

Enhancing urban mobility: predicting cycle paths in Lublin city using GIS and open-source data

Abstract

The study focuses on predicting cycle path development for the year 2030 in Lublin by integrating land cover data with key factors such as demographic trends, cycling path design guidelines, and topographic features. The authors propose a novel method for identifying optimal locations for new bike paths, emphasizing the prioritization of routes, based on a demographic index across Lublin's districts and on land cover forecasts for 2030. This forward-looking approach ensures that the proposed network aligns with future urban development and population distribution patterns, creating a cycling infrastructure that is both adaptable and responsive to the city's evolving needs. As a result, the study designates areas of approximately 30 km² for the development of cycle tracks, creating a comprehensive and flexible cycle infrastructure that adapts to projected changes in land use.

Keywords

Cycling network analysis • cycle tracks • prediction • open data • GIS analysis

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Introduction

This study focuses on the growing importance of cycling infrastructure in cities, which impacts many aspects of urban life. Cycling infrastructure tends to be less developed than other types of infrastructure, such as roads for cars or paths for pedestrians, making it difficult to use bicycles (Zahabi et al. 2016). When further developed and enhanced, cycling becomes a more attractive option for individuals, driven by rising urban traffic concerns, the need to reduce greenhouse gas emissions (Hwang et al. 2024), and its impact on road safety for all users (Akar & Clifton 2009). In many cities, bicycles already serve as a viable alternative to cars and public transportation (Builes-Jaramillo & Lotero 2022).

The development of cycling infrastructure is influenced by various factors, including terrain, population density, the distribution of destinations (trip origins and destinations), factors related to other transport infrastructure (e.g. road congestion, the attractiveness of public transport), and land cover changes (Borowska-Stefańska et al. 2020). These changes may require adjustments to existing road infrastructure, which sometimes presents challenges, such as road congestion that may arise from adapting spaces for bike paths, as demonstrated by Lycourghiotis & Crawford (2024) in the case of the city of Patras in Greece. The authors noted that improper road conversions into cycle paths may not yield the expected results if appropriate criteria, such as low traffic intensity or terrain slope, are not taken into account (Siqueira et al. 2020).

For predicting new cycle paths, it is essential to consider changes in land use and land cover (LULC), which are an inevitable, and often irreversible, consequence of population growth and urbanization. These changes are shaped by various environmental and socio-economic factors, such as migration, population density, elevation, access to water, and infrastructure, as well as healthcare and the labour market. As Bielecka (2020)

notes, studies of LULC changes have identified three main research areas, with one key area focused on forecasting these changes. The available GIS tools (for example, SLEUTH, CLUE, MOLUSCE for QGIS) allow precise monitoring and mapping of LULC changes in both temporal and spatial contexts. They utilize various forecasting algorithms, from classical regression analyses to modern deep learning methods and Markov chains. Scientists have demonstrated that these GIS models are crucial for creating future LULC scenarios, allowing for both quantitative and qualitative analyses (see Lambin et al. 2003).

Research purpose

Research shows that well-planned cycling infrastructure that takes changes in land cover into account can significantly increase the popularity of bicycles as a means of transport; they potentially becoming the dominant choice for a large portion of residents (Hardinghaus & Papantoniou 2020). Therefore, the aim of this study was to predict the distribution of cycle paths by the year 2030, based on spatial analyses and land cover forecasts using open data and software. The authors proposed their own concept for designating new cycling routes, considering various factors such as demographics, terrain, and multiple spatial data processing techniques, including GIS analyses and artificial neural networks (for land cover predictions). The research aims to answer the following question: Will changes in land cover require adjustments to existing bike paths and necessitate the development of new routes, and to what extent?

