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ORIGINAL PAPER

APPLICATION OF METHODS OF TWO-DIMENSIONAL DATA ANALYSIS BASED ON OBSERVATION DEPTH MEASURE IN A SAMPLE

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Abstract

In Poland, cycling is becoming increasingly popular as a fast form of transport and recreation. The aim of this study was to assess the density of bicycle paths and the percentage of road accidents involving bicycles as the responsible vehicle in voivodeships, using selected statistical methods based on observation depth measure in a sample. The methods used allowed for the ranking of voivodeships in terms of the values of the diagnostic features studied and the identification of voivodeships with the lowest or highest values of bicycle path density and the percentage of road accidents in which a bicycle was the vehicle responsible. Based on the analysis, it can be concluded that the highest density of bicycle paths in the years under study was recorded in the Pomorskie, Wielkopolskie, and Śląskie voivodeships, while the highest percentage of road accidents in which a bicycle was the perpetrator was recorded in the Małopolskie and Podkarpackie voivodeships. The lowest density of bicycle paths was recorded in the Warmińsko-Mazurskie voivodeship.

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ZASTOSOWANIE METOD DWUWYMIAROWEJ ANALIZY DANYCH OPARTYCH NA MIARACH ZANURZANIA OBSERWACJI W PRÓBIE

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Słowa kluczowe: infrastruktura transportowa, odporne metody analizy danych, miara zanurzenia obserwacji w próbie.

Abstrakt

W Polsce zauważyć można coraz większą popularność jazdy na rowerze, który stał się szybką formą transportu oraz rekreacji. Celem pracy jest ocena gęstości dróg rowerowych oraz odsetka wypadków drogowych, gdzie rower jest rodzajem pojazdu sprawcy w województwach wykorzystując wybrane metody statystycznych oparte na zanurzania obserwacji w próbie. Wykorzystane metody pozwoliły na dokonanie rangowania województw ze względu na wartości badanych cech diagnostycznych oraz na określenie, w których województwach zanotowano najniższe lub najwyższe wartości gęstości dróg dla rowerów oraz odsetka wypadków drogowych, gdzie rower był pojazdem sprawcy. Na podstawie przeprowadzonej analizy można stwierdzić, że największą gęstością dróg dla rowerów w badanych latach charakteryzowało się województwa pomorskie, wielkopolskie oraz śląskie, natomiast największy odsetek wypadków drogowych, gdzie rower był pojazdem sprawcy zanotowano w województwach małopolskim oraz podkarpackim. Najmniejszą gęstością dróg dla rowerów charakteryzowało się województwo warmińsko-mazurskie.

Introduction

Cycling infrastructure is developing very rapidly in Poland. Statistics Poland (*Główny Urząd Statystyczny*, GUS) defines a cycle path as "*a path or part of a road that is not a carriageway, which is marked with appropriate road signs, and is intended for the movement of bicycles, electric scooters and personal transport devices, as well as persons moving with the aid of mobility aids in cases provided for by the Act*". Cycle paths in Poland include lanes enabling bicycle traffic on roads, or specially designated bicycle routes (GUS, 2024).

Cities in Poland are increasingly adopting bicycle-friendly policies. Various strategies and documents support this trend, including the Road Traffic Law, regulations issued by the Minister of Transport and Maritime Economy, the European Strategy for Low-Emission Mobility, and other related bicycle traffic guidelines (Hyła, 2023, p. 13-15).

One can observe the growing popularity of cycling, which has evolved not only into a means of transportation but also an enjoyable and active form of leisure. In 2021, Statistics Poland conducted a survey among households on the participation of Poles in sports and physical recreation. Almost 80% of households had a bicycle, and cycling was a common leisure activity (with over 60% of people participating in this form of recreation). For the period from 1 October 2020 to 30 September 2021, expenditure on bicycles amounted to PLN 92 per household (GUS, 2022).

The bicycle is a means of transport often used by the public. It should be noted, however, that cycling is not the safest form of transport. According to a report presented by the Traffic Department of the Gdańsk City Police Headquarters, the number of traffic accidents involving cyclists, in which they are the victims, is still significant. Although most people assessed the safety of cycling on cycle paths as good, cycling safety is influenced not only by cycling infrastructure but also by traffic regulations and the popularity of cycling (Sommer & Zakrzewski, 2021, p. 313-333).

