantitative and qualitative in character, which in turn allows the ranking of the units surveyed in terms of resources and achieved results. It may be interesting to create a ranking of cities in terms of effectiveness.

The simplest definition of efficiency describes it as the ratio of achieved effects to incurred expenses and, according to the principle of rational management, the greater the effect per unit of expenditure the higher the effectiveness. Nowadays, high competition requires an increase in effectiveness, and this poses a challenge. Economists understand effectiveness as a lack of stoppage time and unnecessary waste generation in the company. Effective enterprises are located at the lowest possible cost curve, which means that they achieve results in the cheapest way possible. Effectiveness is a measure of rationality of business operations and concerns the company's ability to improve its market position and financial performance. Effectiveness studies relate mainly to the analysis of the effects of determined expenditures to achieve intended effects. If both the expenditures and effects can be expressed in measurable units, then it is possible to develop a performance indicator that allows for comparisons with a predetermined base level, plan or effectiveness of other units. Thanks to that, it is possible to identify areas which require improvement, to define courses of action or to monitor progress. Effectiveness can also be examined using the economic, the allocation or the pricing approach.

Assessment of effectiveness allows for the determination of the course through which the transformation of effort into the obtained results occurred. Researchers commonly use methods of effectiveness assessment based on the following three approaches:

- The indicative approach involves constructing a relation regardless of size. It uses profitability indicators remembering that it is important to correctly estimate adopted measures and interpret the calculated indicator properly. This is done by comparing the obtained results with accepted reference points. These may be indicators which have been established in previous years as well as industry or national averages.
- The parametric approach is based on a known function of production, defining the relationship between inputs and outputs. The parameters of this function are determined using the classic tools used in econometric estimation such as Stochastic Frontier Approach (SFA), Thick Frontier Approach (TFA), Distribution Free Approach (DFA) or Frontier Production Function (FPF).
- The non-parametric approach uses the procedure of linear programming. It does not take into account the random factor effect and the relationships between inputs and outputs. The basic methods include Data Envelopment Analysis (DEA) and Free Disposal Hull (FDH).

The Data Envelopment Analysis method was initially presented by Charnes, Cooper and Rhodes in 1978. These researchers based their assumptions on the concept of productivity formulated by Debreu and Firrelle and understood as the quotient of a single result and a single effort (Guzik, 2009, pp. 55–75). The DEA method was used in situations in which there is more than one effect and more than one effort. Using linear programming to estimate efficiency measures, they created their first model called CCR with constant return-to-scale in which they accepted the assumption that scale effects are constant. In time, both the methodology and its application become more widely used. In 1984, Banker, Charnes and Cooper proposed a model which they called BCC with a variable return-to-scale. These models are used to study company efficiency.

The DEA method focuses on studying the dependence between the level of multiple inputs and outputs. The technological efficiency score is calculated without knowing the initial weights. DEA calculations are based on seeking weights that maximize the efficiency of each object. Finally, the DEA method allows the determination of the limiting curve of effectiveness. If objects are on the curve, then they are considered to be efficient. Otherwise, they are seen as inefficient (Guillermo, & Vincent, 2016, pp. 328–350). An object's effectiveness is measured in relation to other objects being studied. Analysis units of the DEA are called Decision Making Units (DMU). The subject of analysis, on the other hand, is the productivity with which DMU's transform inputs into outputs. The measure of efficiency is the relation between the productivity of a given object and its maximum productivity or that which can be achieved under specific technological conditions.

The DEA method is used to measure the technological effectiveness of non-profit institutions, business enterprises (Kozłowska, 2014, pp. 305–317) and public institutions. It has been employed, among other things, to assess the effectiveness of public institutions such as hospitals, libraries, universities (Nazarko *et al.*, 2008, pp. 89–105), schools (Chodakowska, 2015, pp. 112–125), state forests national forest holding and banks (Balcerzak *et al*., 2017). This method can also be utilized to evaluate and create rankings of cities, regions and countries. It is especially recommended where it is impossible to appoint a functional relation between inputs and outputs, and ascertaining their weights is impossible. DEA studies conducted in recent years are presented in Table 1.