Data and methods

Study area

The analysis covered the city of Lublin (area: 147.5 km²), located in the eastern part of Poland in the Lublin Voivodeship. Administratively, the city is divided into 27 districts (Fig. 1). It is

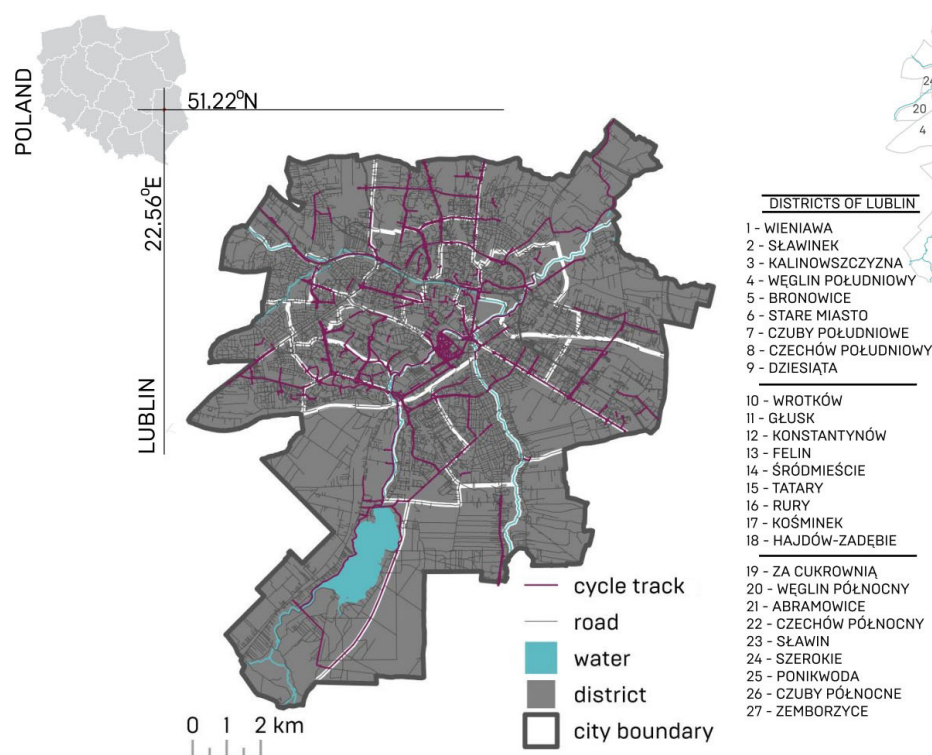


Figure 1. Network of cycle tracks in the districts of Lublin
Source: own study

Table 1. Length of cycle tracks in Lublin by type (as of December 2023)

Type of cycle track	Characteristics	Length [km]
Segregated path	A section with separate lanes for pedestrians and bicycles	132.7
Shared use path	Possibility of cycling on footpaths	12.4
Cycle track	Clearly separated and independent of other roads	16.0
Contraflow cycle lane	Allows bicycle traffic in the opposite direction on one-way roads (e.g. by separating the road and the bicycle lane)	5.4
Cycle passage	Road surface intended for bicycles	6.8
With-flow cycle lane	A separate road lane for bicycles only (cycle lane in the same direction as traffic)	30.4
Designed	Sections designed – not yet implemented or in progress	9.0
Total		212.7

Source: own study

the largest economic, academic, and cultural centre in this part of Poland, with a population of 308,000 people. The terrain of Lublin is divided into two zones by the Bystrzyca River. The area to the east is flat, while the western side has varied topography, featuring valleys and loess gorges.

In terms of cycling transport potential, Lublin has the best-developed bike-sharing system in Poland (Gawroński et al. 2019). The cycling network in Lublin is evenly distributed across the entire city (Fig. 1) and it is being gradually expanded and supplemented. The increase in cycling traffic has contributed to the rapid development of the cycling infrastructure, including both hard investments, such as dedicated bike paths, and soft measures in traffic management, such as bike lanes or contraflow cycle lanes. As of December 2023, the length of the cycling network is 203.7 km, with an additional 9.0 km planned (Table 1). For comparison, the total length of the road network is 1,734.6 km.

The existing cycling infrastructure, relative to the city's area, amounts to 1.4 km per km². In terms of population, this equates to 0.6 km per 1,000 residents.

