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THE RELATIONSHIP BETWEEN BICYCLE TRAFFIC AND THE DEVELOPMENT OF BICYCLE INFRASTRUCTURE ON THE EXAMPLE OF WARSAW

Tomasz KRUKOWICZ[1], Krzysztof FIRLĄG[2], Aleksander SOBOTA[3], Tomasz KOŁODZIEJ[4], Luka NOVAČKO[5]

[1, 2] Warsaw University of Technology, Faculty of Transport, Warsaw, Poland

[3] Silesian University of Technology, Faculty of Transport and Aviation Engineering, Gliwice, Poland

[4] Public Roads Authority of Warsaw, Department of Sustainable Mobility, Warsaw, Poland

[5] University of Zagreb, Faculty of Transport and Traffic Sciences, Zagreb, Croatia

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Abstract:

The article presents the relationship between the intensity of bicycle traffic volume and the development of bicycle infrastructure on the example of Warsaw. There has been a big increase in cycling over the last decade. At the same time, the linear and point bicycle infrastructure developed very strongly. Similar trends are also observed in other cities in Poland. The article presents the types of infrastructure available to cyclists. Then, the method of assessing the bicycle infrastructure is presented, taking into account the five features of good bicycle infrastructure: cohesion, directness, attractiveness, safety and comfort. In terms of coherence, the analysis covered the bicycle infrastructure network in the vicinity of the measurement site. The directness was tested by checking the accessibility of several dozen of the most important nodal points of the city's communication network. The attractiveness was examined by checking the availability of public bike stations, bicycle racks and bike-sharing stations. The infrastructure adjusted to the technical class of the road was adopted as a measure of safety. The comfort was checked by analyzing the quality of the road surface, which affects the driving comfort and energy expenditure. All the factors presented impact the cyclist's assessment of the infrastructure. To standardize the assessment rules, an aggregate index of the development of bicycle infrastructure was determined. The analysis was carried out for 10 sample points for four consecutive years. The points were characterized by different bicycle infrastructure, location in the city road network and different results of bicycle traffic measurements. The analysis showed a strong positive relationship between traffic and cycling infrastructure for most of the analyzed places. There was a negative dependence in the case of the construction of alternative routes in relation to the place of traffic measurements. The obtained results are the same as in the works of other authors. However, the effects of work do not allow to determine which of the examined factors is the cause and which is the effect but only show the existing relationship.

Keywords: *bicycle, cycle path, bicycle infrastructure, Warsaw, bicycle volume, sustainable transport, vulnerable road users*

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Contact:
1) tomasz.krukowicz@pw.edu.pl [https://orcid.org/0000-0002-5461-4396] - corresponding author; 2) krzysztof.firlag@pw.edu.pl [https://orcid.org/0000-0002-0563-0840]; 3) aleksander.sobota@polsl.pl [https://orcid.org/0000-0002-8171-7219]; 4) kolodziejtomasz@yahoo.pl; 5) luka.novacko@fpz.unizg.hr [https://orcid.org/0000-0001-8376-4222]

1. Introduction

In recent years, the bicycle has been used not only as a sports and recreation tool. It becomes a means of transport used for daily commuting to work and school. In large cities, air pollution and traffic congestion are significant problems. For this reason, Poles more and more often replace a car with a bicycle. The issue of travel costs is not without significance, as they are much lower than in the case of a vehicle.

In the years 2014-2017, there was a very strong development of bicycle infrastructure in Warsaw. The length of the bicycle infrastructure increased by 30% in this period (Table 1) (Czajkowski et al., 2014; Brzeziński et al., 2015; Błaszczak et al., 2016; Gołębiowska et al., 2017). The concept of bicycle infrastructure includes bicycle paths, bicycle and pedestrian paths, bicycle lanes and streets with a cycle counter. In the following years, the high pace of bicycle infrastructure development continued (Górecki et al., 2020).

Table. 1. Length of bicycle infrastructure in 2014-2017 and 2020

Year	Length of bicycle infrastructure [km]
2014	412.5
2015	457
2016	493
2017	537
2020	680.35

Along with the development of the bicycle infrastructure, the share of bicycle traffic in journeys within the territory of Warsaw increases. In the first half of 2018, it was 7%. An interesting research issue is to check whether the development of bicycle infrastructure is related to the increase in bicycle traffic volume. Outside the city center, Warsaw is characterized by a rather loose development. It is the result of the city's reconstruction after World War II. On the one hand, this causes the extension of daily journeys, and on the other hand, it allows for the addition of bicycle infrastructure along the existing streets in many places. The biggest problems with building new bicycle routes occur in the city center.

2. A literature review on bicycle traffic

2.1. Cycling related publications

The subject of bicycle infrastructure is the subject of many current publications. The articles include both research aimed at learning about the laws governing bicycle traffic, research evaluating the impact of bicycle infrastructure on traffic, assessing the safety of bicycle infrastructure, and research related to the sociological aspect of bicycle traffic. Between the 1950s and 1970s, there was a decline in bicycle traffic and increased car traffic in many countries (Wardlaw, 2014; van Goeverden et al., 2015). The actions of the governments of many countries interrupted this trend and resulted in a change of tendency. Due to the increasing importance of cycling has been the subject of many assessments and reports in recent years. One of such documents is (Deloitte, 2018). The report presents the City Mobility Index based on the volumes related to bicycle traffic and public transport for cities located in Asia, South America, Central America and Africa. In most cities, the share of bicycle traffic is negligible.

