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SPECIAL SECTION

Geographic Information System-based assessment of cyclist safety in urban environments

Kinga ROMAŃCZUKIEWICZ and Justyna GÓRNIAK-ZIMROZ*

Department of Geodesy and Geoinformatics, Faculty of Geoengineering, Mining and Geology,
Wrocław University of Science and Technology, Poland

Abstract. In recent years, cycling has become an important part of urban transport, providing a fast and convenient means of transport in densely populated and congested urban areas. The dynamic growth of cycling brings with it new challenges related to cyclist safety. This article presents a study aimed at identifying high-risk areas for cyclists in a medium-sized city in Central Europe, using spatial data analysis. The proposed methodology combines GIS-based spatial analysis techniques, in particular heat map visualization and Getis-Ord Gi* hotspot detection, with a customized risk classification system that considers environmental and infrastructure variables affecting cyclist safety. A criteria assessment system was used, assigning points to conditions such as lighting, weather, road surface quality, and infrastructure completeness. The locations with the highest risk scores were then examined in relation to areas with the highest traffic intensity to identify high-risk zones where infrastructure deficiencies coincide with increased exposure of cyclists, thus indicating increased vulnerability to hazards. A classification system was developed to assess environmental and infrastructure conditions based on their potential impact on cyclist safety. The results show that high-risk areas are concentrated in central districts, along major thoroughfares with heavy traffic, with incomplete infrastructure, and in densely populated districts in the south, north, and west of the city. The results provide a basis for urban mobility planning, enabling targeted measures to improve cyclist safety. Furthermore, the proposed approach can be transferred to other medium-sized European cities with comparable infrastructure, demographics, and transport dynamics.

Keywords: active bicycle transportation; high-risk zones; bicycle safety; urban analytics; sustainable transport.

1. INTRODUCTION

Bicycle transportation, along with public transportation, is one of the most important sustainable forms of achieving acceptable levels of citizen mobility and environmental, social, and economic sustainability in urban transportation [1–7]. In recent decades, many European countries in major cities have begun to promote cycling as a means of urban transportation. These include the Netherlands (Amsterdam), Denmark (Copenhagen), Germany (Munich, Berlin), Switzerland (Basel), France (Paris), and Spain (Sevilla) [1–3, 8]. The European Commission, in its Sustainable and Smart Mobility Strategy – putting European transport on track for the future [9], has identified areas of action leading to the development of sustainable transport. One of the milestones is in the next 10 years to develop bicycle infrastructure to enable mobility within cities and between cities. Despite measures taken to improve the quality of infrastructure for bicycle transportation, the main factor discouraging the use of this form of transport is the stress experienced by cyclists with the danger of riding on roads shared with motor vehicle traffic, [3, 5, 10–12], with collision points with other transport participants [13–17], with the condition of the bicycle road surface [13, 18–20], with the incompleteness of bicycle routes, with noise, vibration and air pollution [10, 18–22], and with bicycle-related injuries and trauma [13, 16, 18, 19].

Since 1993, the Council of the European Union has maintained the Community Database on Road Accidents, CARE [23, 24], enabling analysis of road safety problems. This database also collects information on accidents involving cyclists. Figure 1 shows data from 2022 on the compilation of the number of

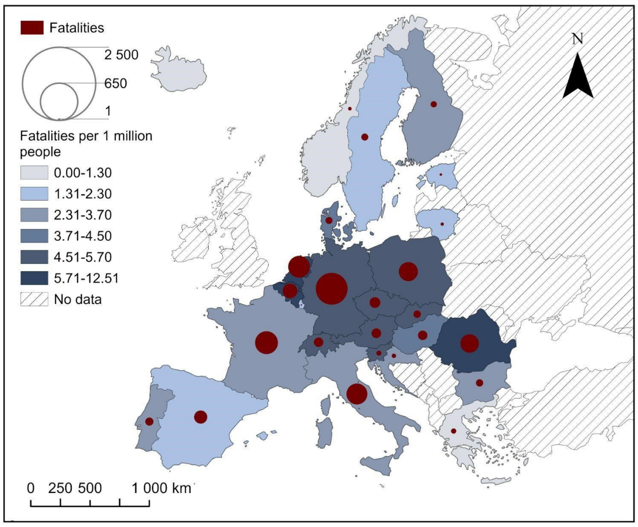

Fig. 1. Cyclist fatalities per million inhabitants in 2022 (Based on data from [24])

*e-mail: justyna.gorniak-zimroz@pwr.edu.pl

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fatal accidents per million inhabitants in EU countries. The highest number of these accidents was recorded in the Netherlands, the country with the most developed and consistent bicycle infrastructure. It can be concluded that this situation is mainly due to the high volume of bicycle traffic [25, 26].

In order to increase the number of bicycle users in urban transportation, cyclists should be provided with adequate conditions to achieve a certain level of safety and convenience comparable to those provided by other means of public transportation. Therefore, in order to improve efficiency in existing urban transportation systems, dangerous places for bicycle users should be identified in order to improve their comfort.

The popularity of the bicycle as a fast mode of urban transportation and a means of recreation results from the finding that using this form of transportation does not require high physical skills and financial investment in the purchase of equipment [27]. Particularly in cities, it is a convenient mode of transportation that has significant advantages over public transportation and automobiles. Urban areas of today, struggling with problems of traffic congestion and air pollution, are increasingly promoting so-called "soft mobility", involving cycling, walking, and other alternative forms of transport. This is a response to the low average speeds of car traffic and public transport in urban areas, which make cycling a competitive mode of transport for short distances [28].