DEA models can be used to determine effectiveness, but also, at times, for setting benchmarks, benefits of scale, ranking objects, as well as for figuring out ways to improve the efficiency and structure of optimal technologies for inefficient objects. An important advantage of the DEA method is its non-parametric character, allowing its use without the knowledge of functional dependencies between outputs and inputs. Another advantage of this method is the possibility of using data expressed in different units of measure for both inputs and outputs. In relation to variables, the configuration of the DEA model is therefore characterized by high flexibility, which significantly affects the range of applications in which the method can be used (Sarkar, 2016, pp. 740–751). Environmental variables which influence DMU's effects or inputs, and which are not controlled by the object can also be introduced as part of the analysis. These variables reflect geographical, legal or economic conditions. The DEA method also has some limitations, including: high sensitivity to erroneous data and variables which differ significantly from others, sensitivity to changes to the number of test items or the need for appropriate balance between the number of objects and the number of variables.

A decision to make use of the DEA method involves searching for weights that maximize the efficiency of individual units, and efficiency expressed as the score of the weighted sum of the outputs to the weighted sum of inputs:

$$\theta = \frac{\sum_{r=1}^{s} y_r \lambda_r}{\sum_{i=1}^{m} x_i \lambda_i} \tag{1}$$

where:
x_i – amount of input i utilised by DMU;
y_r – amount of output r utilised by DMU;
λ_i – weight for input variables of DMU;
λ_r – weight for output variables of DMU;
m – number of input variables;
s – number of output variables;
θ – efficiency score for DMU.

Two criteria are used simultaneously in the classification of DEA models: (I) model orientation and (II) the type of scale effects. The first criterion indicates whether inputs efficiency (in order to minimize inputs to produce the same outputs) or the outputs efficiency are calculated (in order to maximize outputs given the current inputs). The second criterion defines which assumptions concerning scale effects have been accepted in the model: variable return-to-scale (VRS), constant return-to-scale (CRS) or non-growing return-to-scale (NIRS). The number of input and output variables in the DEA model depends on the number of decision-making units. The sum of inputs and outputs should not significantly exceed the number of units surveyed (Karlafis, 2004, pp. 354-364). In order to obtain reliable results, it is recommended to maintain a certain dependence between sample size (n) input variables (contributions — m) and the outputs variables (results — s), such as (Sarrico, 2007, pp. 1408–1409):

$$n > \{m \times s;\ 3 \times (m + s)\}\,. \tag{2}$$

DEA is a method which is well-known worldwide, and is often used to solve problems related to the analysis of effectiveness. This is supported by a very rich bibliography available through many foreign studies, connected to this method (Liu *et al.*, 2013, pp. 3-15). In Poland, this method has been mainly used to analyze the effectiveness of financial and educational institutions. This is the reason this study attempts to use the DEA method to investigate urban transport effectiveness.

Research methodology

The research focuses on the technological effectiveness of urban transport. The study uses the BCC model. The research consists of three steps which include: selection, evaluation and analysis. The study was conducted using the procedure presented in Figure 1.

Source data comes from the Local Data Bank of the Central Statistical Office and refers to the year 2015. The selection of variables in the model was carried out based on the analysis of literature and was determined by the limited scope of the statistics given concerning city sections (Díaz, & Charles, 2016, pp. 328–350; Wiśnicki *et al.*, 2017, pp. 9–15). The sample for analysis includes 18 cities with poviat status from 150 to 500 thousands inhabitants. The calculation has been made using Frontier Analyst Application software dedicated to the DEA method.

The main objective of this study is to assess the technological efficiency of transport in selected Polish cities. Detailed goals include: (I) to create a ranking of the efficiency of urban transport; (II) to identify city-benchmarks; (III) to analyze classes of efficiency; (IV) to determine the relation between the efficiency score and transport expenditures; (V) to identify areas for improvement in inefficient cities in relation to benchmarks.