Guidelines for designed cycling roads

The road network, including cycling routes, should provide direct connections between destinations to minimize detours. Studies (Caggiani et al. 2019; Hwang et al. 2024) have proposed methods for adding new cycling routes, each using different data and objectives, resulting in identified network segments for route expansion. The cycling network expansion in Lublin follows the WR-D-42-1 guidelines by the Ministry of Infrastructure (Brzeziński et al. 2022), specifying technical requirements for cycling infrastructure.

The transport concept defines two types of routes: primary routes, connecting key districts along major roads, and

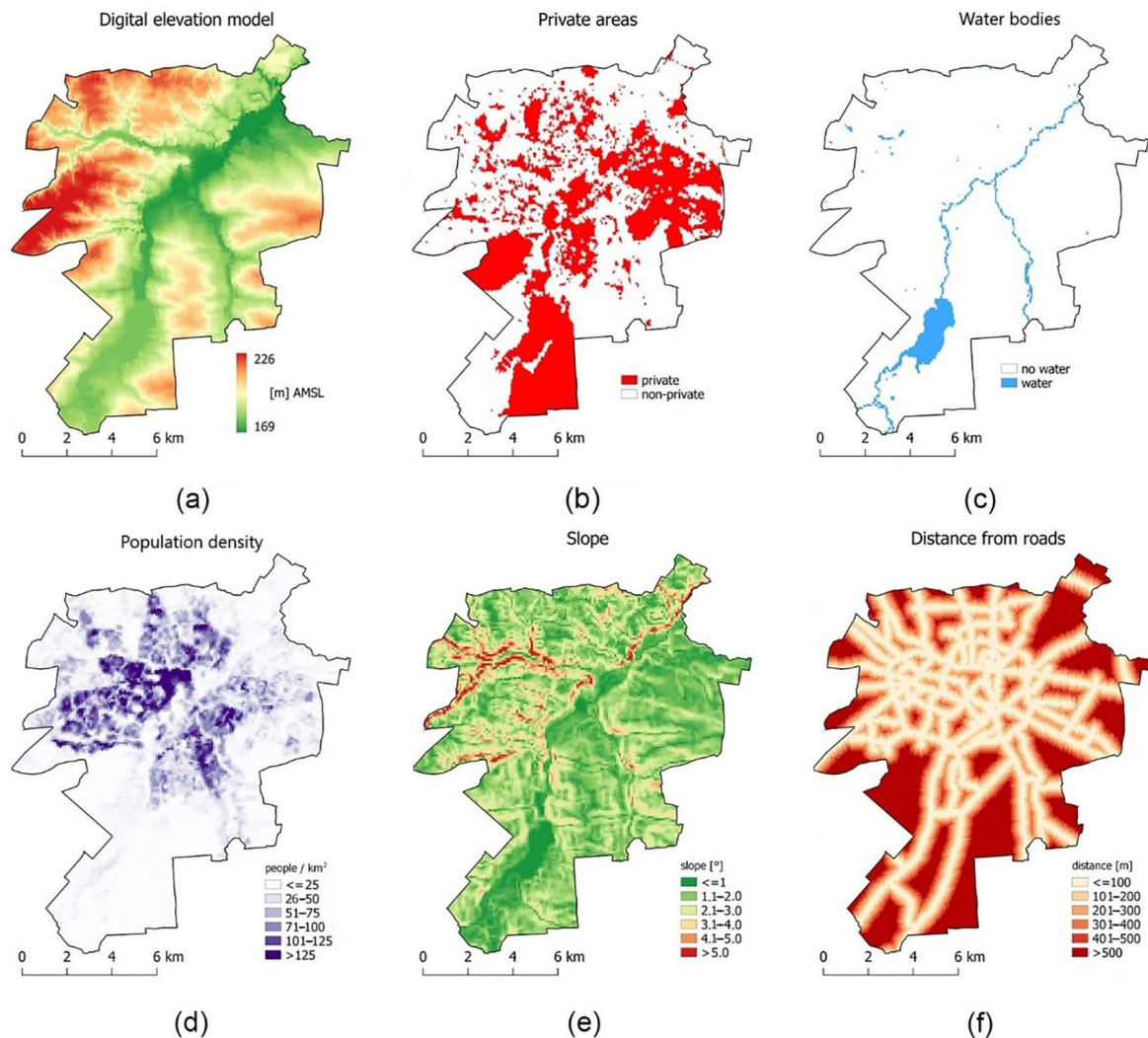


Figure 2. Explanatory variables: (a) digital elevation model; (b) private areas map; (c) water bodies map; (d) population density map; (e) slope map; (f) proximity to roads map
Source: own study

supplementary routes, which distribute bike traffic along local roads for everyday use (e.g. work, school, services). Road classifications served as the basis for new cycling routes.

The development process for new routes included: (1) identifying destinations; (2) mapping primary cycling directions; (3) designing the connectivity grid; (4) analysing demographic trends; (5) forecasting land use for 2030; and (6) prioritizing routes for phased implementation.

Data used

The study utilized free QGIS software and open-source spatial data. The data were obtained from various sources and include both international data and data covering only Poland or the city of Lublin. A summary of all the data used in the study is provided in Table 2. The data acquired in subsequent studies were standardized to a single level of detail, namely a hexagon grid with a side length of 50 metres.

Land cover prediction

Land cover prediction was conducted using the MOLUSCE plugin in QGIS, which, written in Python 2, is compatible only with

QGIS version 2.X. The plugin's open-source code is available on GitHub (GitHub 2024). MOLUSCE enables land cover change forecasting by processing input data such as current land cover maps, demographic data, land use plans, and environmental factors. The analysis begins with selecting a predictive model from the plugin's options, which include various statistical methods and machine learning algorithms, offering multiple approaches to predicting future land cover changes.

The following explanatory variables were used for the prediction, which influence land cover development in the coming years: elevation above sea level, private areas, water bodies, population density, slope, and proximity to roads (Fig. 2).