Depending on the type of bicycle infrastructure used, cyclists behave differently (Aldred & Dales, 2017). The type of infrastructure involves wearing sports clothes, reflective elements and helmets. The study of bicycle traffic includes not only the volume of traffic, but also many other parameters. One of them is the share of bicycles in travel (Bartuska et al., 2016). It depends on the size of the city. In cities with up to 50,000 inhabitants, it is on the order of 7-9%. It decreases in the case of larger towns. There is also a relationship between the distance of the journey and the share of cycling. In the case of trips below 1 kilometer and over 8 km, its percentage is small. The largest share can be observed for journeys of approximately 2 km, which amounts to 17%. The development of a bicycle network is also often associated with the area's prosperity (Flanagan et al., 2016). The lack of cycling investments in poorer regions results in a lack of growth in cycling. Also, the share of sex in cycling is not equal. Although the percentage of women in cycling is increasing, more men still cycle (Dudek & Ostaszewski, 2020). A factor that prompts women to cycle is the fact that the bicycle infrastructure is separated from the road (Garrard et al., 2008). A study (Marqués et al., 2015) shows that increasing the length of cycling infrastructure, increases cycling. Similar conclusions related to the increase in the density of bicycle networks are presented in other articles (Pistoll & Goodman, 2014). Other sources of data on cycling are GPS-based cycling data. They can be used to assess the need to build new cycle routes (Olmos et al., 2020). However, despite its positive impact, the infrastructure itself is not the only factor influencing the development of road traffic. Transport policy and spatial planning are also important (Pucher et al., 2010).

In many studies, indices aggregating various features were used to assess the cycling infrastructure. They take into account traffic safety, cyclist comfort, the route's attractiveness, and its directness. Such an index can be used to assess the sequence of implementation of bicycle investments (Arellana et al., 2020). A similar solution has been proposed in (Makarova et al., 2020). In this method, the number of intersections, bicycle crossings, railway crossings, and route length are assessed. Residents positively evaluate the construction of bicycle infrastructure (Crane et al., 2016). There are negative opinions among the owners of retail outlets, as the number of parking spaces is decreasing. The indicator of the assessment of cycling infrastructure is often the travel time. However, the energy expenditure of a cyclist can be used for this purpose (Cruz et al., 2020). It is possible to optimize the traveled route to minimize energy consumption. The construction of a new bicycle path does not have to cause a decrease in traffic intensity on another road (Heesch et al., 2016). The development of bicycle infrastructure may increase the number of people using this mode of transport. Different conclusions are presented in (Pritchard et al., 2019). In the presented case study, the construction of a new cycle route reduced traffic in another city area. The development of bicycle infrastructure increases residents' independence from cars and public transport. The authors of the study (Rahul & Verma, 2018) indicate that the assessment of such infrastructure should be multi-criteria and also take into account environmental pollution, costs and reducing social inequalities. On the other hand, the study (Song et al., 2017) indicates that the mere expansion of infrastructure is not a sufficient factor to increase bicycle traffic. During the development of bicycle traffic systems, it is reasonable to follow the example of other countries with good experience in this field (Zhao et al., 2018). Cultural differences should also be taken into account, e.g. the need to fence cycle paths to prevent parking.

The surveys show the expectations of traffic participants in relation to the infrastructure. A study in India (Basu & Vasudevan, 2013) shows that building bicycle paths encourages cycling. Research also shows that the presence of bicycle infrastructure affects the sense of safety of cyclists (Branion-Calles et al., 2019). The presence of bicycle infrastructure influences the choice of a given route by a cyclist (Caulfield et al., 2012). Other factors are travel time, speed and volume of bicycle traffic. Road users assess Bicycle paths subjectively (Vallejo-Borda et al., 2020), which should also be considered when assessing road infrastructure. The construction of bicycle paths requires political support (Wilson & Mitra, 2020).

Bicycle traffic safety is an important issue. A study (Billot-Grasset et al., 2016) shows that the most critical circumstances of road incidents are using a bicycle less than once a week, no use of reflective clothing, skidding and a lack of reaction time. Other studies (Kapousizis et al., 2021) indicate the presence of a bus lane, fences, parking lots and a narrow lane width as factors influencing the severity of accidents involving cyclists. The behavior of cyclists also depends on the type of bicycle infrastructure (Cieśla et al., 2018). Especially a lot of abnormal behavior can be observed in places of short discontinuities in the bicycle infrastructure. Due to the significant development of bicycle networks, it is possible to compare different solutions in the field of road safety. A meta-analysis (DiGioia et al., 2017) assesses over a dozen infrastructure solutions. Such studies can be used when selecting the type of line infrastructure and the type of intersection. The use of good road marking, segregating road users, has a positive impact on bicycle traffic safety (Götschi et al., 2018). When crossing the road, the bicycle lane or path for bicycles is the last element of the road cross-section to be crossed (Lachapelle & Cloutier, 2017). For this reason, the elderly may not be able to cross the cycle path on time, which poses a risk of an accident. In addition to the issues of traffic safety, from the cyclist's point of view, the issue of bicycle theft is also essential (Márquez & Soto, 2021). In this study, the most significant number of crashes with fatalities was recorded in accidents with buses and trucks. An important road safety problem is turning vehicles and crossing a bicycle lane (Ng et al., 2017). In such a case, a safer solution is to give way by a cyclist (unlike in Poland). The proliferation of electric bicycles negatively impacts road safety (Rich et al., 2021) due to the increase in the severity of road incidents. An indirect measure of traffic safety is the stress of road users. Road bicycle lanes are more stressful than dedicated bicycle paths, separated from carriageways (Teixeira et al., 2020). Likewise, driving on the main roads is more stressful than on roads of lower categories. Increasing the volume of bicycle traffic requires the introduction of new solutions in the field of road safety (Thompson et al., 2017). Studies conducted in Kazan and Kaliningrad (Trofimenko & Shashina, 2017) also indicate greater safety of the dedicated bicycle infrastructure and the need to reduce the speed of cyclists at collision sites. Road traffic safety studies in the 1950s and 1970s showed that the decline in bicycle traffic in this period contributed to an increase in the number of fatal road accidents (Wardlaw, 2014). Factors unrelated to infrastructure also affect the risk of a road accident. These include weather conditions (Pazdan, 2020), affecting both the bicycle traffic volume and the grip and the ability to observe the road. While most of the work focuses on the risk to cyclists from vehicle traffic, cyclists are a risk to pedestrians (Bauer et al., 2021). Along with the increase in bicycle traffic, the number of such events increases. It is important to take this issue into account when designing bicycle infrastructure.