Beyond its environmental and mobility benefits, cycling plays a significant role in public health, particularly by preventing lifestyle-related diseases and promoting physical activity. However, the common injuries among cyclists pose a serious public health policy challenge and require systemic action to prevent and improve infrastructure safety. Injury prevention is, therefore, becoming an integral part of urban safety and transportation equity strategies. Moreover, traditional studies in cyclist injury prevention often rely on survey-based or self-reported data to assess perceived safety and behavioral patterns. In contrast, integrating spatial data analysis offers a complementary, data-driven perspective by incorporating objective records of traffic incidents and environmental variables. This increases the accuracy of urban health risk assessments and supports more targeted infrastructure planning for cyclists in areas with documented injury concentrations [29, 30].

This study aims to identify potentially dangerous areas within the urban transport system of a mid-size city located in Central Europe that pose a heightened risk to cyclists, based on an analysis of spatial patterns of road traffic incidents and selected infrastructural and environmental factors. With regard to research conducted on the safety of cyclists, Geographic Information Systems (GIS) are still used less frequently. The proposed approach is distinguished by its integration of accident and collision data with bicycle traffic density, road infrastructure quality, and factors such as lighting and weather conditions, all within a GIS environment. The research contributes to the ongoing dialogue on changes regarding different modes of transportation in the context of alternatives to the automobile and the development of safe mobility systems in urban environments. Although the case study focuses on Wroclaw, the methodology presented in this research can be applied to other medium-sized urban areas, especially in Central and Eastern Europe. These cities often share similarities in terms of their infrastructure and demographics, which makes it possible to transfer and apply the framework to other conditions. The following sections present the current state of knowledge on bicycle safety and the importance of infrastructure planning in urban transportation (Section 2), describe the study area, data sources and methods used (Section 3), present the results of the spatial analysis and their interpretation (Section 4) and provide final conclusions and practical recommendations for improving cyclist safety in the selected research area (Section 5).

2. STATE OF THE ART

2.1. The importance of planning in cycling transportation

Bicycle routes in large cities are usually conducted as elements directly in the flow of traffic and pedestrians. In large urban areas, bicycle routes are typically integrated into existing vehicular and pedestrian traffic networks due to the constraints posed by established infrastructure, which is challenging to modify within densely built environments. In expansive cities, the integration of bicycle and motor vehicle traffic ensures directness and continuity of travel, enhancing the efficiency of urban mobility. However, the shared use of transport corridors can increase the risk of accidents, particularly in zones with high traffic intensity and limited space for dedicated cycling infrastructure [31]. In the literature, a number of studies show that cyclists and motorcyclists are the most vulnerable drivers in urban areas [32]. Particularly dangerous for road users are junctions between different road classes and road intersections [8, 33]. In contrast, in less densely populated areas or regions characterized by dispersed development, cycling paths are more frequently designed as separate and independent routes, located away from main traffic arteries. This approach is facilitated by the availability of undeveloped land, allowing for the creation of dedicated infrastructure that enhances both safety and the quality of cycling experiences. The ability to plan infrastructure from the ground up enables the integration of safer and more efficient cycling routes, reducing the potential for conflicts with motorized traffic [34]. Decisions on the planning of cycle routes and the choice of a specific location are mainly influenced by the factors of safety, directness, comfort, cohesion, and attractiveness [35]. The criteria are adapted according to the local conditions and determine urban planning issues in order to reduce the risk of accidents and promote urban mobility.

In 2021, the United Nations General Assembly proclaimed the Decade of Action for Road Safety 2021–2030 through Resolution 74/299. The goal of the Global Plan of Action of the Decade is to reduce road traffic fatalities and injuries by at least another 50% by 2030 [36]. Achieving this target requires a comprehensive understanding and monitoring of transport behaviors and the events occurring on roads and daily travel routes, which are essential for effective planning and development of metropolitan areas [37]. Proper identification of travelers' behaviors and related phenomena allows for the detection of potentially hazardous situations, the prediction of risk zones, and the subsequent design of safe, well-organised transport systems [38]. In this perspective, the dynamic growth of interest in cycling as a sustainable and efficient mode of transport presents new challenges. Unfortunately, the growing popularity of cycling has been accompanied by an increase in the number of accidents and collisions involving cyclists, highlighting the urgent need to integrate behavioral studies and accident analysis into transport planning.

2.2. Urban mobility risk assessment methods

The approach to the study of hazards for cyclists in the literature is characterized by its multidisciplinary and multifaceted approach [39], reflecting the complexity of the factors influencing cyclist safety [27, 40]. Assessment tools and approaches vary depending on the factors influencing cycling participants, such as environmental and demographic factors [41], traffic, and their ability to ride in an urban environment [42] or the direct influence of the design of cycle routes [14]. However, studies are increasingly including the use of data-driven models, such as Kernel density estimation [34, 43, 44], machine learning, and spatial-temporal modeling, which allows for a more dynamic and continuous risk assessment.

Analyzing the cyclists' ability to ride a bicycle, it can be defined as the degree to which the actual and perceived environment is conducive and safe for cycling [45]. A natural and common approach to perceiving risk is to use road traffic incident statistics [46, 47]. They can be classified as either a collision or an accident, depending on the consequences. A collision can be defined as an event primarily involving material damage, such as harm to vehicles, infrastructure, or roadside infrastructure, without significant harm to individuals. In contrast, an accident is defined as a more serious event in which personal injuries are suffered by those involved, including drivers, passengers, and pedestrians, as well as property damage. In the context of Polish Law, there is no single definition of "collision". It is a colloquial term and is used in practice. However, "road traffic accident" is defined in legal acts and case law, in particular in The Criminal Code [48]. Factors that were identified as increasing the risk of accidents include high traffic congestion, higher speed limits [41], and the complexity of junctions. A particularly important aspect in the context of road risk analysis is the increasing presence of electric bicycles (e-bikes) in the urban transport system. Electric bicycles are often seen as a more accessible alternative to traditional bicycles due to their higher average speeds and the lower physical effort required to ride. However, these features may also contribute to an increased risk of accidents, particularly when users are older or less experienced cyclists [49]. The conjunction of higher velocities and limited cycling skills could result in a cyclist's diminished capacity to respond effectively to unexpected traffic conditions, particularly in a complex traffic environment.