Prior to initiating the study, an assessment was made whether all the variables included in the expenditures are characterized by sufficiently high volatility. Coefficients of variation were calculated for each feature (V). It was found that all variables were characterized by high volatility and therefore could carry important information about the phenomena being examined. Table 2 presents the basic descriptive statistics for analyzed variables. In order to determine the technological effectiveness for the transport cross-section of cities with poviat status the following variables were isolated, which included three effects:

Y_1 – the length of gmina and poviat hard surface roads per 10 thousand residents [kilometers/10000 residents];

Y_2 – the length of bus-line per 10 thousand square kilometers [kilometers/10000 square kilometers];

Y_3 – the length of bicycle paths per 10 thousand square kilometers [kilometers/10000 square kilometers].

Adopted set of inputs included one variable:

X – expenditure of poviats budgets in the transport section [PLN per capita].

The variables used in the model and expressed as expenditures were also checked with respect to the existence and the strength of their correlation with the effects. The highest correlation was shown between the length of bicycle paths (Y_3) and the expenditures for transport (X).

Results and discussion

The technological efficiency results, shown in Figure 2, were determined using the BCC model. The initial step of the study was to create a ranking of urban transport efficiency and to identify city-benchmarks. Units which are considered to be fully efficient achieved a factor of 100%. A ranking of objects in order of efficiency from the highest to the lowest can show which cities are inefficient, and which can be classified as leaders. Five cities have been established as benchmarks: Białystok, Sosnowiec, Bielsko-Biała, Olsztyn, Rzeszów. Eight cities did not reach the 30% threshold of efficiency. This class included Zabrze, Bytom, Kielce, Gdynia, Czestochowa, Gdańsk, Radom and Gliwice which had the lowest level of efficiency at 2.77%. Cities which were considered in the study have demonstrated an average technological efficiency of 51.11%, with standard deviation reaching 36.97%.

Analysis of classes of efficiency was the next step within the research process. Efficient cities made up the most numerous class. These benchmarks consisted of five objects considered within the study. There were two cities with efficiency between 70-99.99% and eight cities whose efficiency rating below 30%. Figure 3 presents the number of cities in each efficiency class.

The next step of research concerned the examination of the relationship between the efficiency score and transport expenditures. An increase in transport expenditures reduced the efficiency score. The correlation coefficient between the efficiency score and transport expenditures was -0,37928. Cities displaying full efficiency allocate anywhere from PLN 21.26 to PLN 902.24 per 1 inhabitant for transport. In contrast, the city with the lowest efficiency spends as much as PLN 2110.04 per 1 inhabitant. The results of these considerations are shown in Figure 4.

Designated lambda values show how the level of technology in ineffective cities should be adjusted for them to become effective. The last step of the study was to determine the ways in which inefficient cities could improve in relation to benchmarks. For instance, Szczecin's level of technology should be equal to the sum of technologies of: (1) Bielsko-Biała multiplied by 13.1, (2) Sosnowiec multiplied by 59.7 and (3) Olsztyn multiplied by 27.2. The same interpretation applies to other inefficient cities of Katowice, Toruń, Lublin, Bydgoszcz, Zabrze, Bytom, Kielce, Gdynia, Częstochowa, Gdańsk, Radom, Gliwice. Lambda values for inefficient cities presented in Table 3.

Conclusions

The DEA method enriches the methodology used by scientists to study urban transport efficiency. In comparison to parametric methods, it presents many advantages. It makes the determination of the unit's effectiveness in the presence of many inputs and outputs possible. At the same time, it does not require knowledge of functionality between the variables. Additionally, it allows the expression of inputs and outputs in different units.

Measuring of efficiency is a complex and multivariate process. The use of the BCC model within this publication as a method of assessing effectiveness enables the isolation of technologically effective and ineffective transport in cities. The ranking of cities prepared upon this foundation can be questionable and its application to analyze other variables could perhaps yield different results. However, this ranking has been based on a model having particular specification and should be treated as a stimulus for further analysis in order to better understand occurring phenomena, for instant the use of other types and combinations of input and output signals.