The features of bicycle traffic also affect the parameters adopted when designing the bicycle infrastructure. The speed of cyclists is used when designing traffic lights to calculate the minimum intergreen times (Buda et al., 2017). Another important aspect of the assessment of bicycle paths is the quality of the surface. It has a significant impact in the evaluation of cycling infrastructure (Calvey et al., 2015). The unevenness and roughness of the surface also impact road traffic safety (Wasilewska, 2019).

Building a bicycle infrastructure requires significant financial outlays. In Poland, this is the task of the road administration, but in other countries, solutions such as crowdfunding and additional taxes for the development of the bicycle system are also analyzed (Miller & Coutts, 2018). Research shows that new infrastructure solutions have a positive cost-benefit balance. Such studies (Rich et al., 2021) also consider the health costs of residents and the costs of road incidents. The construction of bicycle infrastructure faces many problems. The main problems include (Robartes et al., 2021) lack of financing, opposition from residents, modernization of the existing infrastructure. The external cost of transport is also environmental pollution. A study (Zahabi et al., 2016) shows that increasing the length of cycling infrastructure by 7% reduces greenhouse gas emissions by 2%.

2.2. Article content

The article is structured as follows. Section 1 and 2 presents the rationale for the topic and literature review. Section 3 presents the research methodology of the conducted research. Section 4 presents the results of the study. The last part of the article (Section 5 and 6) discusses the results in relation to the literature analysis. The aim of the paper is to show the relationship between the development of bicycle infrastructure and the intensity of bicycle traffic.

3. Methods

3.1. Cycling transport system in Warsaw

The network of infrastructure used to bicycle traffic in Warsaw does not constitute a coherent whole. However, it is expanded annually as a result of planned investments related to the development of cycling infrastructure or as a result of the expansion of the road and street network. In the years covered by the survey, only one north-south bicycle route, the Nadwiślański Cycling Trail, passed through Warsaw downtown, and since mid-2017 an East-West route along Świętokrzyska Street and Tamka Street. The remaining routes of the downtown cycling network were not consistent and did not provide opportunities for longer distance cycling using dedicated cycling infrastructure.

The Veturilo public bicycle system has been operating in Warsaw since 2012. This system allows you to ride free for 20 minutes. This solution revolutionized the way Warsaw residents thought about bicycle transport and contributed to its significant development. Bicycles are rented at the Warsaw stations, which are located throughout the city.

Another important investment-related to cycling in Warsaw was the installation of approximately 1,000 new bicycle racks, suitable for parking two bicycles. It happened in 2017 (Buciak et al., 2017). Bicycle parking spaces are also provided in the P&R parking spaces.

Self-service bicycle repair stations were also expanded between 2014 and 2017. Each station is equipped with a pump with an adapter to fit all types of tire valves and with basic tools such as screwdrivers, an adjustable spanner, ampoule spanners, and a tire bucket. During these years, the number of such stations in the city has increased from a dozen to 151.

Data on the bicycle infrastructure for the purposes of the study were taken from the Bicycle Reports issued by the Office of the Capital City of Warsaw (Błaszczak et al., 2016; Brzeziński et al., 2015; Czajkowski et al., 2014; Gołębiowska et al., 2017) and the maps of the cycle network attached to them.

3.2. Studies on cycling traffic in Warsaw

Since 2014, complex cycling traffic surveys have been carried out in Warsaw. These surveys are carried out in spring and summer at several dozen points. In addition to the traffic volume, factors such as the cyclists' gender, clothing (sporty or casual), helmet use, type of bicycle and mode of infrastructure use (cycle path, pavement, roadway) are examined.

In 2014, automatic bicycle traffic volume measurement stations were also started to use. These are equipped with induction loops in the cycle paths. The measurements are conducted around the clock, which allows to analyze the variability of the traffic volume in time and also the influence of weather conditions on this volume.

The bicycle traffic data for the purpose of the study was taken from the published results of traffic measurements (WPRR, 2014; PRRW, 2015; Buciak et al., 2016, 2017).

3.2. Index Method for Cycling Infrastructure Assessment

To assess cycling infrastructure, an index method has been used (Kołodziej, 2018). It takes into account the point and line infrastructure. The proposed index is based on the characteristics of a good cycling infrastructure listed in (CROW, 1993). These characteristics include:

- cohesion,
- directness,
- attraction,
- safety,
- comfort.

The method assumes the possibility of calculating an indicator to assess cycling infrastructure anywhere in the network. The indicator is based on five coefficients, corresponding to one cycling infrastructure feature listed in (CROW, 1993).

The proposed index was defined as the weighted sum of the coefficients:

$$W = W_1 \cdot w_1 + W_2 \cdot w_2 + W_3 \cdot w_3 + W_4 \cdot w_4 + W_5 \cdot w_5 \tag{1}$$

where:
W_n – n-coefficient value,
w_n – the weighting of the n-coefficient.

The weights of the coefficients were based on a search carried out among experts. In light of the research carried out, the accessibility of linear infrastructure was considered the most important feature. The values of particular weights are presented in Table 2.