However, to fully capture the spatial dimension of cycling risk, it is insufficient to rely only on aggregated statistical data [50]. Integrating numerical data with spatial information is essential to understand how risk varies geographically and how environmental characteristics influence cyclist safety [51, 52]. This integration is facilitated by the use of Geographic Information Systems (GIS), which enable spatial analyses [34, 53], classifications, and overlaying multiple layers of data such as traffic volume, road geometry, accident locations [54], and land use patterns [55].

3. ANALYSIS OF BICYCLE SAFETY IN URBAN TRANSPORT

Based on the methodological workflow shown in Fig. 2, the following section provides a structured overview of the analyses used to assess cyclist safety. The approach integrates environmental and infrastructure variables with spatial clustering techniques, traffic density, and risk-area identification. To support replicability, a generalized analytical and step-by-step framework is presented, allowing the method to be adapted to other urban contexts with similar data availability.

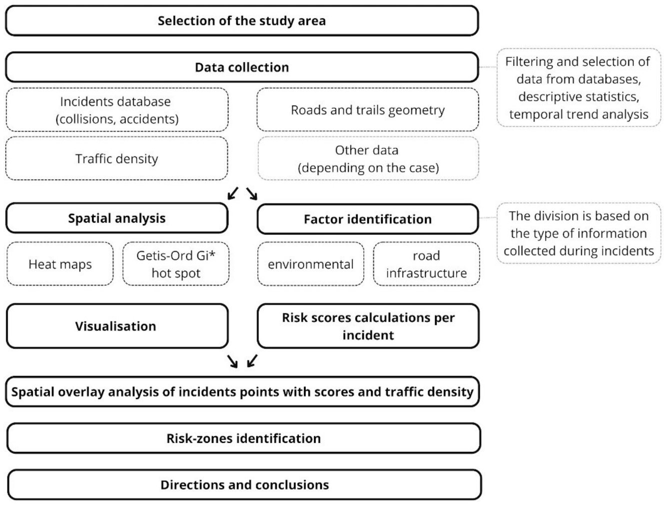


Fig. 2. Proposed workflow (own elaborations)

3.1. Methods

As part of the research, an analysis of cycling in urban transport was conducted. It aimed to identify and assess the risk of dangerous places for cyclists in the context of improving the safety and comfort of riding. The analysis was conducted using a multi-stage approach combining descriptive statistics, temporal trend analysis, spatial analysis, and classification of risk factors related to traffic users.

The data set was assessed and filtered prior to analysis to ensure analytical completeness. Only incidents involving cyclists were considered. Incidents were categorized by month and day of the week to identify temporal patterns. Monthly and weekly time series were created to study the frequency distribution of incidents and collisions involving cyclists. Visualization of incident point locations was performed in a GIS environment using ArcGIS Pro and QGIS. It was used to identify spatial clusters by aggregating points by administrative units – districts. In order to visualize the density of incidents, Heat Maps [56] and Hot Spot [57] analysis were performed. Additionally, Heat Maps were used to represent zones with the highest density of road and bicycle traffic. Particular emphasis was placed on analyzing the impact of the state of the road infrastructure and environmental factors, i.e., weather, lighting. The scores used in Table 1 were assigned based on an assessment of the severity of each condition on bicyclist safety, according to general assumptions used in urban mobility safety studies (e.g., [58]). A score of 1 indicates the most positive conditions, while 4 indicates the most dangerous scenario for cyclists. The classification was developed to support comparative spatial analysis; therefore, it should be interpreted as a relative risk assessment. Scores were given based on the impact on cyclist safety according to a numerical scale, which can be described as factors that have a positive impact on safety, neutral impact, or threaten safety. Some factors may potentially have no impact on safety, but their incorrect operation can negatively affect traffic, such as nonfunctioning traffic lights, distracting traffic participants. Similarly, intense weather conditions or poor road surface conditions can divert the attention of cyclists, who, instead of focusing on riding, are forced to assess external risks, increasing the likelihood of incidents.

Table 1
Risk analysis – factors

Factor	Conditions		Risk level
Environmental	Lighting	daylight	1
		night – road lit	2
		dawn, dusk	3
		night – road with no light	4
	Weather conditions	good weather conditions	1
		cloudy	2
		rainfall	3
		blinding sun	3
		cloudy, rain	3
		strong wind	3
		fog, smoke	4
		snowfall, hail	4
	Surface condition	dry	1
		wet	2
		puddles, spillages, wet	3
		icy, snowy	4
Road infrastructure	Surface condition	dirty	3
		holes, bumps	4
	Traffic lights	present, operational	1
		none	2
		present, not operational	3
	Horizontal signs	present	1
		none	4

In addition, a frequency analysis of individual causes was conducted to identify the most common factors causing road traffic incidents. The causes were divided according to the perpetrator of the incident. Their relationship to different user groups and spatial locations was then analyzed. Figure 3 presents the components used in the risk assessment study.

Fig. 3. Risk analysis components (own elaborations)

3.2. Wroclaw's cycling infrastructure

A medium-sized city located in Central Europe was selected as the research object. Wroclaw, located in the south-western part of the country, has been consistently developing its cycling infrastructure for years, aiming to create a participant-oriented and ecological urban mobility system. Due to its efficiency and low environmental impact, the bicycle has gained strategic importance in urban transport planning. The development of cycling policies can be traced back to the 1930s, when initial regulatory frameworks enabled the implementation of foundational measures in this area [59,60]. In 2010, the City Council approved the Cycling Policy of the City of Wroclaw. The document defined the objectives related to the construction of a coherent, safe, and comfortable cycling infrastructure, including cycle paths, cycle lanes, contraflows, and facilities for cyclists, such as car parks, repair stations, and transfer points. Integration of cycling transport with the public transport system and consideration of cyclists' needs at the stage of planning new investments and revitalisation of public spaces was also an important assumption [61]. The Resolution of 2010 became the foundation for subsequent stages of cycling development in Wroclaw, allowing the conduct of systematic infrastructural investments, also co-financed from European Union funds. Furthermore, the improvement of Wroclaw's cycling infrastructure is reflected in the Concept for the Development of Wroclaw [62], which assumes the introduction of fully zero-emission public transport and sustainable mobility, based mainly on the principles of shared mobility.

