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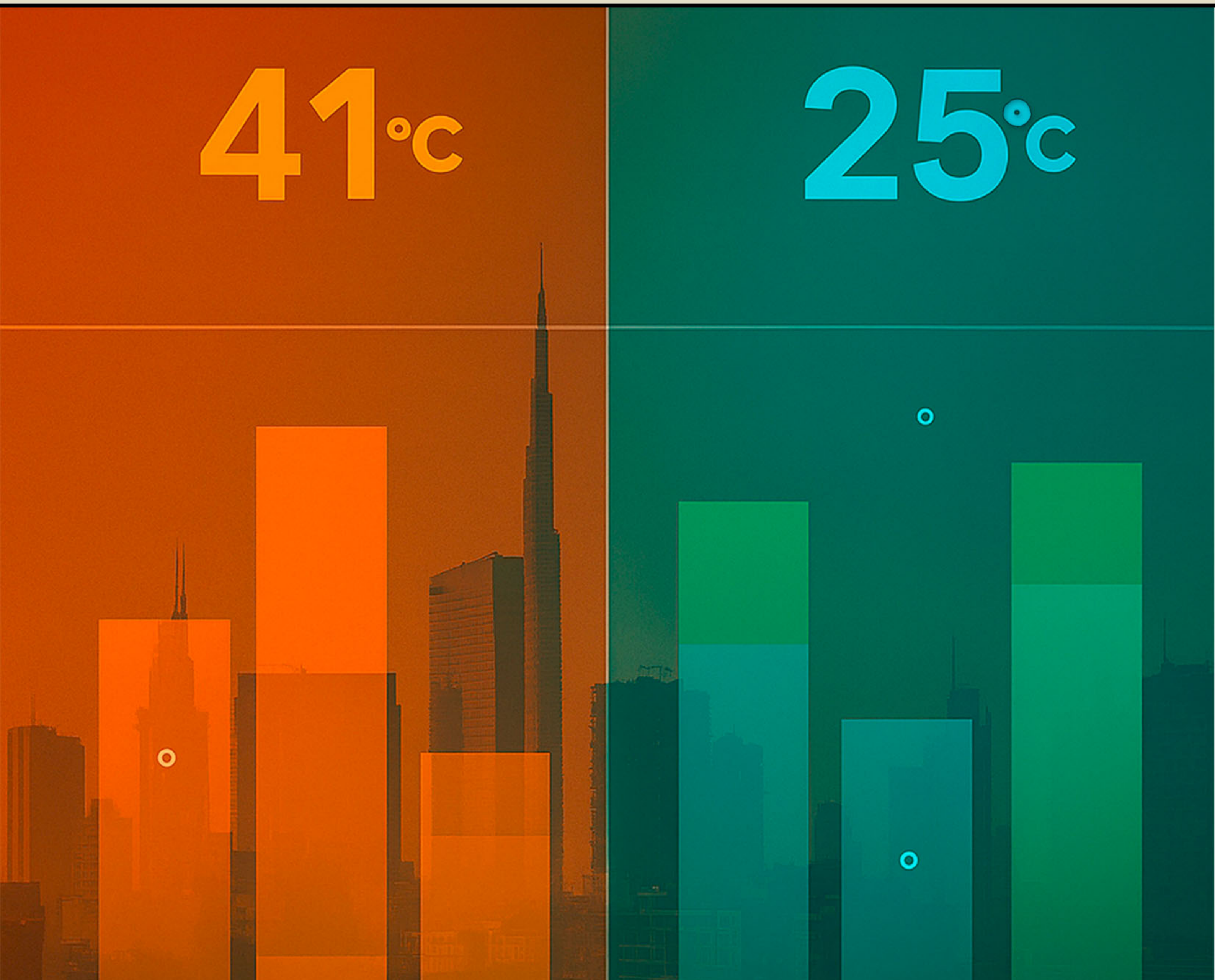

NEW CHALLENGES FOR XXI CENTURY CITIES

Multilevel scientific approach to impacts of global warming on urban areas, energy transition, optimisation of land use and emergency scenario

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3 (2025)

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GIS-based bikeability approach as a tool in determining urban bicycle infrastructure capacity for Eskisehir, Turkey

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Abstract

Urban transportation systems are rapidly evolving to meet contemporary challenges such as traffic congestion, environmental concerns, and sustainable mobility demands. Cycling is increasingly recognized as a viable mode of sustainable urban transportation due to its environmental, economic, and health benefits. However, determining the adequacy and capacity of bicycle infrastructure remains a key challenge for urban planners.

This study assesses the bicycle accessibility of Eskisehir, Turkey, by analyzing both existing and planned bicycle infrastructure using GIS-based methods. The research employs three established methodologies: Bicycle Stress Level (BSL), Bicycle Suitability Score (BSS), and Bicycle Level of Service (BLOS) to evaluate the urban road network and bicycle paths. These methods consider various factors including traffic conditions, road geometry, and infrastructure quality. The results reveal a disparity: while the BSS indicates that a large portion of the road network is "Suitable" or "Highly Suitable" for cycling, the BSL identifies significant "High Stress" areas for cyclists. Similarly, BLOS analysis shows that most of the network functions at "Level B," suggesting a reasonable environment for cycling, yet this contrasts with the high stress levels indicated by the BSL. The study highlights a critical issue where infrastructure classified as suitable may still present considerable stress for cyclists. The GIS-based approach provides a valuable tool for urban planners to identify areas needing improvement, aiming to create more bicycle-friendly cities. Ultimately, the research underscores the necessity for a comprehensive strategy that goes beyond basic assessments to effectively mitigate factors contributing to cycling stress, thereby fostering sustainable urban mobility.