A frequently used method of transport in urban environments is the city bicycle system. The use of this mode of transport significantly reduces travel time in the city and relieves pressure on trams and buses. Polish cities are increasingly promoting this mode of transport. A positive aspect is the fact that the city bicycle system is easy to use and user-friendly (Dębowska *et al.,* 2017).

The objective of this study is to assess the density of cycle paths and the percentage of road accidents in which a bicycle is the vehicle of the party at fault across voivodeships, using selected statistical methods based on observation depth measure in a sample. The relevant computations and figures were produced using the Statistica PL program and appropriate R environment packages.

Research Methodology

Statistical methods enable the analysis of economic phenomena and the identification of patterns that govern them. To this end, methods based on classical or positional characteristics can be used. In a data set, there are sometimes observations that are distant from the others (atypical) due to high or low values of diagnostic features. At the beginning of data analysis, it is essential to identify and address these observations, either by eliminating them or applying robust data analysis methods to mitigate their impact. The use of classical statistical methods that are not robust to the occurrence of outliers may distort statistical analysis and lead to incorrect conclusions. Methods for detecting outliers in multi-dimensional samples have been explored by Heilpern (2005) and Pawełek & Zeliaś (1996). Additionally, robust data analysis methods have been discussed by Maronna *et al.* (2019) and others.

Statistical methods based on observation depth measure in a sample are robust methods increasingly used in statistical data analysis. They can be used to determine statistical measures, perform statistical inference, rank and order multi-dimensional observations, or detect outliers. By using observation depth measure in a sample, it is possible to assess the distance of an observation from the centre of the data set under analysis (Kosiorowski, 2012; Mosler, 2013, p. 17-34; Mosler & Mozharovskyi, 2022, p. 348-368). Selected methods concerning observation depth measure in a two-dimensional sample have been described by Wagner and Kobylińska (2002), among others.

The concept of observation depth measure in a sample was introduced by Tukey (Tukey, 1975, p. 523-531). Statistical methods based on observation depth measure in a sample have been widely discussed in the literature on the subject and are increasingly used in statistical data analysis. They require, however, that certain related concepts be introduced.

Let us assume that a two-dimensional set is being analysed $P_n^2 \in = \{x_1, x_2, \dots x_n\}$, where each vector is x_i regarded as a point in a 2-dimensional space. In this study, data analysis was conducted for each point belonging to two-dimensional data sets. Liu's simplex depth measure (*Lzan*$_2$) for point θ in a sample P_n^2 is used to denote the function:

$$Lzan_2(\theta, P_n^2) = N_3^{-1} \sum_{1 \le i < j < k \le n} \mathrm{I}\left[\theta \in \Delta\left(x_i, x_{j,} x_k\right)\right], \quad (1)$$

where $\Delta(x_i, x_j, \dots x_k)$ are closed simplices such that $x_i, x_j, \dots x_k \in P_n^2$. N_3 specifies the number of all the simplices that can be constructed from the elements of the sample P_n^2, whereas I(A) is an indicator function that takes the value of 1 if the point θ belongs to simplex $\Delta(x_i, x_j, \dots x_k)$, or the value of 0 in the opposite case (Liu, 1990, p. 405-414; Liu *et al.*, 1990).

The values of observation depth measure in a sample belong to the range of <0; 1>. The observation corresponding to the higher depth measure value is situated more centrally in the data set under study. The lowest values of these measures correspond to the observations that are most distant from the data set centre due to low or high values of diagnostic features (Struyf & Rousseeuw, 2000, p. 415-426).

Let us assume that k is the minimum number of points in the sample P_n^2, belonging to a two-dimensional half-plane, whose dividing line passes through the point θ. Point θ does not necessarily belong to the sample P_n^2.

The set $R(k) = \{\theta: zan_p(\theta, P_n^2) \ge k\}$, where $zan_p(\theta, P_n^2)$ defines the depth of point θ in sample P_n^2 is called the area enclosed by the contour of the k-th degree of depth. The depth contours are determined as the common part of all half-planes with the k-th degree of depth. Depth contour figures are convex and ascending polygons. An observation situated inside a particular contour has a depth value higher than k, whereas if it lies outside the contour, it has a depth value lower than k. A particular observation corresponds to a depth value equal to k if it belongs to the edge of the contour with a k-th degree of depth (Ruts & Rousseeuw, 1996, p. 153-168).