According to data from the Statistical Office in Wroclaw, by the end of 2024, the population of the city of Wroclaw was 673 500 inhabitants, but the actual population is significantly higher [63]. Already in 2022, the actual population of Wroclaw was one-third higher than the number of people registered in Wroclaw [64]. This large and constantly growing population makes Wroclaw one of the most dynamically developing urban centers in Poland, generating a high demand for daily mobility and efficient transportation solutions. In Wroclaw, according to the latest data, up to 1.4 million journeys are made every day, both commuting and recreational [65]. In the Comprehensive Traffic Surveys, in 2018, Wroclaw was the third city in Poland in terms of cycling traffic at a level of 6.3% [66]. In contrast, in

2024, also based on the Comprehensive Traffic Surveys, cycling declined to 4.3% [65]. For a more complete presentation of the topic of cycling infrastructure in the city, a map of the cycling traffic network and accompanying infrastructure with marked locations of car parks and bicycle repair stations was presented (Fig. 4).

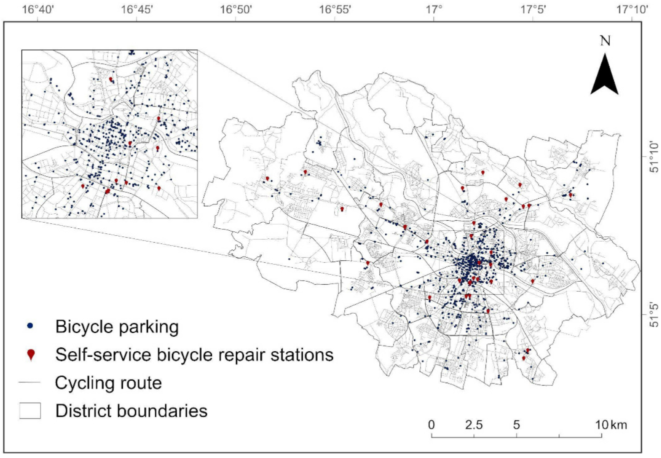


Fig. 4. Bicycle parks and self-service bicycle repair stations on cycling routes in Wroclaw (Based on data from [67])

Wroclaw currently has nearly 1600 km of bicycle infrastructure divided into several types of bicycle routes differing in signage, the place where bicycle traffic is designated (road, roadway, sidewalk, park), the direction of travel, and the rules of use. These are: a pedestrian and cycle path, a cycle path, a cycle lane, a BUS+ROWER lane, a route of flood embankments, a route through a park, and a calmed traffic zone [67]. In the city the cycling infrastructure is designed to ensure the integration of cycling with public transport, providing the possibility to transport bikes on trams and buses or to change between modes of transport. The central part of the city shows a clear concentration of infrastructure, corresponding to areas of high traffic intensity and population density. To ensure the comfort and integrity of commuters, the city is investing in bicycle racks, shelters, and self-service bicycle repair stations, which are located at key points in the city. As Fig. 4 shows, these elements are not only distributed in the central area but also in selected peripheral districts. Their placement is intended to improve accessibility for residents outside the city centre and support longer-distance commuting by bicycle.

3.3. Materials

In the research, for the risk assessment, a dataset of traffic accidents and collisions that occurred within the area of Wroclaw was used. The data was obtained from the Wroclaw Spatial Information System through the collaboration between the Department of Spatial Planning of the City of Wroclaw and the Wroclaw Provincial Police Headquarters, ensuring access to verified and comprehensive records necessary for reliable analysis of road safety conditions from 2016 to 2024 (Fig. 5).

The study is based on data from the year 2024 due to the Comprehensive Traffic Survey of Wroclaw performed in that year. The traffic survey conducted in parallel provided valuable data on traffic density throughout the city, traffic density on the roads (including all traffic participants), bicycle traffic, pedestrian traffic, and traffic density on public transport. The approach to measurement differed depending on the type of traffic. For the analysis, traffic density data were selected for all traffic participants on the road, with particular emphasis on cyclists and data from measurements referring only to cyclists, both on roads and on designated routes. This is since cyclists are particularly exposed to other cyclists. The measurement of bicycle traffic was conducted at 43 locations across the city. These data sets encompassed not only cyclists but also individuals propelling scooters. The analysis focused exclusively on the density of cycling traffic.

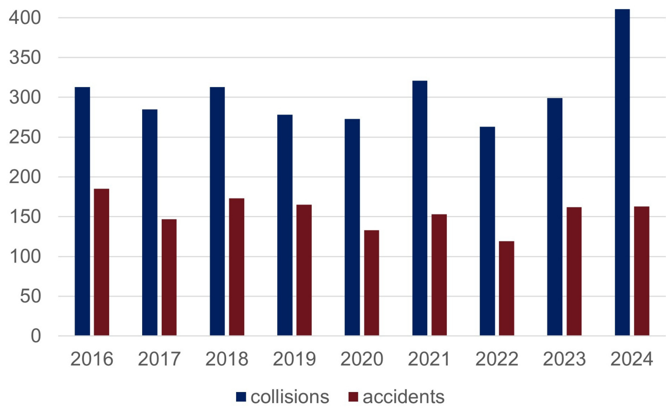


Fig. 5. Number of collisions and accidents in Wroclaw in 2024 (Based on data from [67])

In 2024, 9843 incidents were recorded by the Police, of which 9267 were collisions and 576 were accidents (Fig. 6). A particularly important subset of the data analyzed concerns incidents involving cyclists. Out of a total of 9843 recorded traffic events, 574 incidents (5.83%) involved cyclists (Fig. 7). This group includes 163 road accidents and 411 collisions. In all cycling incidents, 618 cyclists were harmed.