Table 2. Features of the cycling infrastructure with their respective weights

Coefficient symbol and name W_n		Weight w_n
W_1	Accesibility of linear infrastructure	30
W_2	Quality of connections	25
W_3	Technical quality	15
W_4	Accesability of point infrastructure	15
W_5	Safety	15

The value of the W indicator can take between 0 and 100, because the W_n coefficients take values in the range from 0 to 1 and the w_n weights add up to 100.

– Coefficient of accessibility for linear infrastructure W_1

The accessibility coefficient of the linear infrastructure W_1 was defined as the ratio of the length of sections of the cycling infrastructure network L_{DDR} and sections of the public road network L_d, where cycling infrastructure can be created. For situations where $L_{DDR} > L_d$ (for example, cycle tracks are designated off-road), the value of 1 shall be taken. The coefficient is calculated for roads within a distance of 1 km from the place where the coefficient is determined. In case of discontinuities in the cycling infrastructure network, the sections behind the discontinuity are taken with a weight of 0.5.

$$W_1 = \frac{L_{DDR}}{L_d} \tag{2}$$

where:
L_{DDR} – lengths of sections of the cycling infrastructure network [km],
L_d – lengths of sections of the public road network where cycling infrastructure can be created [km].

Examples of data for the determination of W1 are shown in Figure 1.

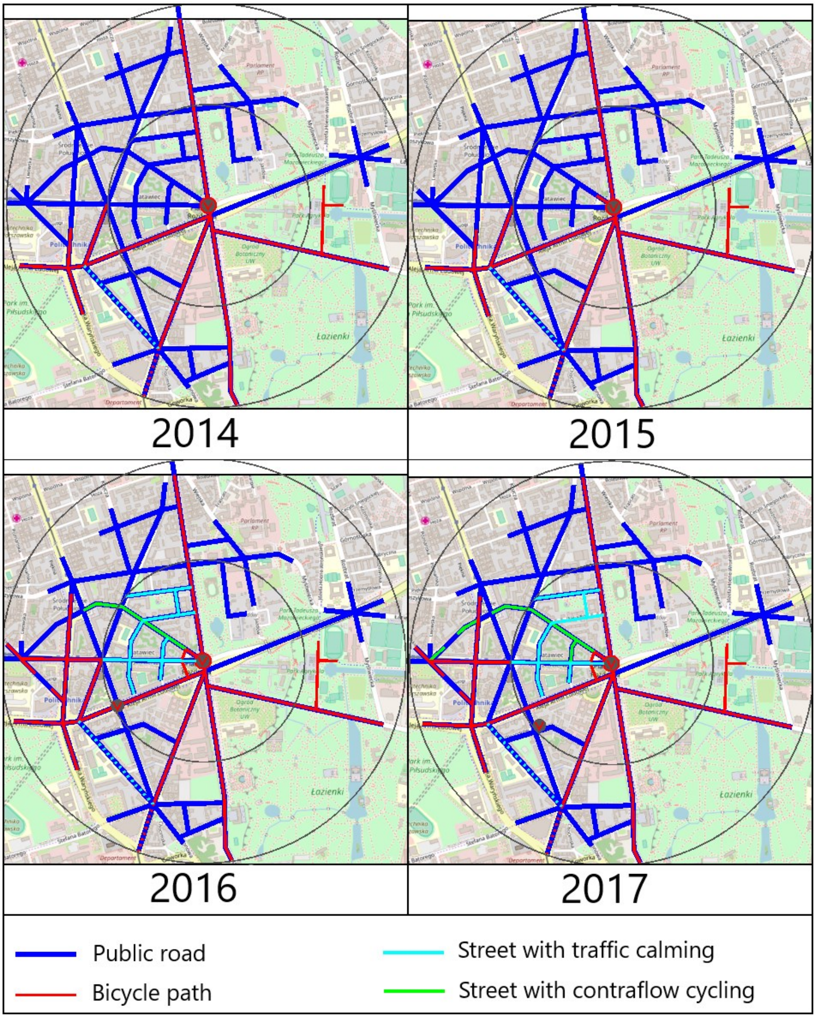

Fig. 1. Road network and network of cycling routes in the neighborhood of Na Rozdrożu square in Warsaw. Background map: OpenStreetMap

– **Coefficient of quality of connections W_2**

The quality connection W_2 is defined as the ratio of the number of main nodes of the cycling network in Warsaw accessible from a given point (P_r) to the number of all transport network nodes (P). For the purposes of the study, the most important public transport interchanges and the main points bordering the city with neighboring municipalities were adopted as main nodes. These places are the origin and destinations of cycling trips connected with transfers to public transport. There are also many points of interest in their vicinity. The 82 points determined in this way are presented in Fig. 2. The formula determines the coefficient:

$$W_2 = \frac{P_r}{P} \tag{3}$$

where:

P_r – the number of main nodes of the cycling network in Warsaw accessible from a given point,

P – the number of all nodes of the transport network.