In the present article, statistical analysis for two-dimensional data was enhanced with methods based on observation depth measure in a sample. The mrfDepth package for the R environment, developed by Pieter Segaert, Mia Hubert, Peter Rousseeuw, Jakob Raymaekers and Kaveh Vakili, was used to determine Liu's simplex depth measure values and to produce depth contour plots.

Analysis of the findings

The present study utilised data on the length of cycle paths and the percentage of road accidents where a bicycle was the vehicle of the party at fault in the years 2018 and 2023. The data was sourced from the Local Data Bank of Statistics Poland.

The analysis used secondary data concerning:

– X18 – density of cycle paths in 2018 (expressed as km per 100 km^2),

– X23 – density of cycle paths in 2023 (expressed as km per 100 km^2),

– Y18 – the percentage of road accidents where a bicycle is the vehicle of the party at fault in 2018 (%),

– Y23 – the percentage of road accidents where a bicycle is the vehicle of the party at fault in 2023 (%).

Firstly, a statistical analysis of the data was conducted using the Statistica PL programme. Figures were produced to illustrate the distributions of the analysed variables and the correlation between them.

Based on the values of the studied variables (Tab. 1), the lowest densities of cycle paths per 100 km^2 in the years under study were noted in Podlaskie, Świętokrzyskie and Warmińsko-Mazurskie voivodeships, where, in 2018, the cycle path density was less than 3 km per 100 km^2. In another year under study, the density of cycle paths in the above-mentioned voivodeships increased by over 50%, with the highest increase of 81.78% in Świętokrzyskie Voivodeship. The highest density of cycle paths in the years under study was noted in Śląskie Voivodeship, where, in 2023, there were almost 12 km of such paths per 100 km^2. Compared to Warmińsko-Mazurskie Voivodeship, the density of cycle paths was more than three times higher. In terms of cycle path density, four voivodeships ranked highest (Kujawsko-Pomorskie, Pomorskie, Śląskie and Wielkopolskie). In 2023, the density of cycle paths in Kujawsko-Pomorskie, Śląskie and Wielkopolskie voivodeships increased by approximately 50%. In 2023, Małopolskie Voivodeship recorded the largest increase in the cycle path density and the percentage of road accidents where a bicycle was the vehicle of the party at fault. The cycle path density increased in 2023 across all voivodeships. Despite the increase in cycle path density, the percentage of road accidents where a bicycle was the vehicle of the party at fault increased in only seven voivodeships, most significantly by 1.2 percentage points in Lubuskie Voivodeship.

In Śląskie Voivodeship, in 2023, the density of cycle paths increased by almost 60%, which may have had a positive effect on the reduction (by 1.06 p.p.) in the percentage of road accidents where a bicycle was the vehicle of the party at fault. The largest increase in the percentage of road accidents under analysis, by 2.57 and 5.61 p.p., respectively, was noted in 2023 in Małopolskie and Podlaskie voivodeships. It is worth noting that in Małopolskie Voivodeship, the highest increase in cycle path density was observed in 2023 compared to 2018.

Table 1

The values of the variables under study in 2018 and 2023

Specification	2018		2023	
	X18	Y18	X23	Y23
Dolnośląskie	4.49	5.96	6.57	7.51
Kujawsko-Pomorskie	5.85	5.45	9.03	6.78
Lubelskie	3.03	7.80	4.89	8.07
Lubuskie	4.28	4.54	6.22	3.34
Łódzkie	4.22	5.75	6.52	5.40
Małopolskie	3.57	7.64	8.11	13.25
Mazowieckie	5.61	5.79	8.50	5.78
Opolskie	4.44	6.04	7.11	6.19
Podkarpackie	3.45	8.09	4.53	7.14
Podlaskie	2.86	3.80	4.37	6.37
Pomorskie	6.79	5.04	8.99	6.55
Śląskie	7.57	6.34	11.99	5.28
Świętokrzyskie	2.36	5.41	4.29	5.51
Warmińsko-Mazurskie	2.29	7.34	3.65	6.40
Wielkopolskie	6.12	6.72	9.45	6.23
Zachodniopomorskie	3.70	4.92	5.70	5.29

X18, X23 – density of cycle paths (expressed as km per 100 km^2)
Y18, Y23 – the percentage of road accidents where a bicycle is the vehicle of the party at fault (%)
Source: Local Data Bank (2025), GUS.