The simulation model was built and validated for the year 2018, while the land cover forecast was made for 2030. Using these maps and explanatory variables, a probability matrix was created, which formed the basis of the land cover model predicted by the ANN-MLP (Artificial Neural Network - Multi-Layer Perceptron) neural network. The MOLUSCE plugin also offers the ability to adjust model parameters, allowing for precise tuning of predictions to specific local conditions and user needs. This enables more accurate and reliable analysis results.

Table 2. Summary of data used

Data / source	Reference years	Coordinate Systems Worldwide (EPSG number)	Data provider (source)	Purpose
Topographic Objects Database (BDOT10k) / vector	2024	ETRS89 / Poland CS92 (EPSG: 2180)	Head Office of Geodesy and Cartography (GUGiK 2024)	Road network, proximity to roads, built-up area, protected areas
Demographic data / PDF	2018–2024	-	Lublin City Office (Urząd Miasta Lublin n.d.)	Number of registrations
Land and building register (EGiB), Topographic Objects Database (BDOT500) / vector	2024	ETRS89 / Poland CS2000 zone 24 (EPSG: 2176)	Geoportal of Lublin (Geoportal of Lublin n.d.)	Administrative boundaries, bicycle infrastructure, right-of-way plots
Global Human Settlement Layer (GHSL) / grid	2023	World Mollweide (Pseudocylindrical) (EPSG: 54009)	Joint Research Centre (JRC) (Schiavina et al. 2023)	Population distribution
CORINE Land Cover (CLC) / vector	2006, 2012, 2018	ETRS89 / Poland CS92 (EPSG: 2180)	Copernicus Land Monitoring Services (CORINE Land Cover 2024)	Land cover
Digital Terrain Elevation Data (DTED) / raster	2004	WGS 84 (World Geodetic System 1984) (EPSG: 4326)	United States Geological Survey (USGS 2024)	Elevation, slope

Source: own study

Based on the trained neural network, the land cover prediction for the year 2018 was carried out. The simulation model was validated by comparing the predicted land cover map with the reference map (CORINE Land Cover 2024) using two indicators: overall accuracy (ratio of correctly classified instances to the total number of instances in the dataset) and the kappa coefficient (which measures agreement between the predicted classifications and the true values). An accuracy of 95.3% and a kappa coefficient of 0.94 were achieved. These high values indicate that the neural network was well trained. Using the obtained model, the land cover simulation for the year 2030 was performed.

