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USE OF DEA AS A MEASURE OF EFFICIENCY OF ACTIVITIES FOR ROAD SAFETY AT THE PROVINCIAL LEVEL

ABSTRACT

There are about 20,000 accidents on Polish roads every year, with over 1,800 people dying and over 24,000 injured in the last five years. Road accidents are a severe socio-economic problem for the country. A number of actions are being taken to affect road safety, but these actions should also have an economic justification. There is no single method to identify which actions have the most beneficial effects. However, it is essential to use tools for decision support that can help them monitor and manage road safety interventions. This article proposes a DEA method to assess the efficiency of road safety improvement interventions at the provincial level. Based on the adopted data, it was shown that the most effective provinces are the provinces of Dolnośląskie, Łódź and Świętokrzyskie. In contrast, the provinces of Śląskie and Podlaskie are the least effective.

KEYWORDS: *efficiency, road safety, DEA method, provices, accidents*

INTRODUCTION

Efficiency is one of the most widely used economic categories for evaluating the activities of both private and public entities (Bartoszewicz &Lelusz, 2016). Many researchers define this concept. In general, efficiency refers to some category of action, so-called human behaviour, which is conscious, purposeful and arbitrary, and as such, is intended by the entity undertaking it to lead to a particular result. (Nguyen et.al, 2008, Pszczólkowski, 1978). From an economic point of view, efficiency is the ratio of the effect (the achieved result of an activity) to the input (the factor of production or the combination that was used in the activity) (Winkler 2010). While measuring efficiency in private sector entities is not a significant problem, there are some limitations in public sector entities (Bartoszewicz &Lelusz, 2016). Public sector entities are distinguished by a more complex relationship with the environment (greater openness, less stable environment, less or no pressure from competitors), a specific bundle of objectives (meeting social needs through provision of public goods and services, increase in welfare, social justice, ambiguity of priorities), a formalised and inflexible organisational structure, and a specific value system of managers (Głodziński, 2014).

Another problem concerning the efficiency of the public sector is to study it not only from the point of view of a single entity but also from specific actions taken by different entities and their efficiency at, for example, the province, municipality or city level. One such area is road safety activities. Traffic safety effectivity is usually based on indicators, such as the number of fatalities per 10,000 residents, the number of fatalities per number of vehicles, or the number of fatalities per number of kilometres travelled (Przygodzka, 2008, Alper et.al, 2015). While each of these indicators is useful for ranking the level of traffic safety in a given location, depending on the indicator adopted, different conclusions may be drawn. In other words, the resulting ranking based on the listed indicators can be significantly different, and selecting a single indicator is sometimes proven to be inadequate. To overcome this difficulty, the Data Envelopment Analysis (DEA) methodology is a tool with convenient functions for combining various indicators into a single index or composite index, which can express in a more relevant perspective the efficiency of measures taken to improve road safety. Although, the assessment of road safety is a key issue both at the micro (e.g. commune) and global level and considerable research has been conducted in this area, to the author's knowledge, the assessment of the effectiveness of road safety measures in Poland has not been included in the literature. The aim of this paper is to present the achievements concerning the application of the Data Envelopment Analysis (DEA) method to the assessment of efficiency in the area of road traffic safety worldwide and to use it to compare and assess the technical efficiency of road traffic safety measures at the provincial level in Poland.

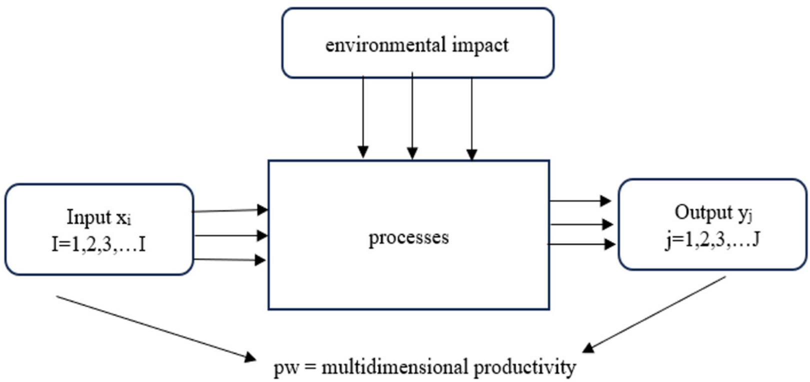
Literature review

One of the rapidly developing methods of performance evaluation is Data Envelopment Analysis. The creators of this method are A. Charnes, W.W. Cooper and E. Rhodes, who in 1978 published a paper providing the theoretical basis for this approach to performance evaluation. The idea behind the method is based on Debreu and Farell's definition of productivity, understood as the ratio of a single effect to a single input