Keywords

Bikeability; Bicycle infrastructure; GIS; Urban mobility; Sustainable transportation

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1. Introduction

Urban transportation systems are undergoing significant transformations to address contemporary challenges such as traffic congestion, air pollution, and the urgent need for sustainable mobility options. Cycling has emerged as a significant sustainable transportation mode due to its numerous benefits, including environmental sustainability, cost-effectiveness, and positive health impacts (Pucher et al., 2010; Mateu & Sanz, 2021). Research indicates that cycling not only reduces carbon emissions but also promotes physical health and well-being, making it a vital component of urban mobility strategies (Yang et al., 2021). The increasing use of bicycles, particularly in European bicycle-friendly cities, underscores the potential for cycling to contribute to sustainable urban transport (Castanon, 2024; D'Amico, 2023). For instance, cities like Utrecht, Münster, and Copenhagen have reported average bicycle usage reaching 35 %, reflecting a cultural shift towards cycling as a primary mode of transportation (Stults-Kolehmainen & Sinha, 2013). This shift gained unprecedented momentum during the COVID-19 pandemic, as cities worldwide accelerated bicycle infrastructure projects to promote safe and socially distanced mobility (Fenu, 2021).

To align with the European Union's 2030 and 2040 environmental targets, efforts must be made to enhance the bikeability of urban areas. This involves raising awareness of cyclist rights, improving safety measures, developing cycling infrastructure, and promoting bike-sharing schemes (Blanc & Figliozzi, 2016; Van Dyck et al., 2012). Integrating cycling into transportation frameworks underlines the determination and improvement of the bikeability of cities (Banister, 2008; Ewing & Cervero, 2010; Rodrigue, 2016). A bikeable city provides safe and comfortable cycling options for both commuting and recreational purposes, necessitating a cultural shift that recognizes cycling as a viable transportation mode (McNally et al., 2022). Bikeability has various definitions and generally refers to the assessment of an urban environment in supporting and encouraging cycling (Lowry, 2016) through a diversity of factors including the availability and quality of cycling infrastructure, safety measures, connectivity of bike paths, accessibility, and supportive policies (Hardinghaus, 2021; Lowry et al., 2012). Improving bikeability goes beyond infrastructure; it also requires creating a cultural shift toward recognizing cycling as a viable and desirable mode of transportation.

Still, the physical environment and availability are of critical significance regarding their key role in supporting bicycle transportation. The assessment of physical convenience is realized through the adoption of different approaches and methods to determine the suitability of the physical and environmental conditions of the geographical context for bicycle transportation.

Name of the Method	Acronym	Reference
Bicycle Safety Index Rating	BSIR	Davis (1987)
Bicycle Stress Level	BSL	Sorton & Walsh (1994)
Road Condition Index	RCI	Epperson (1994)
Hazard Interaction Score	HIS	Landis (1994)
Bicycle Suitability Rating	BSR	Davis (1995)
Bicycle Suitability Score	BSS	Turner et al. (1997)
Bicycle Compatibility Index	BCI	Harkey et al. (1998)
Bicycle Suitability Assessment	BSA	Emery & Crump (2003)
Rural Bicycle Compatibility Index	RBCI	Jones & Carlson (2003)
Compatibility of Roads for Cyclists	CRC	Noel et al. (2003)
Bicycle Level of Service	BLOS	Zolnik & Cromley (2007)
Bicycle Environmental Quality Index	BEQI	San Francisco Public Health Department (2009)
Bicycle Quality Index	BQI	Birk et al. (2010)

Tab.1 Methods used for determination of the bicycle transportation conditions (Pareek & Parbhakar, 2018; Callister & Lowry, 2013; Duc-Nghiem, Tung, Kojima & Kubota, 2017)

The literature on bikeability has evolved to encompass various interdisciplinary fields, including urban planning, transportation studies, public health, and environmental psychology. Murphy & Owen (2019) highlight the multifaceted nature of bikeability, emphasizing the need for comprehensive assessments that capture infrastructure quality, safety, accessibility, and convenience. Forsyth et al. (2013) further elaborate on this by presenting a conceptual model that integrates physical, social, and perceptual factors influencing cycling. Their model underscores the importance of both objective measures, such as the presence of bike lanes, and subjective experiences, such as perceived safety and comfort, in shaping cycling behavior. Methodologically, a variety of approaches have been employed to measure bikeability, ranging from qualitative assessments to complex quantitative indices. Geographic Information Systems (GIS) have become a common tool for analyzing spatial data related to cycling infrastructure and urban form (Ahmed et al., 2024). For example, Fonseca et al. (2023) introduced a multi-criteria analysis method for evaluating and designing bicycle networks in a Portuguese city, which is similar to the methodology applied in our study. In addition, field surveys and observational studies have been instrumental in evaluating cycling conditions and cyclist behavior, as evidenced by Dill & Carr's (2003) research in Portland, which established a positive correlation between high-quality cycling infrastructure and increased cycling rates. This article also aligns with studies such as Ahsan et al. (2023) that emphasize the importance of perceptual factors by examining barriers to walking in urban areas.

This study deals with the assessment of the environmental features that enable cycling in a city, commonly put forward through bikeability or other similar indexes. The study focuses on Eskisehir, one of the most livable cities in Turkey, known for its modern approach to urban planning and development. Eskisehir's relatively flat topography and compact urban form, with an urban population of approximately 810,000 inhabitants according to 2023 data, make it naturally suitable for cycling. However, investments in cycling infrastructure and efforts to promote this mode of transportation provide an interesting case study for examining the implementation and impact of bikeability initiatives. The goal of this study is to provide an overview of the possibilities of measuring how suitable the existing and planned bicycle roads in the Odunpazarı and Tepebası regions of Eskisehir province are for cycling. In this context, the most frequently used methods in the literature were used to measure bikeability. The visualization of the results provides guiding results for case studies conducted in the study area. The main contribution of this study is to reveal the urban bicycle transportation capacity with the perspective of bicycle accessibility with selected methods. An advantage of the transportation capacity presented is that it provides ideas for measuring the suitability of routes for existing or planned bicycle paths and making these lines efficient. The approach used is also useful for detecting inconveniences in road networks with different spatial coverage.