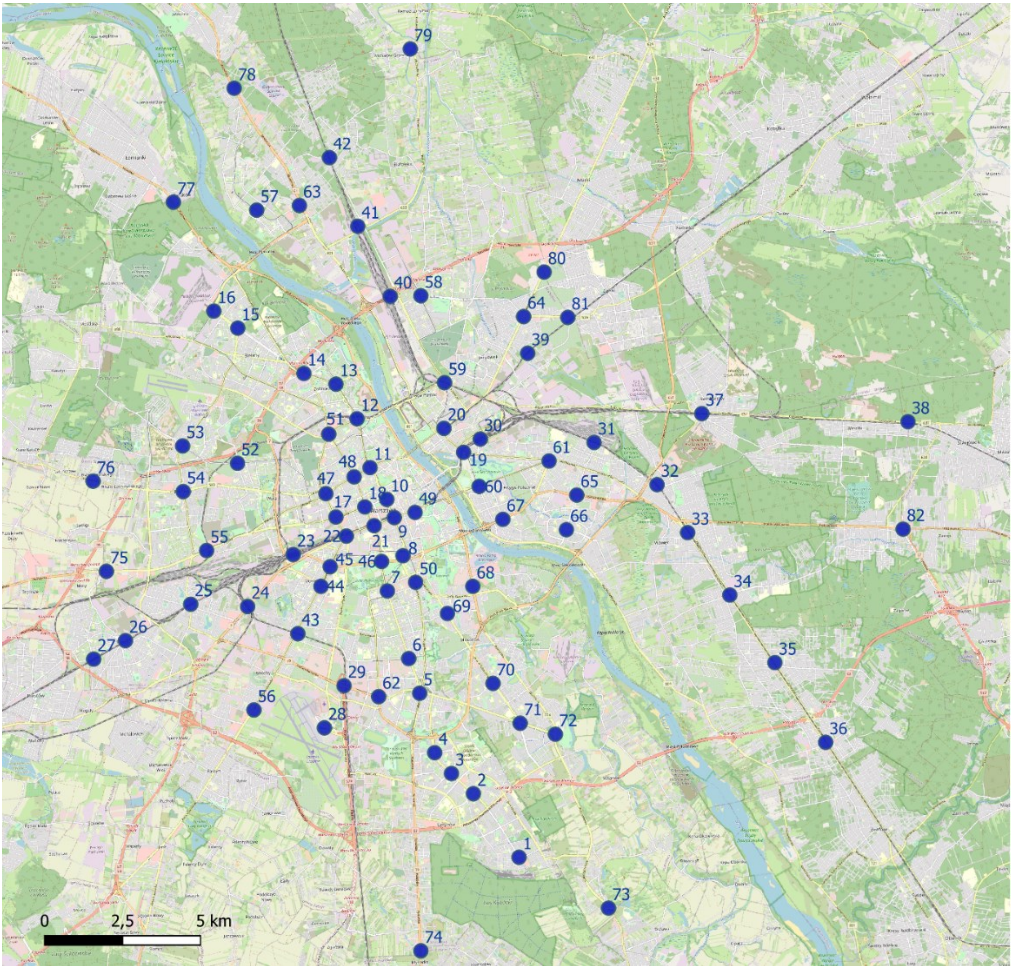

Fig. 2. Main nodes of the road network to be analyzed. Background map: OpenStreetMap

– **Coefficient of technical quality W_3**

The technical quality coefficient determines whether the infrastructure complies with the standards set in the binding ordinance of the Mayor of the Capital City of Warsaw (BDiK, 2010). This coefficient has been included in the method because in the past cycleways have been built without standards referred to in that ordinance. The W_3 factor is defined as:

$$W_3 = \frac{S_r}{S} \cdot \gamma \cdot \varphi \tag{4}$$

where:

S_r – width of linear cycling infrastructure [m],

S – recommended width of cycling infrastructure according to (BDiK, 2010) [m]; in case of $S < S_r$, then $S = S_r$,

γ – surface type coefficient:

- 1.0 for asphalt surfaces in good condition,
- 0.8 for asphalt surfaces in poor condition,
- 0.3 for surfaces made of concrete blocks or slabs in good condition,
- 0 for surfaces of concrete blocks or slabs in poor condition,

φ – horizontal curve coefficient defined as the ratio of the number of curves that comply with the required minima specified in (BDiK, 2010) to the number of all arcs.

– Coefficient of accessibility for point infrastructure W_4

The point infrastructure accessibility factor W_4 is defined as:

$$W_4 = 0.80 \cdot \frac{V}{6} + 0.15 \cdot \alpha + 0.05 \cdot \beta \tag{5}$$

where:

V – number of Warsaw Veturilo bike-sharing stations within a radius of 500 m from the measuring point, not more than 6,

α – 1, if there are at least two u-type bicycle racks within a radius of 50 m from the measuring point, otherwise α shall be 0,

β – 1, if a do-it-yourself bicycle repair station is located within a 500 m radius of the measuring point, and β otherwise takes the value 0.

The result of adopted distances and numbers is derived from the fact that with a higher density of points of a given type (bike-sharing stations, racks and repair stations), no significant improvement in the quality of cycling infrastructure takes place in the perception of cyclists.

– Coefficient of Cycling Safety W_5

The coefficient of cycling safety W_5 takes one of the following values:

- 1.0 – if the infrastructure is as recommended for the technical class of road,
- 0.6 – if the type of infrastructure is not recommended for a given road technical class, but more than one additional means of protecting cyclists have been applied,
- 0.3 – if the type of infrastructure is not recommended for the road technical class but an additional measure is applied to protect cyclists,
- 0 – if the type of infrastructure is not recommended for the given road class and no additional measures to protect cyclists are applied.

4. Research and results

4.1. Research characteristics

Calculating the bicycle infrastructure development index defined according to the presented method is possible for each point of cycling infrastructure. An example of an application of the method is presented by carrying out a survey in Warsaw. The research points were selected based on measurements carried out by the Public Roads Authority of Warsaw. The analysis was carried out for 10 points for which complete data on cycling traffic levels and cycling infrastructure were available for given years. The selected sites were located in various locations in Warsaw. The locations where decreases and increases in cycling traffic were recorded in particular years were selected. The selection of the points surveyed is shown in Table 3.

Table 3. Measurement points selected for analysis

Point no.	Cycle route	Name of crossed street	Approach from direction
1	Jana Pawła II	Stawki	S
2	Prymasa Tysiąclecia	Górczewska	N
3	Prymasa Tysiąclecia	Kasprzaka	N
4	Plac na Rozdrożu	Aleje Ujazdowskie	N
5	Tamka	Topiel	W
6	Belwederska	Spacerowa	S
7	Puławska	Domaniewska	N
8	Most Świętokrzyski	-	-
9	Most Siekierkowski	-	-
10	Most Śląsko-Dąbrowski	-	-

Measurements of distances and lengths were taken using maps of the cycling network attached to Warsaw Bicycle Reports. The geometric parameters of the cycling routes were read from archival orthophoto maps available on the Warsaw City Hall website (Serwis Mapowy Urzędu m. st. Warszawy, 2021). The relationship between the quality of the cycling infrastructure and the level of cycling traffic was carried out using the Pearson correlation coefficient.