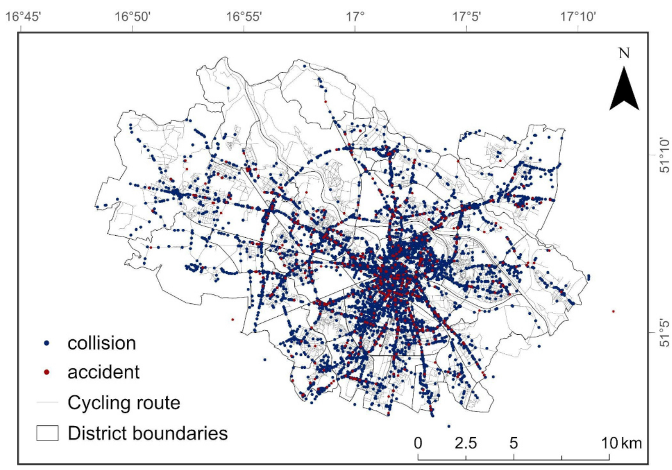


Fig. 6. Collisions and accidents in Wroclaw in 2024 (Based on data from [67])

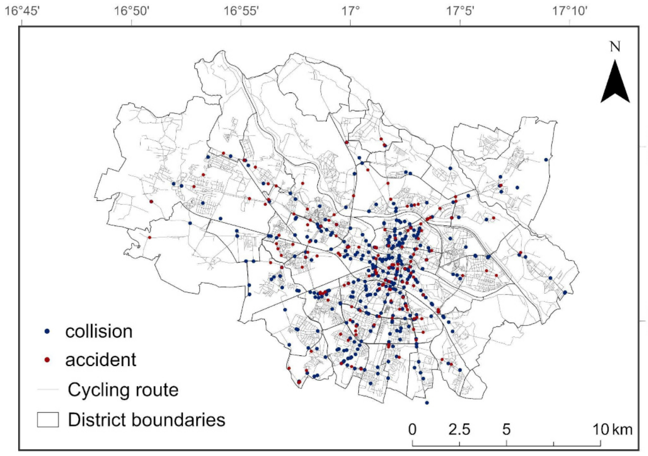


Fig. 7. Collisions and accidents in Wroclaw in 2024 in which cyclists participated (Based on data from [67])

Figures 6 and 7 show the locations of all recorded road traffic incidents in Wroclaw in 2024, including both collisions and accidents, and data incidents in which cyclists were harmed. A spatial analysis of the distribution of these events reveals a concentration in the central districts of the city and along primary transportation corridors. This observation indicates that areas characterised by high mobility demand and complex road networks are particularly vulnerable to traffic incidents.

To ensure the reliability of the subsequent analyses, the entire dataset was evaluated in terms of quality. The completeness of key variables was assessed, including incident type, date, number of participants, cause, vehicle type, and spatial identifiers (street name or intersection). The dataset was evaluated as complete, with over 98% of records providing full temporal and categorical details. However, fields such as specific address and cross-street (used to locate intersections) showed partial data availability, with 31% of cases lacking detailed address information and 70% lacking cross-street references. However, these attributes are not considered for further analysis.

4. RESULTS AND DISCUSSION

The spatial analysis conducted in this research revealed clear patterns in the distribution of cycling incidents across Wroclaw. The following results highlight important spatial clusters of risk and provide insights into the environmental and infrastructural conditions that contribute to cyclists' vulnerability in the urban area.

4.1. Spatial distribution of cycling-related incidents

The spatial distribution of cycling-related road traffic incidents was visualized using a heat map technique, which highlights the intensity of incidents throughout the city of Wroclaw. The Heat Map and Hot Spot analysis reveal clear clusters of incidents in the central districts, particularly within the inner city ring road and in areas of high traffic density. These hotspots in the Old Town, Oławskie suburbs, Świdnickie suburb and Nadodrze districts coincide with densely built-up areas characterized by mixed traffic patterns and high levels of interaction between cyclists and motor vehicles (Fig. 8). This corresponds to the map on which the incidents in each district are aggregated (Fig. 9). This analysis is particularly useful in the context of areas with less frequent traffic, in which case it is possible to identify the area of potential risk. In contrast, peripheral neighbourhoods showed fewer incidents, which may reflect both lower cycling traffic and the separation of cycling from traffic. However, some peripheral areas showed isolated clusters of incidents despite lower population density, indicating the influence of specific local infrastructure conditions or environmental factors. The use of a Heat Map allowed for a simple visual identification of high-risk areas, which are crucial to make recommendations for infrastructure improvements and policy interventions for specific locations.

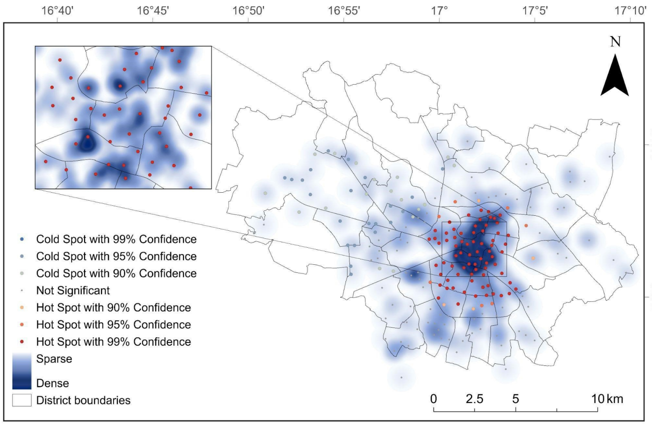


Fig. 8. Heat Map of incidents involving cyclists (Based on data from [67])