2. Material and methods

2.1 Study area

The study area comprises the urban areas of Odunpazarı and Tepebası districts, which are the central districts of Eskisehir province. Eskisehir is located in the northwest of Turkey, between 29-32 degrees east longitude and 39-40 degrees north latitude (Fig.1), spreading over 13,925 km². According to 2024 records, the province hosts 922.538 inhabitants, of whom 89.52 % live within the study area boundaries.

The basic information about the demographic and topographic structure of the study area highlights cycling potential in the city. According to the demographic data, 21.3 % of the population in the study area is under the age of 15, and 11.9 % of the population is over 65. The median age is 35.5, and the young population is predominant (Turkish Statistical Institute, 2024). The study area has a slope varying between 1-9 %, which is considered close to flat, providing a relatively suitable topography for bicycle transportation (Fig.2). In other words, the city has significant potential for bicycle transportation due to its topographic structure.

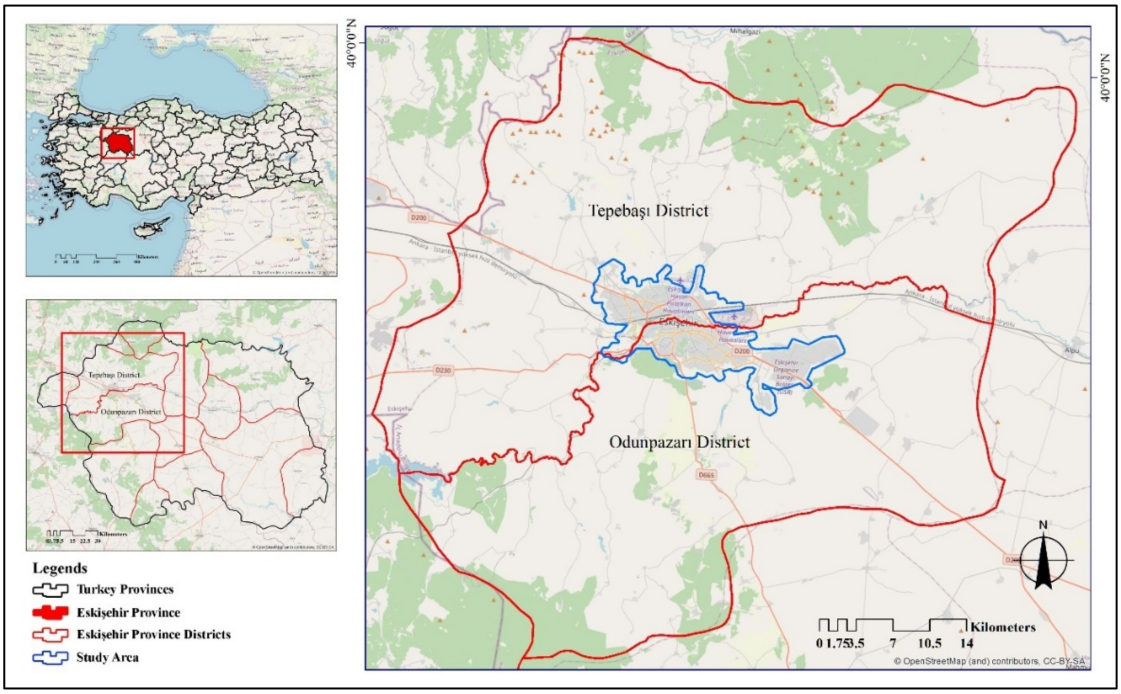

Fig.1 Location and boundaries of the study area

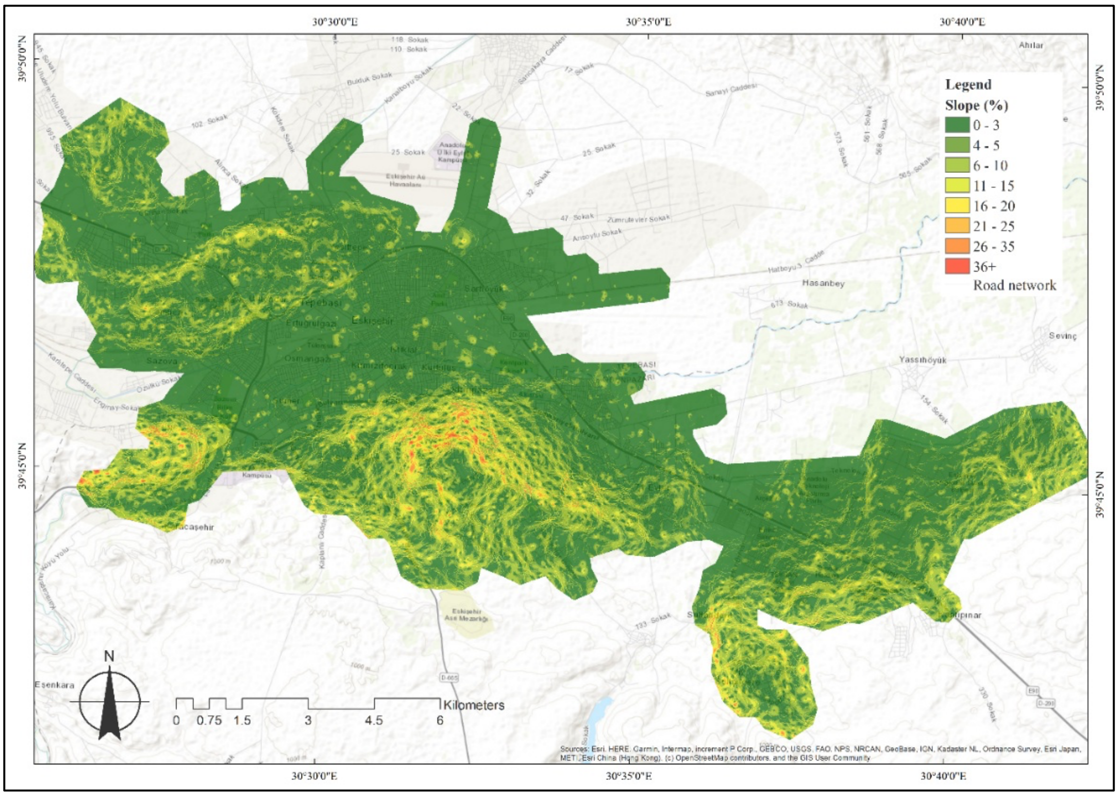

Fig.2 Slope map of the study area

This situation has given way to encouraging bicycle transportation in the study area to some extent. There are 64.5 km of existing and 30.3 km of planned bicycle roads in the study area (Fig.3). 13.3 km (20.7 %) of the existing bicycle roads are shared bicycle roads, and the remaining 51.2 km (79.3 %) consist of separated bicycle paths (İstanbul Technical University Transport and Transportation Vehicles Application Research Center, 2017). Separated or shared bicycle roads do not meet the Bicycle Roads Regulation, TS 9826, and TS 10839 standards. Furthermore, there are no provisions for intersection layouts, signaling, marking, cycling bridges, or tunnels to merge bicycle lanes, vehicular highways, or pedestrian walkways. In 2024, the study region had a car ownership rate of 23.5 %. This ownership is 17 % in Turkey (Turkish Statistical Institute, 2024). While this situation shows that the individual car usage rate in Eskisehir province is above the national average, it can also be interpreted as a negative situation in terms of sharing urban transportation infrastructure for cyclists.