4.2. Results

The research was carried out separately for each measuring point. The of the example of the analysis results for one of the points are presented in Tables 4 and 5.

During the analysis of the neighborhood of the survey point, changes in the cycling infrastructure network have been observed due to the designation of traffic-calmed street sections and the increase in the number of Veturilo bike-sharing stations.

Table 5 presents a list of the main points of the road network accessible from the measurement point. In

2014, it was possible to access only 8 nodes of the network by bike. In the course of 4 years, it became possible to access as many as 26 points of the network.

The calculated bicycle infrastructure development indices and measured traffic volumes are shown in Table 6. Due to the single measurement performed between 2014 and 2017, the average traffic volumes measured during the morning and afternoon peak were used for further calculations.

The analysis of the results allowed to conclude that for four measurement points in 2015 an incomprehensible increase of bike traffic volume on the day of the measurements was observed - (example of Fig. 4). Such anomaly was not observed for the remaining measurement points (example of Fig. 5).

Table 4. Results of calculation of the cycling infrastructure development index for measurement point No. 1 - Jana Pawła II avenue

Variable	Year			
	2014	2015	2016	2017
Length of continuous linear cycling infrastructure $\mathbf{L_C}$ [m]	3482	3482	3975	4108
Total length of linear cycling infrastructure after discontinuity $\mathbf{L_P}$ [m]	23	23	835	835
$\mathbf{L_{DDR}}=L_C+0.5\cdot L_P$	3493.5	3493.5	4392.5	4525.5
$\mathbf{L_d}$ [m]	16491	16491	16491	16491
$\mathbf{W_1}$	0.21	0.21	0.27	0.27
$\mathbf{P_r}$	8	10	17	26
P	82			
$\mathbf{W_2}$	0.10	0.12	0.21	0.32
$\mathbf{S_r}$ [m]	2.0	2.0	2.0	2.0
S [m]	2.5	2.5	2.5	2.5
$\mathbf{g}^{1)}$	0.3	0.3	0.3	0.3
$\mathbf{j}^{2)}$	0.33	0.33	0.33	0.33
$\mathbf{W_3}$	0.08	0.08	0.08	0.08
V	3	3	5	5
α	0	0	0	0
β	1	1	1	1
$\mathbf{W_4}$	0.45	0.45	0.72	0.72
$\mathbf{W_5}=\delta$	1.0	1.0	1.0	1.0
W	**31.73**	**32.34**	**40.11**	**43.10**

1) Surface made from red concrete block
2) Two corners on the Stawki Street cycle path without radius

Table 5. Interchanges accessible by linear cycling infrastructure from survey point No. 1 - Jana Pawła II Avenue

Points available in 2014		Points additionally available from 2015		Points additionally available from 2016		Points additionally available from 2017	
No	Name	No	Name	No	Name	No	Name
48	Kino Femina	40	Toruńska	17	Rondo Daszyńskiego	23	Dw. Zachodni
51	Rondo Radosława	58	Kondratowicza	18	Rondo ONZ	8	Politechnika
12	Dw. Gdański			10	Świętokrzyska	50	Rakowiecka
13	Pl. Wilsona			21	Dw. Centralny	69	Dolna
14	Marymont			49	Rondo de Gaulle'a	70	Bonifacego
15	Wawrzyszew			19	Stadion Narodowy	71	Sobieskiego
16	Młociny			20	Dw. Wileński	72	Wilanów
57	Tarchomin					63	Białołęka
						78	Modlińska