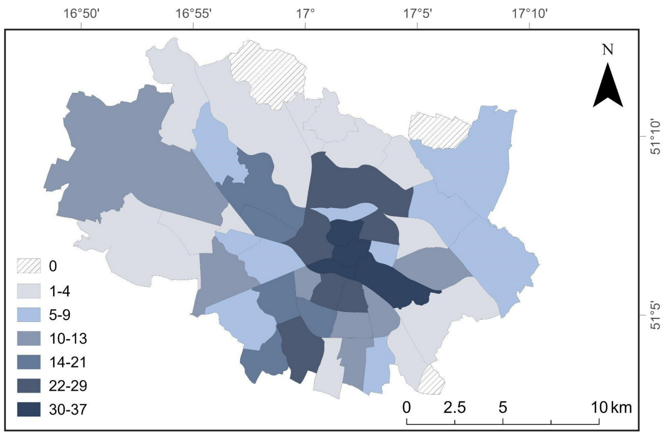


Fig. 9. Number of cycling incidents aggregated in the districts of Wroclaw in 2024 (Based on data from [67])

4.2. Traffic density and exposure

To examine the factors that contribute to road danger, it is crucial to analyze the intensity and density of traffic. To provide contextualization of spatial risk, traffic volume data from the 2024 Comprehensive Traffic Survey were integrated. Comparison of incident density and traffic volume revealed several misalignments: areas with relatively low cycling volumes showed disproportionately high incident rates. This suggests that cyclist safety is not solely a function of exposure, but is influenced by additional factors. Heat Maps of road traffic (Fig. 10) and bicycle traffic (Fig. 11) were generated, revealing spatial disparities in mobility patterns across the city. The road traffic heat map (Fig. 10) highlights the city centre and major arterial roads as high-density zones, consistent with the role of these routes in urban commuting. In the indicated areas, high concentrations of traffic and incidents coincide with daily commuting routes leading to the city centre. The Śródmieście district serves as a major tourist destination and a zone with a high concentration of workplaces in Wroclaw. Currently, the most densely populated areas of the city, apart from the central district, include the southern parts – the Krzyki and Jagodno districts, as well as the western and northern areas. The traffic density map reflects the increased traffic volumes generated by daily travel between residential zones and the city center. Conversely, bicycle traffic intensity, both on the roads and in the context of a study of their overall (Figs. 10, 11), is more dispersed but still shows strong concentrations around the central districts and selected corridors with dedicated infrastructure on roads, around other road users. Heat Maps of cycling traffic density on all types of routes (Fig. 11) show high concentrations are also recorded in the southern part of the city and towards the west. This indicates the existence of a high concentration of cycling users there with low cycling infrastructure density.

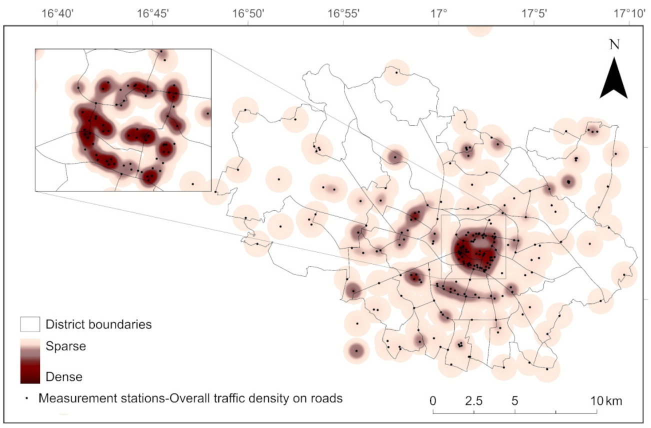


Fig. 10. Traffic density on roads including all means of transport in Wroclaw in 2024 (Based on data from [66])

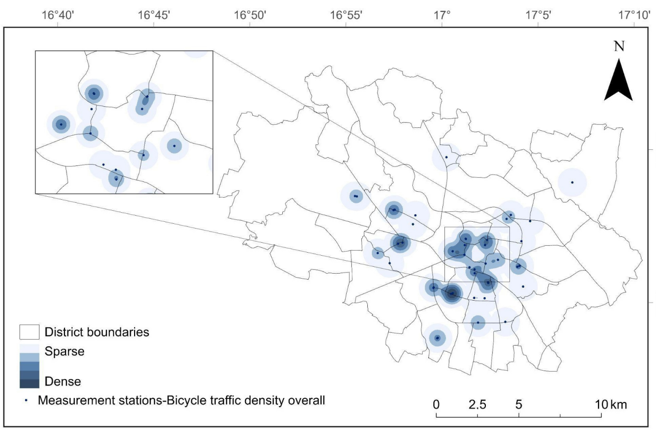


Fig. 11. Traffic bicycle density in Wroclaw in 2024 (Based on data from [66])

4.3. Temporal trends and causes

Analyzing the data set in terms of incidents over time, the highest number of total incidents on the road in Wroclaw was in October (936) and the lowest in August (711). Analyzing the data set in terms of incidents in which cyclists participated, the highest number of incidents, in contrast, was in May (89) and the lowest was in January (16). Looking at the distribution of incidents by season of the year, the highest number is in summer. The pattern of numbers of incidents and accidents was the same in each season and in each month of 2024 (Fig. 12). The number of collisions and accidents involving cyclists clearly increases in the warmer months, reaching a peak between May and September, and then decreases in the autumn and winter periods. This trend is consistent with the general behavior of cyclists, strongly influenced during the year by weather conditions.