$$p = \frac{y}{x}$$

Where: p – productivity, y – single effect, x – single input. This approach allows the evaluation of productivity, often used in microeconomics in the form of a frontier production function. The fundamental disadvantage of this model is that it requires knowledge of the functional relationship between the input and the effect of a given process. The authors of the DEA method proposed to relate such a definition of productivity to a multidimensional situation in which efficiency is considered to be the ratio of weighted sums of effects to weighted sums of inputs, taking into account the influence of the environment on the system (Nazarko, et.al 2008, Nowak &Borowiec, 2013) (Figure 1).

Figure 1. *The concept of productivity*



Source: (Winkler 2010, Alper et.al, 2015)

$$pw = \frac{\sum_{j=1}^{J} \nu_j y_j}{\sum_{i=1}^{I} \mu_i x_i}$$

Where:
x_i – i-th input
y_{i} – j – th output
I – numbers of inputs
J – numbers of outputs
μ_i – weights determining the importance of individual inputs
ν_j – weightings determining the importance of individual outputs.

The essence of the DEA method is based on the use of empirical values of the sum of inputs to the sum of outputs for individual sets of objects called DMUs (decision-making units), which allows the determination of weights that maximise efficiency. The DEA method thus has the advantage of being non-parametric, meaning that it is not necessary to know the weights of individual inputs and outputs and the functional relationships between them (Nowak & Borowiec, 2013, Chodakowska 2009). The efficiency of individual DMUs is determined by the so-called relative efficiency, which is determined by the object characterised by its optimal coefficient (100%) relative to the other DMUs. This means that the other facilities cannot improve the performance of individual inputs or outputs without degrading other inputs or outputs (Nowak & Borowiec, 2013, Szumarzyński 2009).

Since then, the method has seen many modifications and developments (Szumarzyńska, 2009, Charnes et. al 1994, Fura, 2017, Zhu 2009, Paradi et. al 2018). The following basic DEA profiles can be identified:

- CCR – Charnes, Cooper, Rhodes (1978),
- BCC – Banker, Charnes, Cooper (1984),
- SBM (slack-based model) – Charnes, Cooper, Golony, Seiford, Stutz (1985),
- CEM (cross-efficiency model) – Sexton, Silkman, Hogan (1986),
- MM (multiplier model) – Seiford, Thrall (1990),
- SE-DEA (super-efficiency DEA) – Andersen, Petersen (1993),
- NR-DEA (non-radial DEA) – Thanassoulis, Dyson (1992), Zhu (1996),
- CEP (cross-efficiency profiling) – Doyle, Green (1994), Tofalis (1996) (Guzik, 2019).

The basic division of DEA models concerns their orientation. These models can be either input-oriented or output-oriented (Guzik, 2019, Kucharski, 2014). In the case of input-oriented models, optimisation involves minimising inputs while maintaining a certain level of outputs. In the second case (outcome-oriented models), outcomes are maximised at a certain level of inputs. It should be remembered that choosing the appropriate model orientation is a fundamental issue when calculating technical efficiency using the DEA method. An effects-oriented model will be appropriate for entities that focus on profit maximisation (Guzik, 2009b, Kucharski, 2014, Mlynarski, Predki, 2017, Rogowski, 1998). On the other hand, an input-oriented model is helpful in the case of decision-making entities whose priority is to minimise their expenditures, such as NGOs, hospitals and road safety entities, among others (Guzik, 2009a, Allen 1999, Nurmatov et.all 2021).

The earliest publication on the use of the DEA method in traffic safety research dates back to 2005. Odeck [2006], based on the BCC model with the Malmquist productivity index approach, examined the effects of the operations units of the Norwegian Public Roads Administration (NPRA) charged with traffic safety services. This method has also been used to assess the efficiency of traffic safety activities in individual European countries and relation to completed or ongoing activities included in policy documents. Thus, in 2008. Using the DEA method, Hermans et al. (2008) determined road safety efficiency in 21 European countries, pointing to necessary changes in road safety policies. Subsequently, Shen et al. (2019), using the DEA-MI model, measured how much EU countries improved their road safety performance between 2001 and 2010. The DEA-MI-based results indicated significant progress in improving road safety with large disparities between countries. One of the most recent studies on the use of the DEA method in assessing efficiency on EU roads was conducted by Yasin & Shen (2019) and concerned road safety in the EU in 2011 – 2015. The results of the DEA-based research indicate that the overall road safety situation in Europe has also improved during the period under review. However, the pace of development has not kept pace with the EU's *ten-year plan*. Road safety development has slowed compared to the last five years (2006-2010).