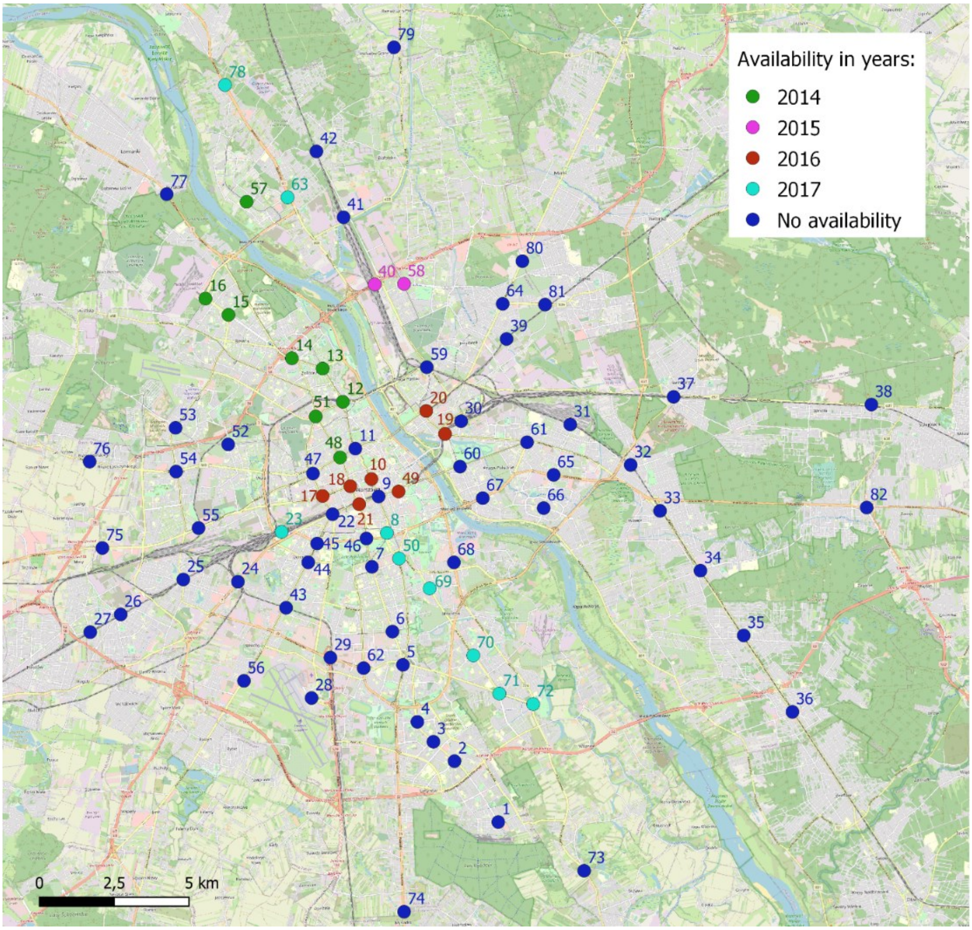

Fig. 3. Interchanges accessible by linear cycling infrastructure from survey point No. 1 - Jana Pawła II Avenue. Background map: OpenStreetMap

Table 6. Comparison of bicycle infrastructure development indices with values of cycling traffic volumes for particular measurement points

Name of the point			Jana Pawła II	Prymasa Tysiąclecia (Górczewska)	Prymasa. Tysiąclecia (Kasprzaka)	Plac na Rozdrożu	Tamka	Belwederska	Puławska	Most Świętokrzyski	Most Siekierkowski	Most Śląsko-Dąbrowski
Point No.			1	2	3	4	5	6	7	8	9	10
2014	Bike volume Q [B/h]	mo.	194	272	448	202	69	171	158	158	143	204
		af.	209	382	439	278	69	321	269	184	360	225
		av.	202	327	444	240	69	246	214	171	252	215
	W		31.73	39.82	30.25	47.59	52.68	31.10	37.47	36.16	53.60	17.00

2015	Bike volume Q [B/h]	mo.	149	193	528	324	103	311	233	305	220	228
		af.	258	223	427	357	226	408	280	620	344	220
		av.	204	208	478	341	165	360	257	463	282	224
	W		32.34	40.74	31.17	49.89	56.83	32.63	38.06	40.15	53.91	17.00
2016	Bike volume Q [B/h]	mo.	257	221	550	275	142	288	199	251	256	244
		af.	293	223	466	379	277	364	253	349	435	245
		av.	275	222	508	327	210	326	226	300	346	245
	W		40.11	44.71	36.94	59.72	62.60	49.20	40.11	43.92	55.43	19.25
2017	Bike volume Q [B/h]	mo.	260	182	560	227	200	353	240	311	269	154
		af.	349	208	463	436	378	435	257	340	450	185
		av.	305	195	512	332	289	394	249	326	360	170
	W		43.10	57.32	42.12	63.31	69.79	52.86	43.10	50.63	60.31	21.25

where: mo. - peak in the morning, af. - peak in the afternoon, av. - average value, W – value of bicycle infrastructure development index.

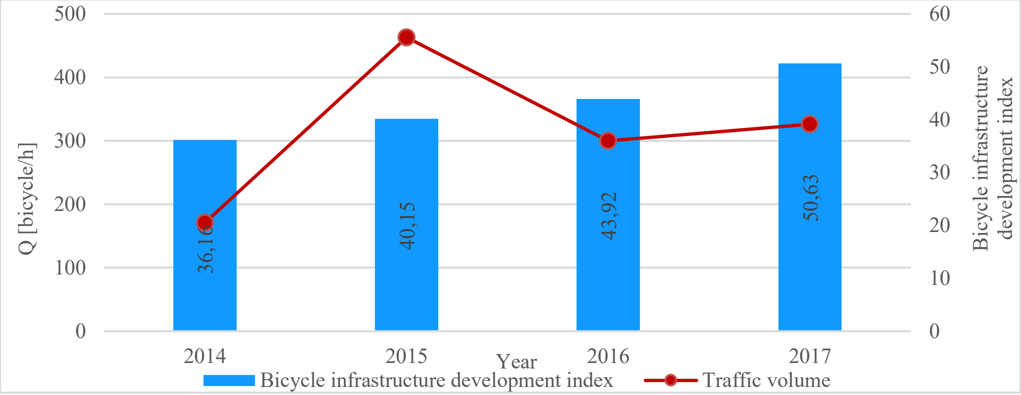

Fig. 4. The value of bicycle infrastructure development index and the volume of cycling traffic on the Świętokrzyski Bridge

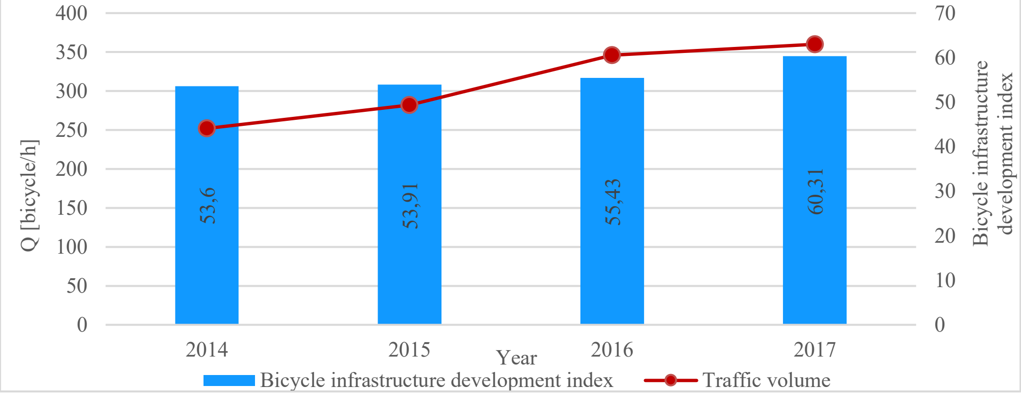

Fig. 5. The value of bicycle infrastructure development index and the volume of cycling traffic on the Siekierkowski Bridge

Measurements carried out in 2015 seem to be not authoritative (trends different from other points of the network). Therefore, for measurement points 4, 6, 7, 8, the results of measurements made in this year were omitted. Pearson correlation coefficients for particular objects are presented in Table No. 7.