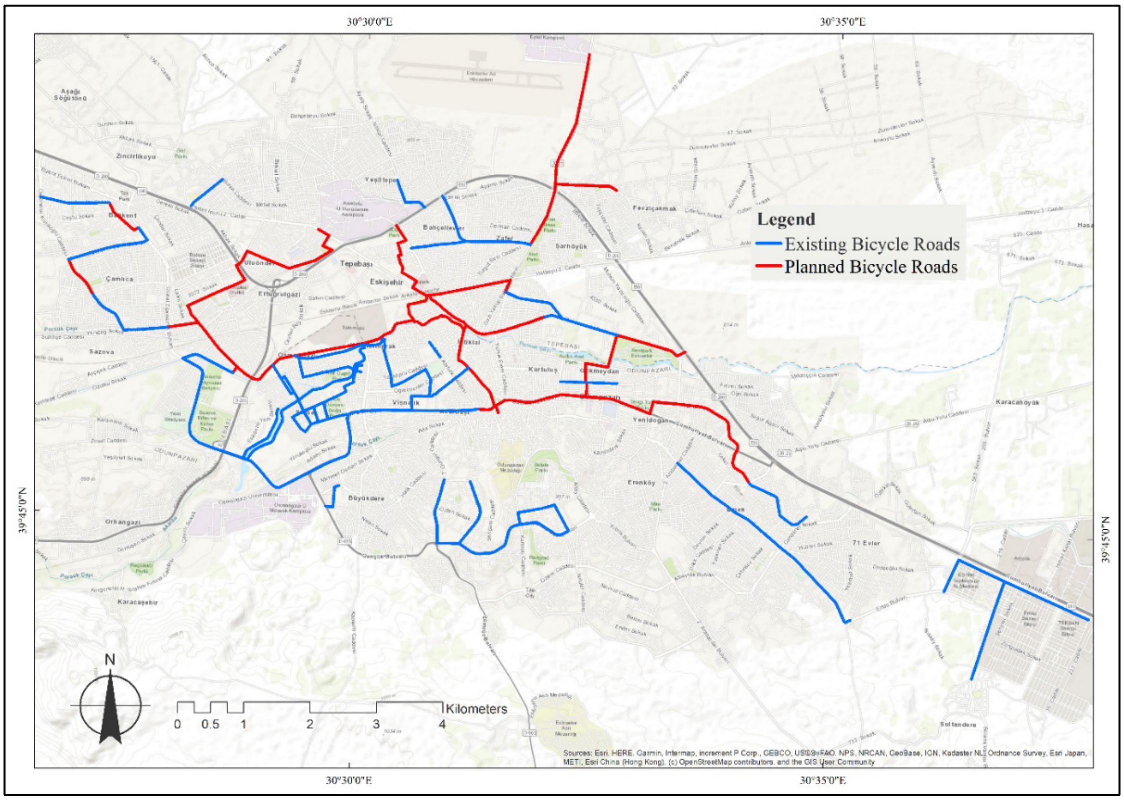

Fig.3 Existing and planned bicycle roads in the study area

2.2 Data Sources

This research was designed as a case study. The material of the study consists of vector data, satellite images and street images. Tab.2 summarizes the primary data used and their sources.

Data Name	Type	Source
Road network map and attribute data	Vector data and attributes	Digitization (originally produced using Arcgis 10.7 software)
Existing and planned bicycle road networks	Vector kml data	Eskisehir Transportation Master Plan (ETMP)2035 Report
Satellite images	Raster images with 0.5-1m resolution from different dates	Google Earth Pro software
Street images	Images and field photos from different dates	Google Street View, field observations
Land use map	Raster images with 0.5-1m resolution	atlas.gov.tr
Terrain slope map	Vector map with 5m resolution	Google Earth Pro software and gpsvisualizer.com
Traffic volume data	Number of vehicles	Ministry of Transport and Infrastructure General Directorate of Highways traffic volume map, field surveys

Tab.2 Data used in the study and their sources

2.3 Method

The main goal of the study is to determine the bicycle accessibility of the study area in Odunpazarı and Tepebası districts of Eskisehir by focusing on common indices based on environmental factors related to the infrastructure. In this context, both existing and planned bicycle roads were analyzed with the bicycle stress level (BSL), bicycle suitability score (BSS) and bicycle level of service (BLOS), which are the most commonly used methods for measuring bikeability as discussed in the literature. Each method used to assess bicycle accessibility facilitates a systematic examination of various metrics related to bicycle infrastructure by categorizing road sections as "road segments".