Registration index

One of the factors influencing the development of the cycling network is population density (Hwang et al. 2024). Based on the number of registered residents in the city's districts, trends in registration numbers were assessed. The data used were from the month of February at yearly intervals (2018, 2019, 2020, 2021, 2022, 2023, and 2024). Using these data, the demographic trend indicator d (see formula) was calculated for each of the 27 districts of Lublin:

$$d = \left(\sum_{i=2018}^{n=2023} \frac{v_{i+1} - v_i}{v_i} \right) \cdot x \quad (1)$$

where: d – demographic trend indicator, v – number of registered residents in each year, x – proportion of registered residents in a district for the year 2024 relative to the total number of residents (307,999 people).

To standardize the trend values across different districts, they needed to be adjusted to a common reference value: the total number of registered residents in the city of Lublin. This adjustment was necessary because the population numbers in various districts vary significantly. In 2024, the lowest number of registered residents was in District 21 – Abramowice, with 1,575 residents (0.5% of the total population); conversely, the highest was in District 16 – Rury, with 24,617 residents (8% of the total population).

Network analyses

Network analyses are an excellent tool for identifying patterns in transportation systems, including cycling routes (Builes-Jaramillo & Lotero 2022). For an analysis to yield accurate results, relationships between origin (O) and destination (D) points must be established (Marko et al. 2009). In this study, the origins of bicycle trips were defined as the centroids of residential neighbourhoods, weighted by residential density. This approach balances data availability with analytical precision, drawing input from higher population density areas. It also prevents errors in indicating the polygon's focal point when it is inaccessible by bike (e.g. military areas, water reservoirs). The destinations were the centroids of buildings with educational, commercial, office, transport, and other functions.

The concept of the connection grid was established as an OD-Matrix with lines and network-based distances as attributes, created using the QGIS plugin, QNEAT3 (Raffler 2018). The network layer and matrix geometry were based on road axes. The origin points (O) were taken from the layer with neighbourhood centroids. For primary routes, the destinations (D) were also neighbourhood centroids (Fig. 3 (a)), while for supplementary routes, the nearest destination points were used (Fig. 3 (b)). Routes with the lowest total cost values were selected.