In Table 7, there is a very strong positive correlation in eight cases, indicating an almost linear relationship, and in two cases, a negative correlation.

5. Discussion

The results of the research indicate at eight points a strong positive correlation between the indicator of cycling infrastructure development and cycling traffic, and at two points a moderate correlation with a negative direction. This can be explained by the location of the No. 2 and No. 10, where these results were observed. Measurement point No. 2 is located along the Prymasa Tysiąclecia avenue at the northern approach of the intersection with Górczewska street. At this point, a decrease in bicycle traffic volume was observed, which was not observed at point No. 3 at the intersection with Kasprzaka Street. The largest decrease in bicycle traffic, by up to 36%, occurred in 2015. This can be explained by the opening of a new bicycle route on Powstaców Śląskich Street. Cyclists from Chomiczówka and northern Bemowo began using the new alternative route and commuted to Prymasa Tysiąclecia Avenue along Górczewska Street. At measurement point 3, traffic volume increased annually by about 8%, which corresponds to the citywide trend observed in Warsaw. For measurement point 10, the largest decrease occurred in 2017. The Śląsko-Dąbrowski Bridge has no cycling infrastructure as the only one of the measurement points. To this day, cyclists use the roadway. In 2017, the Vistula boulevards were opened after renovation, providing convenient access to neighboring bridges with cycling routes. During the renovation, a diversion of the cycleway was designated but in poor technical condition. An annual increase in cycling of a few percent was observed at other measured points.

One should bear in mind the limitation of the presented method, which does not consider the causal relationship between the quantities. It cannot be concluded whether the development of cycling infrastructure at a given point induces cycling traffic or whether the infrastructure is built by the road management as a result of increased demand of cyclists. The results of the study are consistent with those presented in foreign publications. The Warsaw cycling study (Dudek & Ostaszewski, 2020), and foreign works (Aldred & Dales, 2017), also include basic characteristics of cyclists like a type of bike, clothing, helmet use, or gender. The share of cycling in Warsaw is even higher than in other studies (Bartuska et al., 2016), but it should be noted that the measurements cover the spring-summer period and not the entire year.

The Cycling Infrastructure Development Indicator model presented in this publication takes into account five characteristics of good cycling infrastructure. Other cycling works have also described indicators that consider other aspects (Arellana et al., 2020; Makarova et al., 2020). Due to Warsaw's location in a lowland area, issues related to route slope were not analyzed (Crane et al., 2016). As in other works, a positive correlation was observed between the development of cycling infrastructure and cycling volumes (Marqués et al., 2015; Pistoll & Goodman, 2014). However, a negative correlation was observed for the creation of alternative roads (Measurement Point 2 and Measurement Point 10). This phenomenon is also found in some studies (Pritchard et al., 2019).

Table 7. Pearson correlation coefficients between bike traffic volume and the indicator for the development of cycling infrastructure

Name of the point	Jana Pawła II	Prymasa. Tysiąclecia (Górczewska)	Prymasa. Tysiąclecia (Kasprzaka)	Plac na Rozdrożu	Tamka	Belwederska	Puławska	Most Świętokrzyski	Most Siekierkowski	Most Śląsko-Dąbrowski
Point No.	1	2	3	4	5	6	7	8	9	10
ρ	1.00	-0.59	0.88	0.99	0.98	0.95	0.99	0.99	0.82	-0.59

The determined indicator, taking into account the safety aspect, can generally be used to assess the suitability of the technical solution for a given road class. However, the statistics of traffic incidents and the possibilities to improve the safety of the cycling infrastructure were not analyzed (DiGioia et al., 2017; Ng et al., 2017; Teixeira et al., 2020). Future research should also consider pedestrian safety (Bauer et al., 2021). Appropriate bicycle infrastructure design will allow reducing the number of bicycle-pedestrian conflicts. The costs of possible expenditures for infrastructure improvements and environmental impacts were also omitted (Jacyna et al., 2021).

6. Conclusions

In conclusion, the study carried out of the developed method based on the Cycling Infrastructure Development Indicator has confirmed a positive relationship between the development of cycling infrastructure and cycling traffic volume. The limitation of the survey is the small number of measurement points. It would be advisable to extend the survey using GIS techniques (Żochowska et al., 2021; Modinpuroju & Prasad, 2017). It would also be valuable to check whether a similar relationship exists also in other cities. However, precise measurements, which are not carried out in every city, are necessary for such an analysis. This problem is particularly difficult in the case of large agglomerations or conurbations (Żochowska et al., 2018). More factors can be taken into account during further research, especially those related to road safety.

The method also ignores the issue of the influence of traffic signalization on cyclists' travel times and, consequently, the cycleway rating (Bąk et al., 2021; Ostrowski & Tracz, 2019). It is also advisable to consider the average annual cycling traffic, as cycling infrastructure is only used efficiently for part of the year, in contrast to public transport infrastructure or individual vehicles.

However, it should be clearly noted that the values of the correlation coefficients obtained as a result of the case study are high. They confirm the assumptions' validity of the adopted assumptions and structure of the method. The limitations indicated above should be treated as areas for further research.

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