Bicycle stress level

The Bicycle Stress Level (BSL) was developed by Sorton to measure the stress experienced by cyclists when navigating urban roads in proximity to motor vehicle traffic (Sorton & Walsh, 1994; Sorton, 1995).
Cyclists encounter varying levels of stress on the roads due to traffic conditions. A local access road within an urban area, where traffic calming measures are implemented and the speed limit is set at 30 km/h, is considered a very low-stress environment. In contrast, a six-lane arterial road with a speed limit of 82 km/h represents a high-stress environment for cyclists.
BSL divides urban roads into small segments between intersections and calculates stress levels based on three fundamental stress components: "lane widths", "vehicle traffic volumes" and "vehicle speeds". Stress level values range from 1 to 5. According to the scale, a value of 1 indicates the lowest stress level or the best cycling conditions, while a value of 5 represents the highest stress level or the worst cycling conditions.
It is highly probable that as the traffic volume and speed values on a road increase and as lane widths decrease, the stress level on that segment of the road will also rise.
In the BSL, the criteria presented in Table 3 were used to determine the traffic stress levels on urban road segments.

Traffic Volume Index [Vehicles per hour]		**Outer Lane Width Index [meters]**		**Vehicle Speed Index [km/h]**		**Factor Score**
Value Range	**Treshold Value**	**Value Range**	**Treshold Value**	**Value Range**	**Treshold Value**	
0-49	0	4.55	4.55	0-39	0	1
50-149	50	4.25-4.54	4.25	40-49	40	2
150-349	150	3.95-4.24	3.95	50-59	50	3
350-449	350	3.65-3.94	3.65	60-72	60	4
450 ≤	450	0.00-3.64	0.00	73 ≤	73	5

Tab.3 Indicators used to calculate BSL

The index values and threshold values used for the determination of BSL are based on the research of Sorton & Walsh (1994). In this context, the traffic volume index values indicate the total number of vehicles passing in both directions over a designated road segment within one hour, the outer lane width index values indicate the lane width remaining on the far-right side of the road, including parking lanes if available and vehicle speed index values indicate the speed limit values applicable to a road segment.
When calculating the BSL score, a factor score was established for each measured index value for the road segments, and the average of these factor scores was taken (as shown in Tab.5). The calculated BSL scores define five levels of stress. The descriptions of these stress levels, the threshold values, and explanations regarding the appropriate user groups for such bicycle roads are presented in Tab.5.

Calculation Component	Road Segment n
Traffic volume index factor score	F1
Outer lane width index factor score	F2
Vehicle speed index factor score	F3
Bicycle stress level score	**Fort**

Tab.4 BSL calculation matrix

BSL Score Range	Treshold Value	Definition of Stress Level	Suitable Bicycle Users
0.00-1.00	1	Very Low Stress	Cyclists of all ages and abilities
1.10-2.49	2	Low Stress	Some adult cyclists
2.50-3.49	3	Medium Stress	Most adult cyclists
3.50-4.49	4	High Stress	Experienced cyclists
4.50-5.00	5	Very High Stress	Strong and fearless cyclists

Tab.5 Calculation components of BSL

Bicycle suitability score

The Bicycle Suitability Score (BSS) is a methodology designed to assess the appropriateness of a roadway for bicycle travel. Originally introduced by Turner et al. (1997), the BSS framework evaluates current road conditions to determine the most suitable urban routes for cyclists, thereby facilitating the identification of potential enhancements based on these assessments. The BSS determines the suitability of urban road segments by considering various factors, such as outer lane widths, sidewalk dimensions, vehicle traffic volumes, road surface quality, and vehicle speeds. The resulting rankings employ three-point, four-point, and five-point likert scales to convey the level of suitability for bicycle use.

In the BSS analysis, the criteria presented in Table 6 were utilized to determine the suitability levels of urban road segments for bicycle use.

Traffic Volume Index (Vehicles/Day)		Shoulder width index (meters)		Vehicle Speed Index (km/h)		Pavement conditions index*		Factor Score
Value Range	Treshold Value	Value Range	Treshold Value	Value Range	Treshold Value	Value Range	Treshold Value	
0-999	0	1.80 ≤	1.80	0-39	0	1.00-1.90	1	2
1,000-1,999	1,000	1.20-1.79	1.20	40-49	40	2.00-2.90	2	1
2,000-4,999	2,000	0.60-1.19	0.60	50-59	50	3.00-3.90	3	0
5,000-9,999	5,000	0.30-0.59	0.30	60-72	60	4.00-4.90	4	-1
10,000 ≤	10,000	0.00-0.29	0.00	73 ≤	73	5.00	5	-2

* Pavement condition index values are based on the study of Turner, Schafer and Stewart (1997).

Tab.6 Indicators used to calculate BSS

The index values and threshold values used for measuring the BSS are based on the work of Turner et al. (1997). In this context, the traffic volume index values indicate the total number of vehicles passing in both directions over a designated road segment on a daily basis, the shoulder width index values indicate the width of the section between the lane on the far right and the sidewalk, the vehicle speed index values indicate speed limit values and the sidewalk condition index values indicate the physical conditions of the sidewalks, with "1" indicating the worst condition and "5" indicating the best.

When calculating the BSS, the factor scores for the measured index values for each road segment are determined, and the BSS score is established by summing these factor scores (Table 7).

Calculation Component	Road Segment n
Traffic volume index factor score	F1
Shoulder width index factor score	F2
Vehicle speed index factor score	F3
Pavement condition index factor score	F4
Bicycle Suitability Score	**F1 + F2 + F3 + F4**

Tab.7 BSS calculation matrix

The calculated BSS defines four levels of suitability. The descriptions of these suitability levels, their threshold values, and explanations regarding the user groups that are appropriate for such bicycle roads are presented in Table 8.