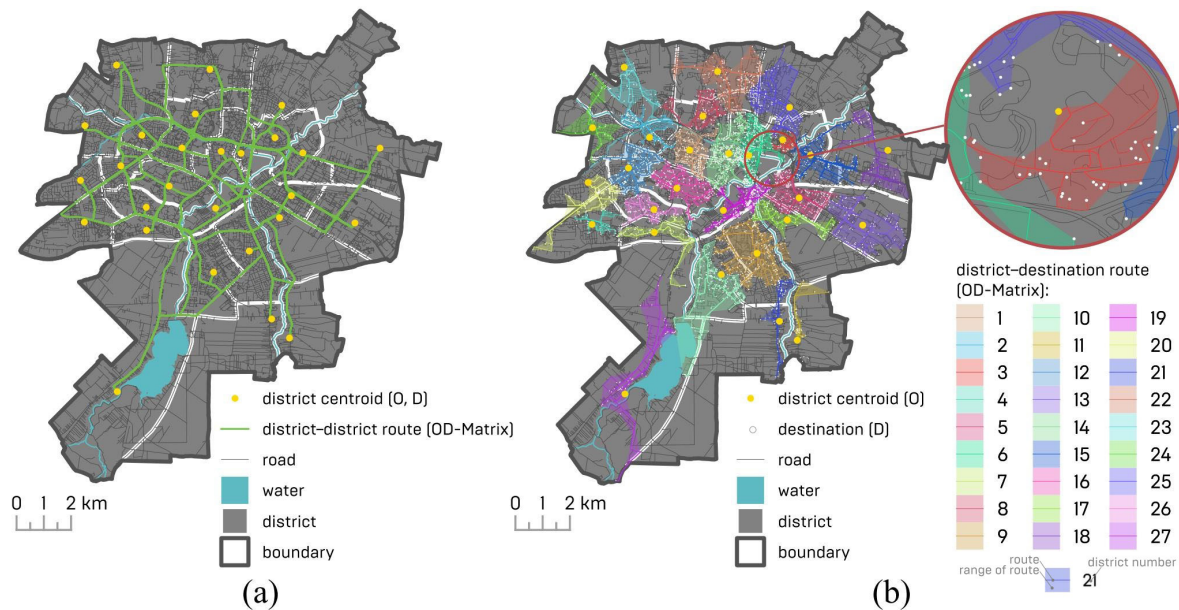


Figure 3. OD-Matrix routes: (a) district–district, (b) district–destination
Source: own study

Table 3. Land cover change statistics [km²]

Land cover	2018	2030	2018–2030
Urban	76.81	80.45	3.65
Agriculture	53.60	50.06	-3.54
Vegetation	17.30	17.29	-0.01
Wetlands	0.00	0.00	0.00
Water	3.27	3.17	-0.10

Source: own study

Normalization of the area of analysis and prioritization

Having completed all the input analyses, a synthesis was performed by dividing the city of Lublin into a grid of regular shapes. A hexagonal grid with a side length of 50 metres was used, resulting in 23,287 hexagonal cells. The hexagonal grid shape allows for a more accurate representation of irregular boundaries and is preferred for analyses involving linear data layers (e.g. connectivity analyses) (Birch et al. 2007). Each of the hexagons created was assigned result attributes from the analyses performed (land cover forecast for 2030, urban demography 2018–2024, and cycling network analysis) of the studies in the form of percentage overlap. Factors with an overlap of less than 1% were excluded from further processing.

The final stage of the analysis involves prioritization, where values are assigned to determine which areas should be developed first and which are less critical. The primary factors used for prioritization were the demographic index for Lublin's districts and the land cover prediction for 2030. The prioritization level was calculated by summing up the reclassified values from the land use prediction maps and the demographic trend index. The results were then categorized based on the road function, distinguishing between prime and supporting roads.

Results

Design of cycling roads

Areas for potential location of cycle routes in road right-of-way plots were obtained. The areas were normalized to hexagons and assimilated to the existing network (Fig. 4 (a)). A total of 5,683 hexagons have been identified for potential cycling infrastructure, covering nearly a quarter of the city of Lublin. Among these, 1,508 hexagons (6% of the city's area) correspond to areas with existing cycling routes, and 103 hexagons (0.4% of the city's area) correspond to planned routes.

Demography of the city

In Lublin, there was a slight decrease in the population over the years 2018–2024 – falling by 14,000 people, which represents a 5% decline. In comparison, the decrease for Poland during the years 2018–2023 was 2% (Statistics Poland 2024). Each district shows a consistent trend of either decreasing or increasing registered residents year by year. To facilitate comparison between districts, these were normalized to a common denominator, which is the proportion of registered residents in each district relative to the total number of registered residents in Lublin (Fig. 4 (b)).

Land cover prediction

Potential locations for new bicycle paths were determined, among other factors, based on the land cover simulation for the year 2030. This simulation was carried out using a pre-trained neural network, with the training process detailed earlier. Notably, the model was trained using standardized data at a 50 m resolution, as this setting delivered the highest overall accuracy. Alternative resolutions of 75 m and 100 m produced inferior results, while a 25 m resolution caused QGIS to crash due to computational overload. Based on the simulation model, land use changes for 2018–2030 were calculated (Fig. 4 (c)). A statistical summary of predicted land use changes during the period 2018–2030 is presented in Table 3.