The article presents the evaluation of urban transport efficiency on the basis of one input (transport expenditures) and three outputs (the length of urban roads, the length of bus-lines, the length of bicycle paths). The study shows that full efficiency occurred in 27.8% of units. The average urban transport efficiency was 51.1% in the BCC model and the lowest efficiency was only 2.77. This means that substantial parts of cities do not use optimal inputs. The analysis shows that urban transport of considered cities was characterized by a rather low technological effectiveness. Although the method involved a number of simplifications these results provide a general overview of the level of efficiency of the units surveyed, and can be a starting point for more detailed analysis of the efficiency of individual units. An important advantage of measuring effectiveness using this method is the identification of potential improvements which inefficient units may implement and objects which they could imitate.

The results of testing the technological effectiveness of urban transport in selected Polish cities are only preliminary. The study does not allow for the analysis of a very large number of inputs and outputs when the sample consists of only 18 units. Further analyses should take into account variables other than those proposed in this study. This will facilitate the comparison of rankings of cities which have been obtained using different models.

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Annex

Table 1. DEA studies conducted in recent years

Category	Topic	Studies
Theoretical	Model improvement	Ćwiąkała-Małys & Nowak (2009); Bartoszewicz, & Lelusz, (2016)
Empirical	Logistics	Wiśnicki et al., 2017; Motevali Haghighi *et al*. (2016); Azadeh *et al*. (2016); Wiegmans, & Dekker (2016)
	Industry	Kozłowska (2014); Kluczek (2017)
	Education	Jill (2006); Nazarko *et al.* (2008); Chodakowska (2015); Brzezicki (2016); Ramzi et al. (2016)
	Agriculture	Coelli & Prasada Rao(2005); Jiang *et al.* (2016)
	Health-care	Hollingsworth (2008); Retzlaff-Robertsa *et al*. (2004)

Table 2. Variables available for analysis

	X	$\mathbf{Y_1}$	$\mathbf{Y_2}$	$\mathbf{Y_3}$
$\bar{x}$	485.27	15.24	353.71	5214.89
S_X	486.47	4.08	509.45	2768.16
V	100.25	26.77	144.03	53.08
Max	2110.00	29.79	1511.40	10770.90
	Gliwice	Bielsko-Biała	Olsztyn	Białystok
Min	21.26	10.19	0.00	2088.19
	Sosnowiec	Bytom	Bielsko-Biała Bytom Zabrze Sosnowiec	Bielsko-Biała

Source: author's elaboration on the basis of https://bdl.stat.gov.pl/BDL/dane/podgrup/temat (07.12.2016).

Table 3. Lambda values for inefficient cities

DMU	Białystok	Sosnowiec	Bielsko-Biała	Olsztyn	Rzeszów
Szczecin	0.0	59.7	13.1	27.2	0.0
Katowice	0.0	65.5	10.2	24.3	0.0
Toruń	68.1	0.0	27.3	0.0	4.6
Lublin	31.0	0.0	3.0	66.0	0.0
Bydgoszcz	0.0	59.3	0.0	40.7	0.0
Zabrze	0.0	94.9	0.0	5.1	0.0
Bytom	0.0	67.3	0.0	32.7	0.0
Kielce	0.0	5.7	2.3	92.0	0.0
Gdynia	0.0	66.9	0.0	33.1	0.0
Częstochowa	0.0	48.2	20.3	31.5	0.0
Gdańsk	0.0	28.6	1.8	69.9	0.0
Radom	0.0	75.2	0.0	24.8	0.0
Gliwice	0.0	77.7	20.9	1.5	0.0