BSS Score Range	Threshold Value	Definition of Suitability Score
(-6) - (-8)	-8	Unsuitable
(-2) - (-5)	-5	Moderately Suitable
(-1) - (5)	-1	Suitable
(6) - (8)	6	Highly Suitable

Tab.8 Definitions and threshold values of the BSS

Bicycle level of service

Bicycle Level of Service (BLOS) is used to determine the comfort levels of bicycle use on roads as a function of the geometric characteristics of the roads and traffic conditions in urban areas.

The methodology for BLOS has evolved over time, with initial frameworks developed by Landis et al. in the 1990s, which adapted the Level of Service (LOS) concept originally designed for motor vehicles to better suit the needs of cyclists (Liu et al., 2021). BLOS statistically assesses the suitability or compatibility of urban roads for bicycle use by utilizing variables such as road width, bike lane width, vehicle traffic volumes, road surface conditions, vehicle speeds, the proportion of heavy vehicles, and the availability and rates of on-street parking. Service levels are typically expressed on a scale where "A" represents roads with the highest comfort level and "F" indicates roads with the lowest comfort level (if a six-point scale is used). In this study, the calculation variables used for BLOS analysis are based on the work of Lowry et al. (2012). The variables are presented in Tab.9.

Calculation Component	Acronym
Outer lane width (m)	Wol
Bicycle path width (m)	Wbl
Shoulder width (m)	Wos
Traffic Volume (vehicle/hour)	v
On-street parking rate (decimal)	Ppk
Presence of pavement (yes/no) (1/0)	C
Number of lanes (in 1 direction)	Nth
Average vehicle speed	SR
Heavy vehicle rate (decimal)	PHV
Pavement condition (poor-excellent) (1-5)	Pc

Tab.9 Variables Used to Calculate BLOS

While calculating the BLOS, the calculated component values for each road network segment were determined and computed according to Eq.1.

$$\begin{aligned}\mathrm{BLOS} = \ & 0{,}76 + \left[-0{,}005\left((\mathrm{Wol} + \mathrm{Wbl} + \mathrm{Wos}) + (2 - 0{,}005v) + (\mathrm{Wbl} + \mathrm{Wos} + 20\mathrm{Ppk}) \ - \ 1{,}5\mathrm{c}^2\right)\right] \\ & + \ 0{,}507\ln(\frac{v}{4\mathrm{Nth}}) \ + 0{,}199[1{,}119\ln(\mathrm{SR} - 20) + 0{,}8103(1 + 0{,}1038\mathrm{PHV})^2] \\ & + 7{,}066(\frac{1/}{\mathrm{Pc}^2})\end{aligned} \quad (1)$$

The calculated bicycle service level values define six service levels. The threshold values and designations for these service levels are presented in Tab.10.

BSL Score Range	Treshold Value	Definition of Service Level
≤ 2,00	A	Perfect environment for cycling
2,00 - 2,75	B	Good environment for cycling
2,75 - 3,50	C	Reasonable environment for cycling
3,50 - 4,25	D	Poor environment for cycling
4,25 - 5,00	E	Inadequate environment for cycling
> 5,00	F	Unsafe environment for cycling

Tab.10 Definitions and limit values of the service level for bicycle use

2.4 Bridging qualitative perception and quantitative assessment

This study moves beyond conventional methods that rely solely on physical metrics for evaluating bicycle paths and road networks, by incorporating the perceptual experiences of cyclists into the process. The three quantitative indices used in the study (BSL, BSS, BLOS) are traditionally based on physical infrastructure parameters such as lane width, traffic volume, vehicle speed, and pavement conditions. In addition to this physical data, perception surveys and focus group discussions were conducted with 256 cyclists in the Odunpazarı and Tepebası districts as part of the study. This qualitative data was not used to directly change the threshold values or weighting schemes used in the calculation formulas of the quantitative indices. Instead, this data was used for two critical purposes:

Validating the results

The perception data were used to validate the findings of the BSL analysis. For example, the 88 % alignment of cyclists' perceived stress with the high-stress areas on the BSL map supports the output of the BSL model, which is based on physical data, and reinforces its methodological robustness. Similarly, the fact that 67 % of female cyclists reported harassment stress shows that areas classified as high-stress on the BSL map are challenging not only due to traffic but also due to social and perceptual factors.

Explaining paradoxical findings

The qualitative data played a vital role in explaining the main finding of the article: the paradox of why "physically suitable" infrastructure is still "high-stress". While models based on physical parameters like BSS and BLOS might classify a road as "suitable" or "reasonable," the stress experienced by cyclists is related not only to physical factors (such as traffic volume or road width) but also to factors that cannot be measured directly with quantitative indices, such as perceived safety, concerns about harassment, and a general sense of discomfort. This shows that cyclist perception and behavior, independent of the infrastructure itself, profoundly affect bikeability. This multi-method approach demonstrates that assessing only the physical infrastructure is insufficient in bicycle transportation research, and that the integration of human-centered, perceptual data is critical for scientific rigor and the replicability of the study.

3. Results and discussions

3.1 Results on BSL

Upon assessing the Eskisehir urban road network based on Bicycle Stress Level (BSL), it becomes evident that most roads exhibit high stress levels for cyclists. Conversely, there are only a limited number of roads that demonstrate very low stress levels, which are primarily found in the city's peripheral areas and consist of roads with minimal traffic loads or those that are closed to vehicular traffic.