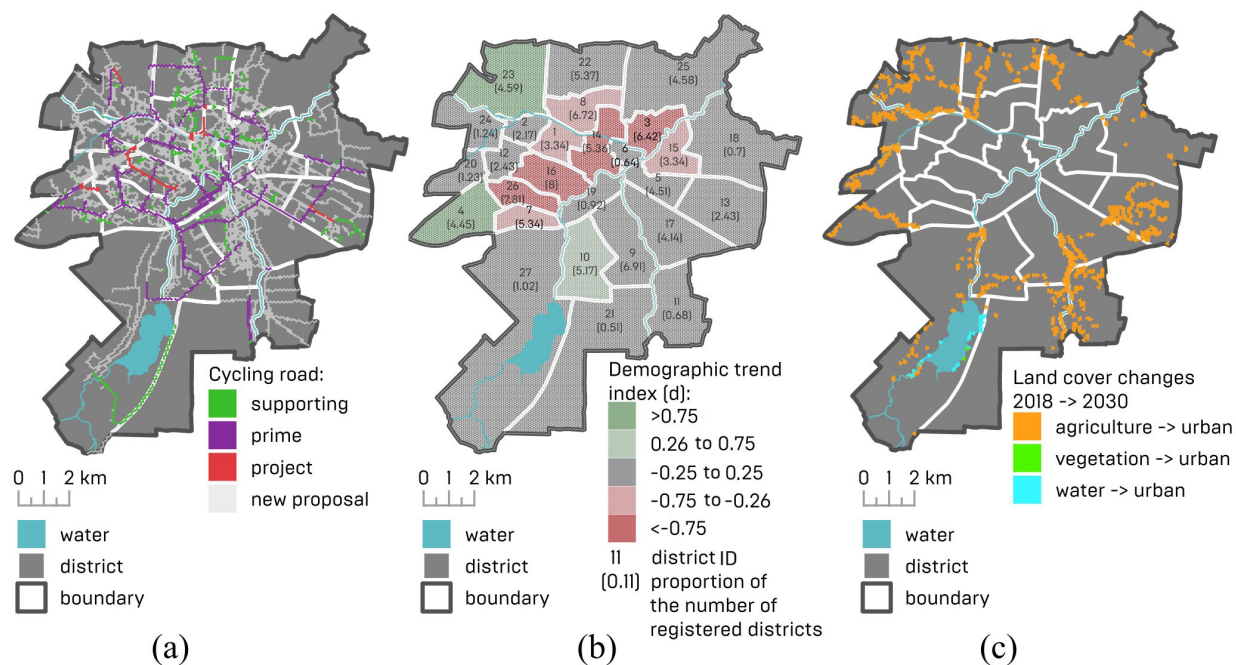


Figure 4. Average results: (a) proposed areas for the cycle path network, (b) demographic trend in 2018–2024, (c) spatial distribution of land cover changes

Source: own study

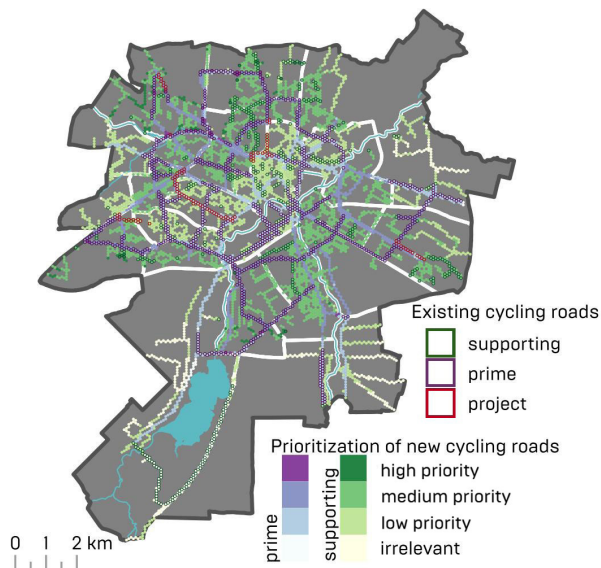


Figure 5. Proposed cycle tracks and their prioritization

Source: own study

Prioritization of new cycling roads

The final data were categorized into four classes: high priority – for roads to be implemented first, based on high population density areas and projected urban development in 2030, where bicycle infrastructure is currently lacking; medium priority – for roads to be developed in the near future, which either have existing bike infrastructure or are in areas with medium