An important area of research using the DEA method in traffic safety is its use to study the efficiency of selected measures. This method was used to determine the level of efficiency of helmet and seatbelt enforcement in reducing traffic fatalities at the national level (Barhoum, Behnood, 2023). The data for this model included three levels, which were the percentage of helmet and seatbelt use (intervention outcomes), enforcement outcomes (intermediate outcomes), and road fatality rates (final outcomes). The intermediate outcomes were qualitative data, and the model in this study was based on fuzzy data envelopment analysis. The study was based on a multi-objective fuzzy DEA model, which included two primary submodels: assessment of final outcomes, which are influenced by intermediate outcome indicators, and assessment of intermediate outcomes, which are influenced by intervention outputs. The results showed that only Finland and Spain had absolute performance in this area. Iran was identified as a low-performing country (19th in terms of inefficiency score). In order to become an effective country based on the benchmark countries' data, Iran would have to increase helmet enforcement by 55.4% while keeping seatbelt laws unchanged. For helmets, the rate was to increase to 77.6% for motorcyclists and 382.5% for passengers. Seat belts were also to be increased by 4.3% for front-seat passengers and 470% for rear-seat passengers in vehicles.

The method is also being used to support road safety management decisions. Fancello et al. (2020) presented a decision support method based on DEA to help urban road safety management practitioners identify those roads where safety improvement needs are most significant. The method was applied to Italy's urban road network to define a hierarchy of hazardous road locations based on safety conditions. For the first time, the social cost, which was calculated according to an equation using data on road deaths, injuries and accidents from 2009 to 2013 and the average number of collision points at intersections and traffic volume, are used as input variables. Another publication that came out in 2024 was a study by Chorfia & Khalaia (2024), which presents an assessment of traffic safety in different regions of Morocco. The study results show that road safety improvements in Morocco during the period under review are unsatisfactory and far from achieving the goals of the current road safety strategy, which aims to reduce fatalities by 50% by 2026. Moreover, the Malmquist Productivity Index (MPI) approach, which decomposes changes in total factor productivity into efficiency and technical changes, revealed that neither component shows a consistent trend throughout the period under study. This indicates that productivity progress over time needs to be improved and falls short of expectations, underscoring the immediate need for technical and managerial improvements to address today's road safety challenges effectively.

Methodology

In order to evaluate the efficiency of road safety improvement measures in each province, the DEA-CCR model was used. Within the model, two groups of characteristics were distinguished: inputs (inputs) and outputs (outcomes). The DEA method recommends that the input data be characterised by, among other things, a uniform direction of preference for inputs/outputs and the homogeneous or nearly homogeneous nature of the objects. The first condition means that an increase in the quantities considered as results is evaluated positively regarding the purpose of the objects under study. Outlays, on the other hand, should be such quantities whose growth, at a certain level of results, is evaluated negatively [14]. In turn, the homogeneity condition allows the comparison of objects within a relatively homogeneous group. As for the number of variables, it is assumed that the total number of inputs and results in DEA should be about three times smaller than the number of objects being compared. Keeping in mind the above limitations, the set of inputs includes (Fura, 2017, Mesjasz-Lech 2014):

I_1 – Number of speed cameras and sectional speed measurements per 100 km of road [pcs/km]

I_2 – Number of police officers per 100 km of road [person/km]

I_3 – Investment expenditures on roads per 100km2 [PLN/km^2].

On the results side were:

Q_1 – the number of people killed and injured per 10000 residents in each province.

The data for the study is from 2022.

The CCR model based on inputs in the sense of Farell-Debreu was used to evaluate efficiency. According to this perspective, the efficiency of an entity is always evaluated relative to others. If no other unit achieves a better result with the same inputs, we are dealing with a fully efficient unit, while if the results of at least one other unit with the same inputs are higher, the unit under study is inefficient (Lisiecka 2007).

The model output is summarised in Table 1.