The numerical characteristics of the variables under analysis (Tab. 2) indicate that the average cycle path density in 2023 increased by approximately 2.5 km per 100 km^2 of the area. In 2023, the density of cycle paths exceeded 6.55 km per 100 km^2 in half of the voivodeships. Unfortunately, this did not contribute to a reduction in the percentage of road accidents where a bicycle was the vehicle of the party at fault. In this case, the mean value increased by approximately 0.53 p.p. in 2023. The distributions of the cycle path density and the percentage

Table 2

Statistical Indicators of Analysis

Specification	Average	Median	Minimum	Maximum	Standard deviation	Coefficient of variation	Skewness
X18	4.41	4.25	2.29	7.57	1.58	35.71	0.54
Y18	6.04	5.88	3.80	8.09	1.23	20.29	0.13
X23	6.87	6.55	3.65	11.99	2.32	33.82	0.54
Y23	6.57	6.30	3.34	13.25	2.09	31.77	2.19

Source: compiled using Statistica PL.

of road accidents under discussion in the particular years were characterised by right-sided asymmetry, although in the case of the distribution of variable Y18, it was very weak. It can be argued that in 2018 and 2023, most voivodeships showed below-average values of the features under study. Notably, in 2023, the percentage of road accidents in which a bicycle was the vehicle of the party at fault was recorded in 11 voivodeships. The direction and strength of asymmetry of the variables under study can be viewed in the histograms (Fig. 1 and 2).

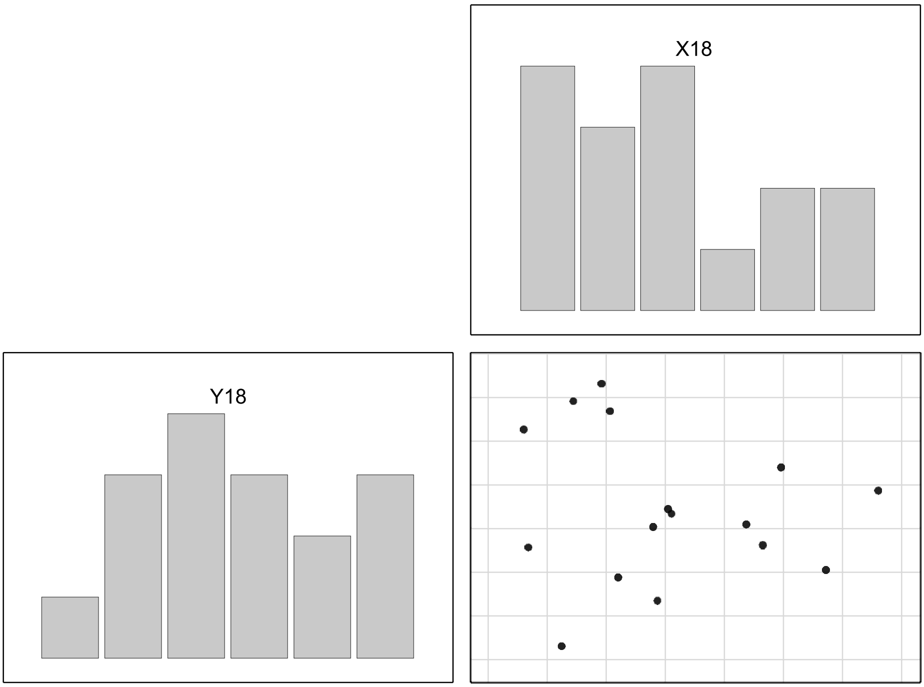

Fig. 1. Matrix figure for the variables in 2018

Source: compiled using Statistica PL.