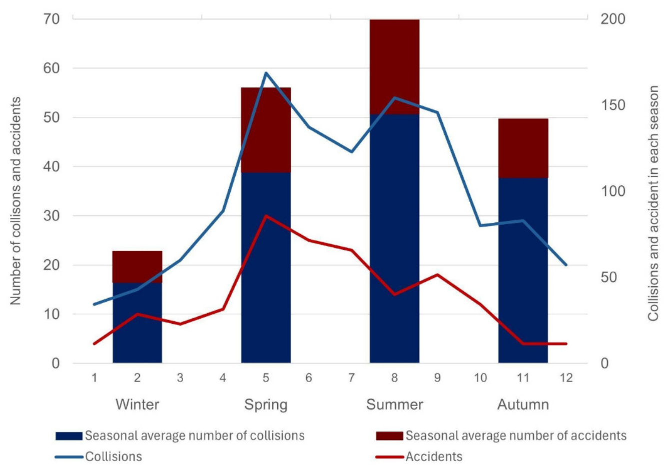
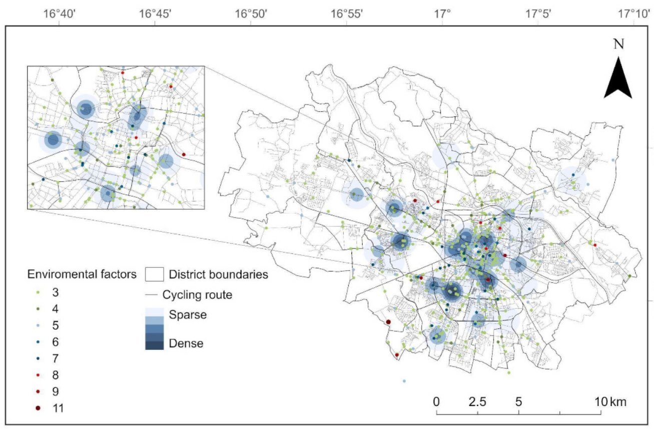


Fig. 12. Number of incidents involving cyclists in 2024 (Based on data from [67])

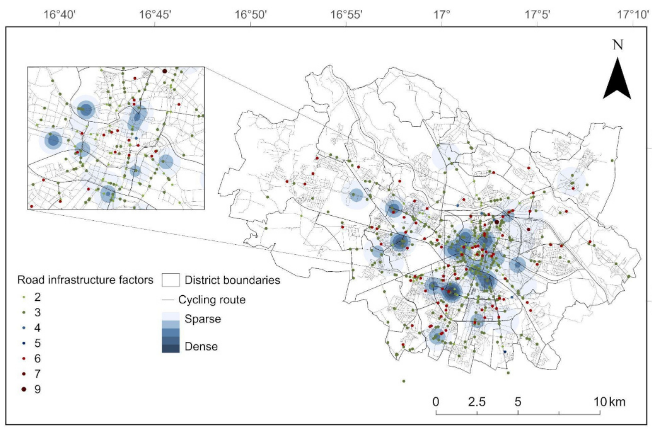
A detailed study of the causes of accidents reveals that most incidents involving cyclists are attributed to motor vehicle drivers (98%). Specifically, the most common causes are failure to give priority, improper turning and unsafe overtaking manoeuvres. The insights obtained from this study serve to substantiate the seasonality of cycling risk, whilst concomitantly underscoring the necessity for targeted interventions to be implemented during the months in which cycling is at its most prevalent. Moreover, the causal factor analysis underscores priority areas for policy enhancement, including enhancing visibility at intersections, clarifying road signage, and augmenting priority areas for cyclists. The identification of areas where incidents between cyclists and other road users are more prevalent may be indicative of deficiencies or malfunctions in the existing infrastructure.

4.4. Environmental and infrastructural risk conditions

To better understand the potential causes of cycling accidents in Wroclaw, incidents were analyzed in terms of two main categories: environmental factors and the condition of the road infrastructure. Each incident was assigned a score based on attributes according to Table 1. The results were visualized using the intensity of the color scale to identify spatial clusters and areas of high frequency of points with higher scores for both types of factors. As shown in Fig. 13a, the spatial distribution of incidents is influenced by weather and atmospheric conditions. While the majority of incidents with mid-range environmental scores (3–5) are dispersed throughout the city, clusters of incidents with higher scores (7–11) tend to be concentrated in peripheral and less densely developed neighborhoods where the road network may be less equipped to handle adverse weather conditions and the site area is less developed. In comparison, Fig. 13b shows that incidents related to infrastructure factors and higher scores (6–9) are more concentrated in central and high-traffic areas. This pattern does not necessarily indicate that the overall quality of infrastructure is lower in central areas. Rather, it may reflect the greater complexity of transport systems and more frequent interactions between modes, which may lead to an increased probability of incidents.



(a)



(b)

Fig. 13. Environmental (a) and road infrastructure (b) risk factors in 2024 (Based on data from [67])

Figure 14 illustrates the density of road traffic in Wroclaw in 2024 and the distribution of cycling incident points, for which cumulative weights of environmental and traffic factors were calculated. Values of points range from 5 to 15, with the highest values (12–15) concentrated in the area of Śródmieście, Krzyki, and along the main traffic arteries, such as Powstańców Śląskich, Legnicka, or Grabiszyńska streets. In particular, black and dark red dots, representing the highest level of hazards, occurred in areas, surprisingly, of moderate traffic and identified intersections of cycle routes. This shows the need for priority intervention to identify potential hazards.

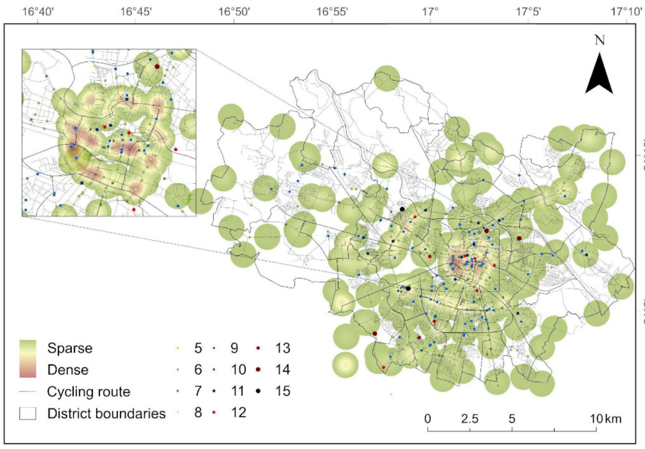


Fig. 14. Risk factors in 2024 (Based on data from [67])

4.5. Implications of the method

The spatial analysis conducted in this study revealed clear clusters of cycling incidents in Wroclaw, offering an important contribution to understanding the relationship between cyclist safety and the surrounding urban environment. In interpreting the results, however, several methodological issues are important to consider. The analysis was based only on incident data from a single calendar year, which limits the temporal representativeness of the results. Traffic density and mobility-related behaviors change depending on season, weather, and social factors, and, therefore, a longer observation period would have increased the reliability of the conclusions.