Figure 1. The scope of the research process

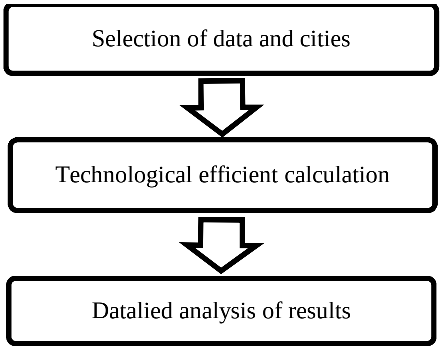


Figure 2. Technological efficiency of urban transport

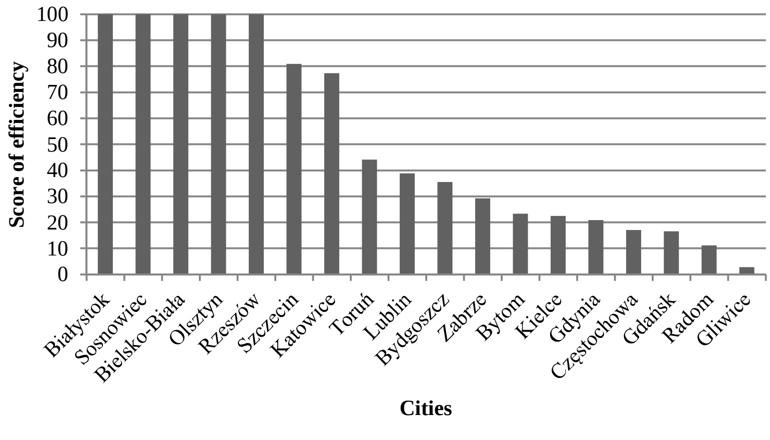


Figure 3. Number of cities in efficiency classes

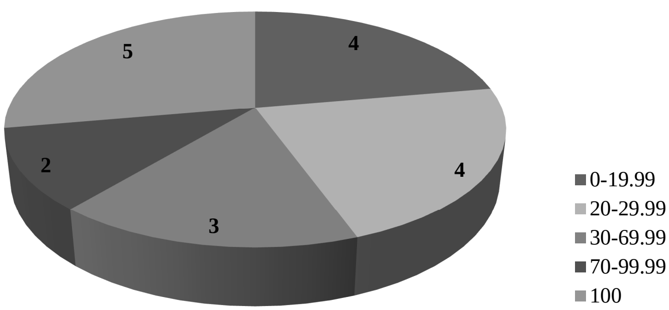
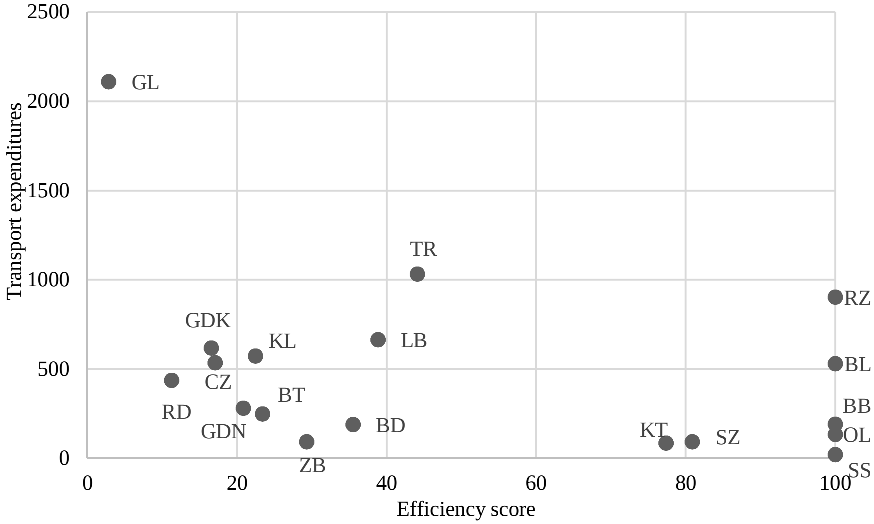


Figure 4. The efficiency score and transport expenditures in cities



Abbreviation: BB Bielsko-Biała; BD Bydgoszcz; BL Białystok; BT Bytom; CZ Częstochowa; GDK Gdańsk; GDN Gdynia; GL Gliwice; KL Kielce; KT Katowice; LB Lublin; OL Olsztyn; RD Radom; RZ Rzeszów; SS Sosnowiec; S Szczecin; TR Toruń; ZB Zabrze.