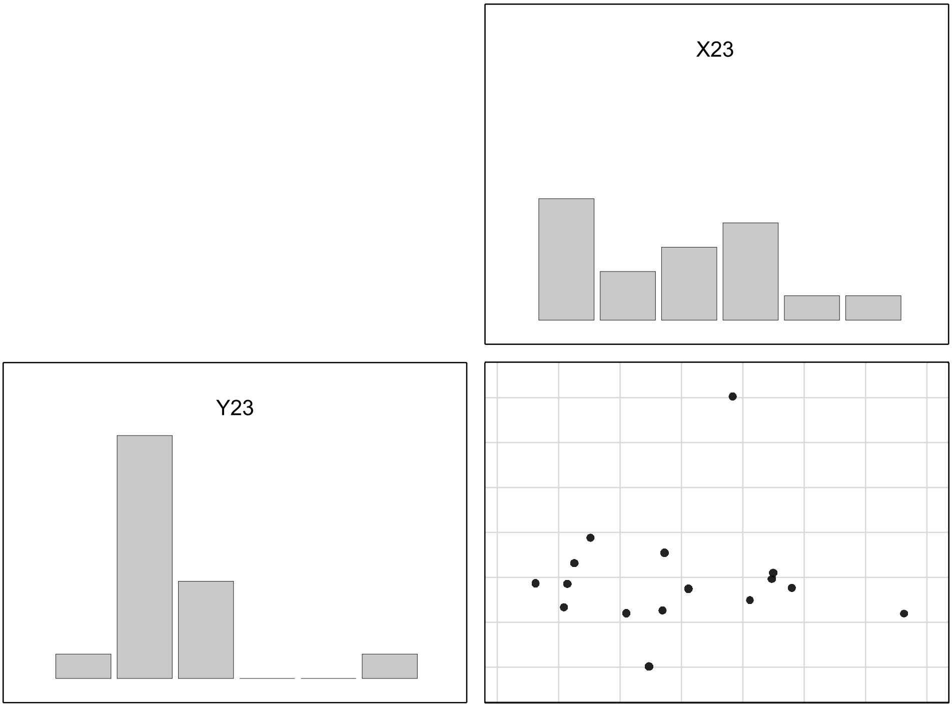

Fig. 2. Matrix figure for the variables in 2023
Source: compiled using Statistica PL.

The matrix figures (Fig. 1 and 2) enable the visualisation of the relationships between the variables. The value of Pearson's linear correlation coefficient between the variables for 2018 is –0.14, whereas for 2023 it is 0.04. The low values of these coefficients indicate a very weak relationship between the variables under study. The correlation figures show the occurrence of points that deviate significantly from the others (atypical) due to extreme values of the feature X or Y.

Liu's simplex depth measure values, provided in Table 3, allowed the voivodeships to be ordered in accordance with their distance from the centre of the two-dimensional samples. Each voivodeship was assigned a rank in accordance with its corresponding depth measure value. It can be noted that in the years concerned, the lowest depth measure values correspond to six and five voivodeships, respectively. In these voivodeships, the density of cycle paths or the percentage of road accidents where a bicycle was the vehicle of the party at fault achieve either low or high values. In 2018, Lubuskie Voivodeship ranked eighth in terms of the depth measure values, whereas in 2023, it is the most distant from the centre of the two-dimensional set due to the lowest percentage of road accidents under analysis. In the years under study, the highest value of Liu's simplex depth measure was observed for Opolskie Voivodeship, indicating that it is most centrally situated in the two-dimensional data sets. The values of variables for this voivodeship are determined by two-dimensional median vectors of the [4.44; 6.04] and [7.11; 6.19] coordinates, respectively. It can be assumed that the cycle path density and the percentage of road accidents where a bicycle is the vehicle of the party at fault in Opolskie Voivodeship reach, in this case, the most typical values. In 2018, Podlaskie Voivodeship was situated at the outside of the data set due to the lowest percentage of road accidents under analysis.

The depth measure values enabled the production of numerical ranges that indicate which voivodeships correspond to specific depth measure values. In each year, the voivodeships were divided into four groups.