The analyses used in the study were based on point data representing incidents and traffic density measurements. The approach used in heat maps and hotspot analysis allowed the identification of spatial clusters in the form of rays. The structure of the road network, however, was not fully reflected using Kernel density estimation. As a result, the method does not accurately identify dangerous road sections, but potentially dangerous areas. This information can be used as the basis for further studies that integrate the current findings with road network datasets that contain detailed representations of infrastructure elements such as lanes, carriageways, and intersections.

Another important aspect is the changing demographic and spatial dynamics of the city. In Wroclaw, some neighborhoods are experiencing significantly increased mobility despite limited representation in official population statistics. This is due to the high percentage of temporary residents who are not reflected in administrative data. As a result, it is difficult to assign reliable exposure rates to such districts. Nevertheless, the actual traffic load in these neighbourhoods is increasing, which puts more pressure on the road infrastructure and may contribute to an increased number of incidents.

Despite these challenges, the study highlights the value of spatial statistics in identifying relationships between cycling incidents and environmental and infrastructure conditions. While the method does not directly account for road network geometry, it offers a practical and scalable approach to highlighting zones of increased risk for cyclists. It would have been significantly useful for the study to include a broader spatio-temporal and user perception that could directly identify and confirm an area that is particularly dangerous for cyclists.

5. CONCLUSIONS

Cycling represents a key element of sustainable urban mobility [68], offering a range of social and environmental benefits. As an active form of transportation, it contributes to improved public health by promoting physical activity. Cycling helps to reduce greenhouse gas emissions, lower noise pollution, and limit urban congestion, making it a useful tool in addressing the challenges of climate change. However, the broader implementation of cycling as a mainstream mobility solution requires systemic support through safe and well-designed infrastructure. Without addressing the spatial and infrastructural factors that contribute to traffic incidents, the potential of cycling to serve as a key element of sustainable urban systems remains limited. Understanding the geography and areas of high levels of traffic density of cyclists' commuting is important for developing transport policies and the planning of cyclist-related investments.

The study offers a spatial analysis of safety conditions for cyclists in the urban environment of Wroclaw. The combination of spatial analysis based on GIS with data on traffic density and road traffic incidents allows to identify spatial patterns related to cyclists' safety. A fundamental element of the study was the classification of factors contributing to two categories: environmental and road infrastructure-related. A spatial analysis of weighted risk indicators, revealed clear clustering of areas exhibiting specific combinations of adverse conditions. Key findings revealed that incidents are not evenly distributed across the city, instead, specific clusters of risk were identified, particularly in central districts such as Śródmieście and Krzyki with high traffic density and complex traffic interactions. The study revealed particularly interesting information in the area of the southern, western, and northern parts of the city. The study indicated a high density of bicycle and road traffic in areas characterized by high population density, a phenomenon that is not reflected in official data concerning the specific number of residents of these neighbourhoods. This focused differentiation allows for a more resource-efficient allocation to improve cyclist safety. The analysis also highlighted strong seasonal patterns, with cycling incidents peaking between May and September, and revealed that the majority of accidents involving cyclists were caused by motor vehicle drivers. This finding indicates the necessity for focused initiatives, especially at intersections and during periods of high traffic volume. The policy recommendations outlined in this study include the following: the improvement of signage, the enhancement of cyclist visibility, and the improvement of road surface quality in critical areas. Detailed directions can be based on the following:

- Prioritize infrastructure modernization in high-risk zones identified through spatial analysis.
- Integrate cyclist safety data into transport planning processes.
- Improve lighting and road surface quality at key intersections with elevated incident rates.
- Leading new bicycle routes or directing bicycle traffic on other routes that are not in direct contact with automobile traffic.

The methodologies employed in this study are based on factors officially recorded in police reports. This approach ensures the reliability of the data, but it also imposes a limitation: the exclusion of many other relevant variables that could improve the analysis. For example, cyclists' perceptions of safety, traffic calming infrastructure, or informal paths and barriers are not recorded in standard incident databases. Also, although the method proved effective in capturing spatial relationships and risk clusters, the study was restricted to a single year of data and did not consider subjective perceptions, informal infrastructure utilization, or longer-term trends. Therefore, future studies will be more comprehensive. They will include multi-year datasets of cycling incidents to examine seasonal trends, long-term infrastructure changes, and the impact of the cities' changing cycling policies. Observations of cyclists' behavior and reported perceptions of safety, collected through surveys or participatory mapping, would be particularly useful in future studies, as they can provide valuable context to complement data from publicly available databases. In addition, adapting the proposed methodology in other urban environments of different sizes, forms, and modal structures would help verify its adaptability and facilitate city comparisons.

Although the spatial analysis focused on a single city, the proposed method can be used as a model for other urban environments facing similar challenges. The integration of spatial traffic data, environmental conditions, and road infrastructure quality using GIS enables cities to identify high-risk zones and prioritize safety interventions more effectively. This approach is of particular value for other mid-sized cities in Central and Eastern Europe, where cycling is becoming increasingly popular but where there is a lack of consistency in safety infrastructure. The study, therefore, offers both practical findings for local policy in Wroclaw and a methodological template that can inform broader urban mobility planning in similar contexts.

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DATA AVAILABILITY STATEMENT

Raw data used in research are available at the following link: https://data.mendeley.com/datasets/5r3vxrhtb9/1.

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