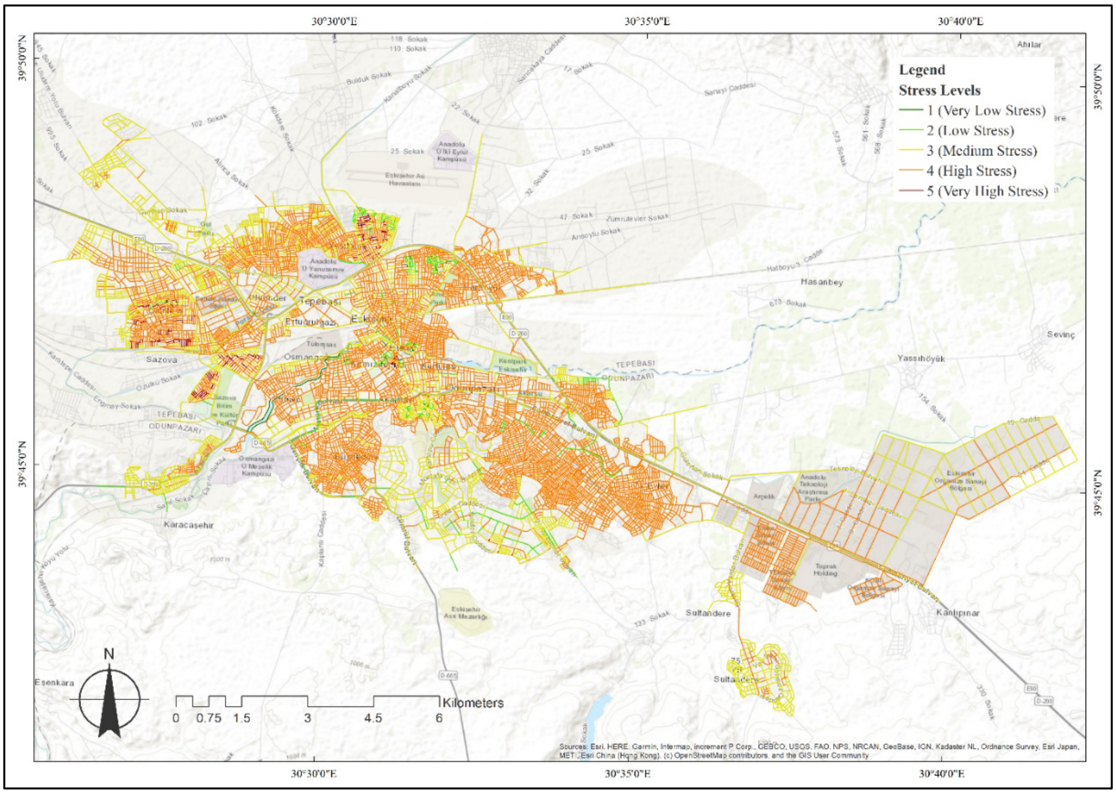

Fig.4 BSL values of the road network in the study area

The results of the BSL analysis including existing and planned bicycle roads, are presented in Tab.11.

		BSL Score				
		Very High Stress	High Stress	Medium Stress	Low Stress	Very Low Stress
Share in the urban road network	km	19.40	1,921.10	725.60	102.80	11.30
	%	0.70	69.10	26.10	3.70	0.40
Share in existing bicycle roads	km	0.00	37.80	17.30	5.40	4.00
	%	0.00	58.60	26.80	8.40	6.20
Share in planned bicycle roads according to ETMP 2035	km	0.00	13.70	14.70	1.90	0.00
	%	0.00	45.20	48.50	6.20	0.00

Tab.11 Results on BSL

According to the results based on BSL, roads with very high stress levels account for 0.7 % of the entire urban road network (19.4 km). There are no roads with this stress level among the existing bicycle roads in the city. It has been observed that roads with high stress levels comprise the largest share, covering 69.1 % of the urban road network (1,921 km). In parallel, 58.6 % (37.8 km) of the existing bicycle roads also exhibit high stress levels. This situation is believed to stem from bicycle roads that do not meet legal standards and the lack of necessary physical safety measures on shared bicycle roads. Roads with a medium stress level, where primarily adult or experienced cyclists can ride with less stress, make up 26.1 % of the urban road network (725.6 km), and 26.8 % (17.3 km) of the existing bicycle roads are located on these roads. Although these bicycle roads are designated as separated paths, they do not comply with the standards specified in the legislation. Low-stress roads, where cyclists aged 5-19 can comfortably ride, constitute 3.7 % of the urban road network (102.8 km). Among the existing bicycle roads, 8.4 % (5.4 km) are situated on these roads, which are separated from vehicle traffic and comply with the standards outlined in the legislation. Roads with very low stress levels, where all cyclists can ride comfortably, represent 0.4 % of the Eskisehir urban road network (11.3 km), and 6.2 % (4 km) of the existing bicycle roads are located on these roads. The primary reason for these roads having the lowest stress levels is that they are free from vehicle traffic.