demographic potential for future development; low priority – for roads that impact transportation but are not currently strategic, and are typically located in less densely populated areas; and irrelevant – for roads that do not significantly serve transportation functions at this time. The visualization of proposed cycle tracks and their prioritization is presented in Figure 5.

Discussion and conclusions

Based on the results presented in Table 3, the land cover changes in Lublin between 2018 and 2030 indicate minor shifts in land use and spatial distribution. The most significant change is projected in urban areas, which are expected to increase by 3.65 km², reflecting ongoing urbanization and infrastructure development. In contrast, agricultural land is forecasted to decrease by 3.54 km², likely due to urban expansion. Vegetation areas show a minimal decline of 0.01 km², suggesting relative stability in green spaces despite growing urbanization. Wetlands are projected to remain unchanged, maintaining their current area, while water bodies are expected to decrease slightly by 0.10 km². These changes emphasize the city's transformation, with a clear trend towards urban growth at the expense of agricultural land, while natural areas, such as vegetation and wetlands, remain relatively stable.

Changes in land cover impact the planning of future cycling routes. Urban expansion necessitates modifications to existing routes to provide enhanced connectivity to new developments. As urban areas grow, more cycling paths will be required to meet demand. The impact of changes in land cover is integral to developing cycling infrastructure because it ensures new routes align with the city's evolving landscape.

Analysing the final results, it is evident that a significant portion of the relevant cycling infrastructure has already been constructed or is in the design phase. The resulting data are

Table 4. Number of hexagons of new bicycle infrastructure compared to the existing one

cycle tracks priority	prime				supporting			
	proposed		existing		proposed		existing	
	number	share	number	value compared to the proposed ones *	number	share	number	value compared to the proposed ones *
high priority	40	2%	25 [2]	68%	106	3%	14 [0]	13%
medium priority	1 079	54%	498 [34]	49%	1 910	52%	210 [13]	12%
low priority	877	43%	430 [40]	54%	1 288	35%	147 [14]	12%
irrelevant	22	1%	3 [0]	14%	361	10%	78 [0]	22%
total	2 018	100%	956 [76]	51%	3 665	100%	449 [27]	13%

[number] – designed routes

* When calculating the percentage of existing routes, designed routes were also taken into account.

Source: own study.

juxtaposed in Table 4 to present them in a more detailed, visual, and consolidated manner, offering a clearer overview of the infrastructure's current and planned status.

The analysis shows that 51% of completed cycle tracks are primary routes, reflecting the priority to develop the main network, with supporting routes planned for later. Among the primary routes, 68% are high priority, while 13% of supporting routes have been completed, mainly recreational tracks near areas such as the Zalew Zemborzycki reservoir. These findings are based on technical and spatial assumptions, and are subject to change with public input and terrain considerations, which are critical for daily cycling. The results, structured as 6,500 m² hexagonal grids, highlight the effectiveness of free GIS software for large-scale cycling infrastructure planning.

The 2030 land cover prediction, based on neural network simulations, indicates urban growth, with urban areas expanding

by 3.65 km² and agricultural land decreasing by 3.54 km². These findings demonstrate that changes in land cover can affect the alignment of existing bike paths and play a significant role in the development of new ones. Urban expansion will necessitate modifications to current routes to accommodate shifting transportation needs, while also shaping new infrastructure. Approximately 6.5 km² of primary paths and nearly 23 km² of supporting paths are proposed to align with future land use. The results obtained underscore the significance of prioritising bicycle infrastructure in areas of urban expansion. They also emphasise the necessity of incorporating land cover predictions into transportation planning.

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