Table 3

Simplex depth measure values for variable data

Voivodeship	$Lzan_2$ (2018)	Range 2018	Voivodeship	$Lzan_2$ (2023)	Range 2023
Podkarpackie	0.188	3.5	Lubuskie	0.188	3
Podlaskie	0.188	3.5	Małopolskie	0.188	3
Pomorskie	0.188	3.5	Śląskie	0.188	3
Śląskie	0.188	3.5	Świętokrzyskie	0.188	3
Świętokrzyskie	0.188	3.5	Warmińsko-Mazurskie	0.188	3
Warmińsko-Mazurskie	0.188	3.5	Lubelskie	0.211	6
Lubelskie	0.211	7.5	Kujawsko-Pomorskie	0.230	7.5
Lubuskie	0.211	7.5	Podkarpackie	0.230	7.5
Wielkopolskie	0.246	9	Pomorskie	0.266	9
Małopolskie	0.273	10	Wielkopolskie	0.268	10.5
Zachodniopomorskie	0.295	11	Zachodniopomorskie	0.268	10.5
Kujawsko-Pomorskie	0.311	12	Podlaskie	0.275	12
Mazowieckie	0.341	13	Dolnośląskie	0.293	13.5
Łódzkie	0.404	14	Mazowieckie	0.293	13.5
Dolnośląskie	0.416	15	Łódzkie	0.295	15
Opolskie	0.418	16	Opolskie	0.425	16

Source: compiled using the mrfDepth package.

The first group includes voivodeships for which low or high values of the studied features were noted in the years under study. In 2018. Podlaskie Voivodeship showed the lowest percentage of road accidents (3.8%), whereas in 2023, this percentage increased by approximately 2.5 p.p. Śląskie, Świętokrzyskie and Warmińsko-Mazurskie voivodeships belong in each year to group 1 due to the

Table 4

Groups of voivodeships with individual depth measure values

Voivodeship group number	Interval of values for the depth measure	Voivodeships (year 2018)	Voivodeships (year 2023)
Group 1	<0; 0.211)	Podkarpackie, Podlaskie, Pomorskie, Śląskie, Świętokrzyskie, Warmińsko-Mazurskie	Lubuskie, Małopolskie, Śląskie, Świętokrzyskie, Warmińsko-Mazurskie
Group 2	<0.211; 0.266)	Lubelskie. Lubuskie. Wielkopolskie	Lubelskie. Kujawsko-Pomorskie. Podkarpackie
Group 3	<0.266; 0.295)	Małopolskie, Zachodniopomorskie, Kujawsko-Pomorskie	Pomorskie, Wielkopolskie, Zachodniopomorskie, Podlaskie, Dolnośląskie, Mazowieckie, Łódzkie
Group 4	<0.95; 0.425>	Mazowieckie, Łódzkie, Dolnośląskie, Opolskie	Opolskie

Source: compiled using the mrfDepth package.

very high cycle path density (Śląskie Voivodeship) and a very low value of this feature as compared to the other voivodeships (Świętokrzyskie and Warmińsko-Mazurskie) respectively.

The contours of depth shown in Figures 3 and 4 represent convex and ascending polygons. The shape of the internal contours of depth is more circular for the data in 2018. This indicates a lower concentration of the values of the analysed variables around the centre of the two-dimensional sample, as compared

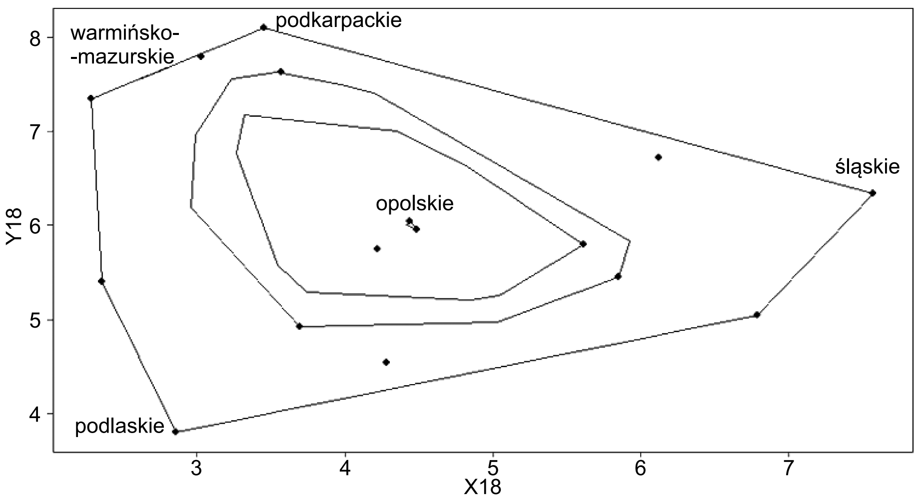

Fig 3. Depth contour figure for the data from 2018
Source: compiled using the “mrfDepth” package.