Table 1. *Outlays and results by province in 2022*

Province	(I_1) Number of speed cameras and sectional speed measurements per 100 km of road	(I_2) Number of traffic police per 100 km of road	(I_3) Expenditure on roads per 100 km^2	(O) Number of road accident victims per 10000 inhabitants (killed and injured)
dolnośląskie	0,16	4	3668156,77	8
kujawsko-pomorskie	0,10	2	2392903,42	5
lubelskie	0,18	2	3060365,53	5
lubuskie	0,38	3	2877895,56	7
łódzkie	0,22	3	2199091,46	12
małopolskie	0,14	3	2139248,70	8
mazowieckie	0,29	3	5066776,77	7
opolskie	0,14	3	1665817,84	6
podkarpackie	0,20	4	3552591,04	7
podlaskie	0,23	3	1778514,59	5
pomorskie	0,30	4	2485831,81	9
śląskie	0,22	5	2068163,39	6
świętokrzyskie	0,11	2	970345,62	7
warmińsko-mazurskie	0,19	2	5179233,81	7
wielkopolskie	0,17	3	4575902,37	8
zachodniopomorskie	0,20	3	4626958,82	7

Source: own study

Based on the inputs and outputs adopted in the table, the efficiency of the provinces' road safety measures will be determined.

Characteristics of inputs and outputs

Table 2 summarises descriptive statistics on the characteristics acting as inputs and outputs.

Table 2. *Descriptive statistics*

Descriptive statistics	Number of speed cameras and sectional speed measurements per 100 km of road	Number of traffic police per 100 km of road	Expenditure on roads per 100 km^2	Number of road accident victims per 10000 inhabitants (killed and injured)
min	0,10	2	970346	5
max	0,38	5	5179234	12
average	0,20	3,00	3019237	7
standard deviation	0,07	1	1254758	2
coefficient of variation [%]	35,18	24,56	41,56	24,58

Source: own study

Analysing the first of the outlays included in Table 2 and the baseline data, it can be seen that the highest number of speed cameras and sectional surveys per 100 km of road is in Lubuskie Province, while the lowest is in Kujawsko-Pomorskie Province. The Podkarpackie and Zachodniopomorskie Provinces obtained the average value of I1 effort. There are no significant disparities between the provinces, as indicated by the coefficient of variation of about 35%. Considering the following input I_2, it can be seen that the lowest number of traffic police per 100 km is found in four provinces: kujawsko-pomorskie, lubelskie, świętokrzyskie and warmińsko-mazurskie, while the highest is found in Śląsk. There is no significant disproportion between the variables (coefficient of variation 25%). There is no significant disproportion in the third I_3 input either. The lowest value of the I3 input is found in the Świętokrzyskie Province and the highest in the Warmińsko-Mazurskie Province.

Determination of efficiency and ranking of facilities

Based on the DEA CCR method, the level of efficiency of road safety measures at the provincial level in 2022 was recognised (Table 3).

Table 3. *Results of input-oriented CCR*

Province	Efficiency
dolnośląskie	**1,000**
kujawsko-pomorskie	0,786
lubelskie	0,625
lubuskie	0,583
łódzkie	**1,000**
małopolskie	0,898
mazowieckie	0,583
opolskie	0,673
podkarpackie	0,550
podlaskie	0,448
pomorskie	0,596
śląskie	0,429
świętokrzyskie	**1,000**
warmińsko-mazurskie	0,626
wielkopolskie	0,752
zachodniopomorskie	0,611

Source: own study

As can be seen from Table 3 above, fully effective, due to all inputs, are the three provinces of Łódź, Świętokrzyskie and Dolnośląskie. The remaining thirteen provinces are inefficient. Significant disproportions exist between provinces regarding the efficiency of transforming inputs into results. The least effective is Śląskie Province, whose efficiency is 42.86% of that which it could have achieved if it had constructed its *technology* of road safety measures along the lines of that of the Świętokrzyskie Province). Podlaskie Province has a similarly low efficiency of 44.84%. The fully effective provinces selected were benchmarks for ineffective provinces. The main benchmark for benchmarking was the Świętokrzyskie province – 11 times with the Łódzkie Province – 10. The Dolnośląskie Province, despite being fully effective, did not fulfil the benchmark even once.

Efficiency of scale and optimal technologies

Table 4 shows the coefficients of scale efficiency economies of scale) and the intensity of scale inefficiency. Scale efficiency reflects the impact of the scale of road safety activities carried out on its efficiency in a given province. The greater the discrepancy in scale efficiency ratings, the lower the scale efficiency and the more adverse the effect of scale on efficiency (Thanassoulis, 2011). Information on economies of scale is very important for deciding on the desired size of road safety measures at the provincial level. If a province is at a point where there are increasing economies of scale, then it makes sense to increase the scale of the policy in order to achieve greater benefits, as there will be more increase in policy expenditures.