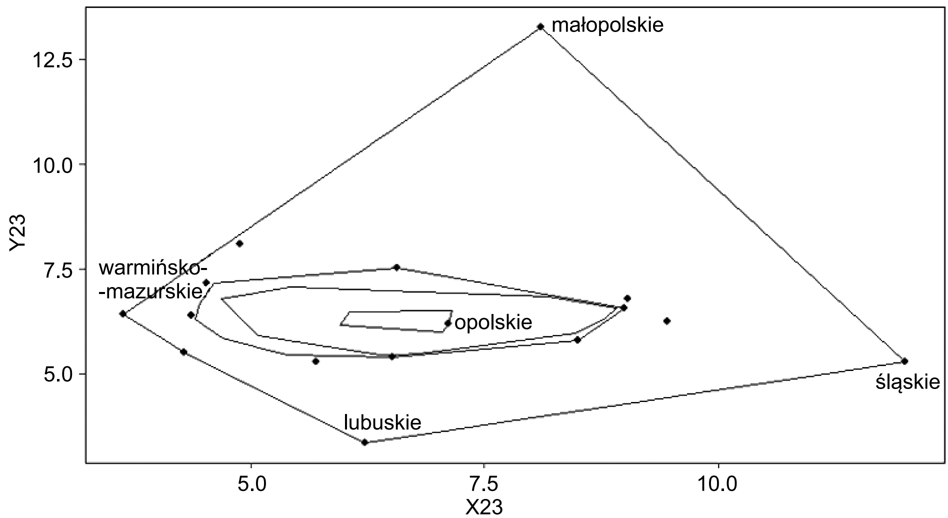

Fig. 4. Depth contour figure for the data from 2023
Source: compiled using the “mrfDepth” package.

to 2023. It is worth noting that Opolskie Voivodeship is situated centrally on the figures produced. In this voivodeship, the values for cycle path density and the percentage of road accidents in which a bicycle is the vehicle of the party at fault are the most typical. In Śląskie Voivodeship the percentage of road accidents in which a bicycle is the vehicle of the party at fault is similar to the values noted in Opolskie Voivodeship; however, the cycle path density is significantly higher, with almost 12 km per 100 km^2 in 2023. It can be noted that the shape of the convex hull (the outermost depth contour) is more “elongated” for the data from 2018, due to the high and low values of the features noted in this year in Śląskie and Warmińsko-Mazurskie voivodeships.

Summary and conclusions

Based on the analysis conducted. it can be concluded that:

– the voivodeships that showed a high density of cycle paths in the years under study included Pomorskie, Wielkopolskie and Śląskie,

– the highest percentages of road accidents where a bicycle was the vehicle of the party at fault were noted in Małopolskie and Podkarpackie voivodeships,

– the lowest density of cycle paths was observed in Podlaskie, Świętokrzyskie and Warmińsko-Mazurskie voivodeships,

– in 2018, in Podlaskie Voivodeship, the lowest percentage of road accidents where a bicycle was the vehicle of the party at fault was noted, whereas in 2023, this percentage increased in this voivodeship by approximately 2.5 p.p.,

– the most typical values of the analysed features in the years under study were noted in Opolskie Voivodeship,

– in Warmińsko-Mazurskie Voivodeship, the lowest cycle path density and a high percentage of road accidents where a bicycle was the vehicle of the party at fault were noted,

– Śląskie Voivodeship noted the highest density of cycle paths in the years under study, and in 2023, it ranked second in terms of the percentage of road accidents under analysis.

Data analysis methods based on observation depth measure in a sample can be used to:

– organise voivodeships according to their distance from the central sample concentration,

– identify the voivodeships that can be considered the most typical in terms of the diagnostic feature values,

– identify the voivodeships that showed very low or very high values of the diagnostic features under analysis,

– rank voivodeships according to the values of the diagnostic features under analysis,

– determine the concentration of the values of the variables under study in Let us assume that a two-dimensional set data sets.

It is noticeable that. in recent years. cycling has become increasingly popular as a means of transportation. This is a beneficial phenomenon. especially in terms of environmental protection and public health. It is worth noting that the density of cycle paths in Poland is increasing. To encourage Poles to cycle to work and on tourist trips. it is essential to increase the density of cycle paths and maintain cycling infrastructure in a technical condition that ensures its safe use.

Translated by Joanna Jensen

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