Table 4. *Indicators of economies of scale*

No.	Province	Scale efficiency	Type of economies of scale
1	**dolnośląskie**	1	fixed
2	kujawsko-pomorskie	0,714	increasing
3	lubelskie	0,417	increasing
4	lubuskie	0,583	increasing
5	**łódzkie**	1	fixed
6	małopolskie	1,143	declining
7	mazowieckie	0,583	increasing
8	opolskie	0,875	increasing
9	podkarpackie	1	fixed
10	podlaskie	0,575	increasing
11	pomorskie	0,974	increasing
12	śląskie	0,857	increasing
13	**świętokrzyskie**	1	fixed
14	warmińsko-mazurskie	0,797	increasing
15	wielkopolskie	1,094	declining
16	zachodniopomorskie	0,722	increasing

Source: own study

As can be seen from Table 4, 10 provinces show increasing economies of scale, suggesting an increase in their road safety activities. Four provinces show constant economies of scale, while two show decreasing economies of scale. Pomorskie and śląskie Provinces have the largest increasing economies of scale.

Table 5. *Empirical and Optimal Technologies*

No.	Province	Empirical technology			Optimal technology		
		I_1	I_2	I_3	Q_1	Q_2	Q_3
1	**dolnośląskie**	0,16	4	3668156,77	0,16	4	366156,77
2	kujawsko-pomorskie	0,10	2	2392903,42	0,08	1	693104,01
3	lubelskie	0,18	2	3060365,53	0,09	1	916288,11
4	lubuskie	0,38	3	2877895,56	0,13	2	1282803,35
5	**łódzkie**	0,22	3	2199091,46	0,22	3	2199091,46
6	małopolskie	0,14	3	2139248,70	0,13	2	1108966,42
7	mazowieckie	0,29	3	5066776,77	0,13	2	1282803,35
8	opolskie	0,14	3	1665817,84	0,09	2	831724,82
9	podkarpackie	0,20	4	3552591,04	0,11	2	970345,62
10	podlaskie	0,23	3	1778514,59	0,09	1	797427,47
11	pomorskie	0,30	4	2485831,81	0,16	2	1481650,57
12	śląskie	0,22	5	2068163,39	0,09	2	831724,82
13	**świętokrzyskie**	0,11	2	970345,62	0,11	2	970345,62
14	warmińsko-mazurskie	0,19	2	5179233,81	0,12	2	1122764,03
15	wielkopolskie	0,17	3	4575902,37	0,13	2	1145591,51
16	zachodniopomorskie	0,20	3	4626958,82	0,12	2	1178650,77

Source: own study

As seen from Table 5, in the case of the Śląskie province, which was the least efficient of the surveyed provinces, all three outlays should be reduced by approximately 30 – 40%—similarly, Podlaskie Province. The largest change in outlays I_1 should be made in Lubuskie and Podkarpackie Provinces by about 30%. The least change in outlays I_1 should occur in the provinces of małopolskie and wielkopolskie. The outlay I_2 should change the least in the provinces of Śląskie (ca. 65%) and Podkarpackie (ca. 55%). On the other hand, the most minor change for this outlay should be made in the Wielkopolskie and Kujawsko-Pomorskie Provinces (ca. 30%). The I_3 outlays are used least effectively in the Warmińsko-mazurskie, Wielkopolskie, Zachodniopomorskie and Mazowieckie Provinces (about 20%), while they are used most effectively in the Pomorskie and Małopolskie Provinces (about 50%). Outlay I_3 is the least effectively used of all outlays.

Summary

The problem of road safety efficiency research is reflected in many publications. Research on road safety efficiency using the DEA benchmarking method refers to many aspects. The most common ones in the literature include research on the efficiency of European countries, implementation of selected road safety problems or decision support for actions taken. Based on research carried out into road traffic safety measures by province, using the DEA – CCR model, it appears that the fully effective provinces are the Dolnośląskie, Łódzkie and Świętokrzyskie. On the other hand, the provinces of Śląskie and Podlasie are the least effective. The technical efficiency of most provinces is low. Of the provinces studied, three achieve constant economies of scale; these are fully efficient, nine have increasing economies of scale, and two have decreasing economies of scale.

The DEA method's use to assess the efficiency of road safety measures in Poland is an essential tool in decision-making at various levels of governing. At the same time, as in the case of other methods of assessing road safety measures, they are challenging to define quantitatively, and they require great caution in formulating conclusions. It seems necessary to consider additional information and data on the course of the analysed processes to make rational decisions.

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