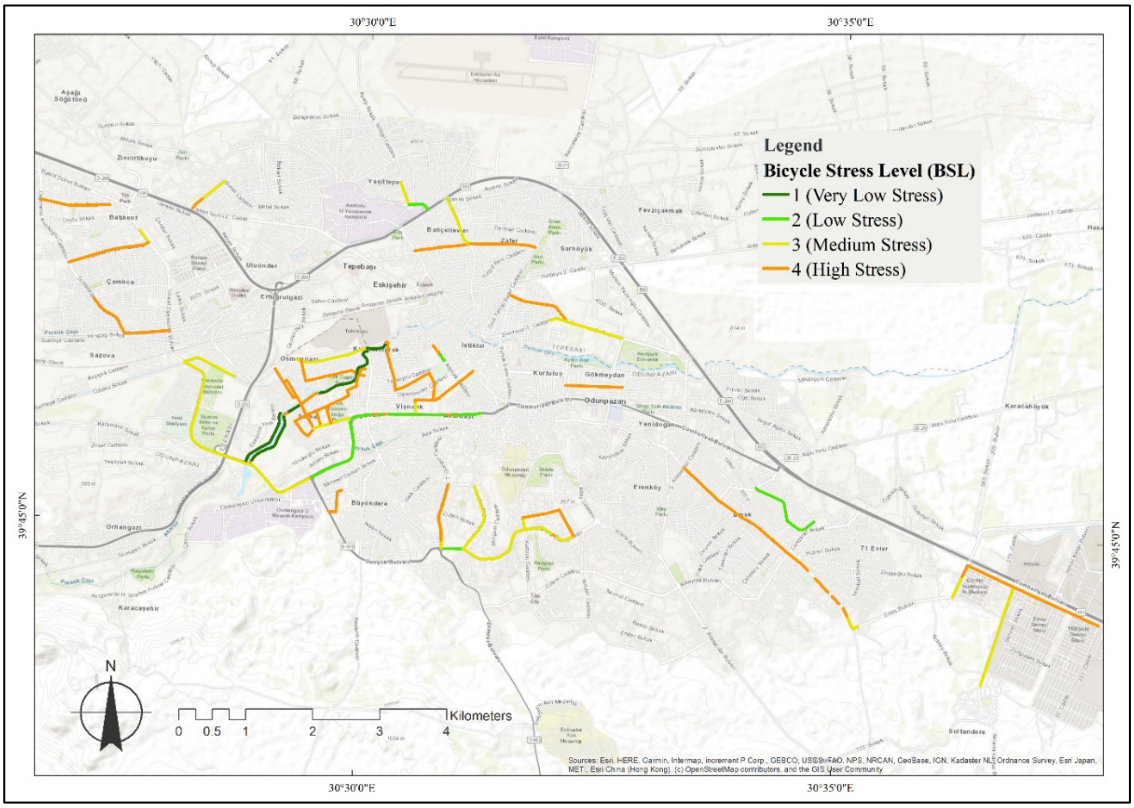

Fig.5 BSL values of existing bicycle roads in the study area

Upon evaluating the planned bicycle route alignments in accordance with ETMP 2035 and the Bicycle Stress Level (BSL), the following conclusions were drawn. Within the planning period from 2015 to 2035, a total of 30,373 meters of bicycle roads are intended to be developed.

The BSL analysis indicates that none of the proposed routes fall into the categories of very high or very low stress levels; instead, only 1.9 kilometers of the paths are classified as low stress, which represents just 6.2 % of the overall planned bicycle infrastructure. Additionally, it was noted that the lengths of bicycle roads categorized as medium and high stress levels are quite similar. Specifically, the medium stress level paths total 14.7 kilometers, making up 48.5 % of the planned bicycle routes, while the high stress level paths total 13.7 kilometers, accounting for 45.2 % of the overall planned bicycle roads.

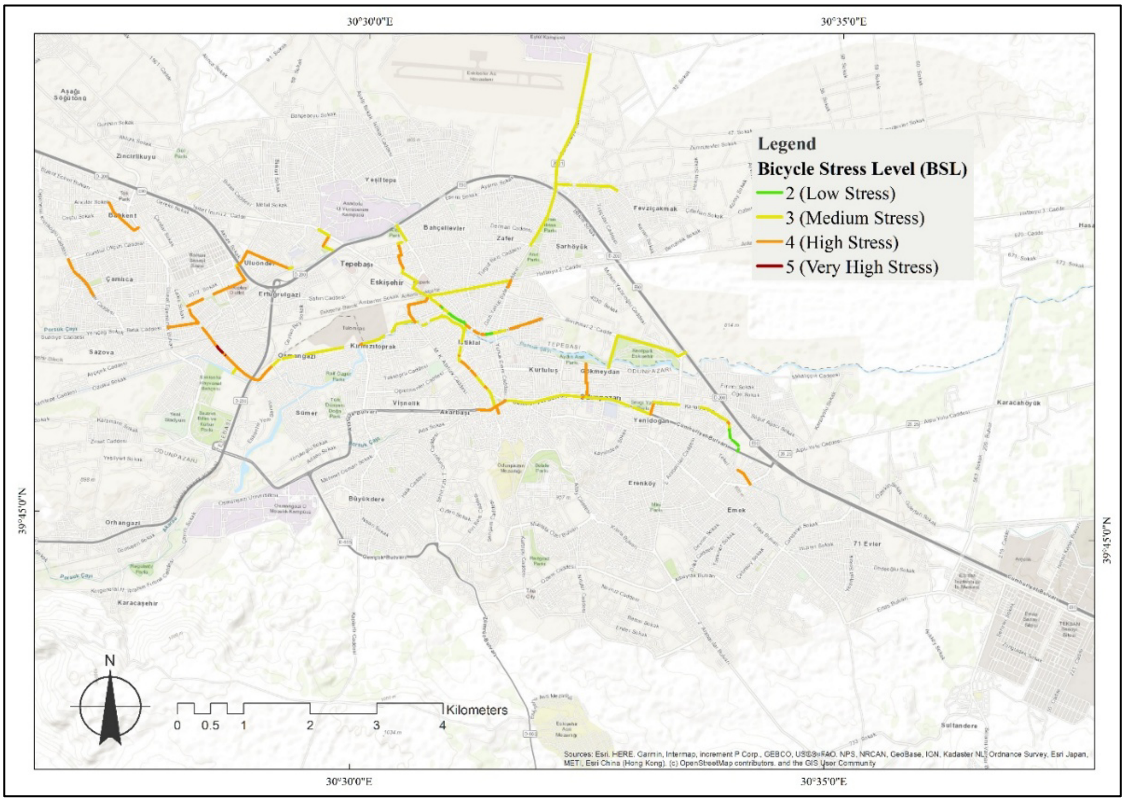

Fig.6 BSL values of bicycle roads planned according to ETMP 2035 in the study area

3.2 Results on BSS

Upon assessing the Eskisehir urban road network using the Bicycle Suitability Score (BSS), it is evident that a considerable majority of the roads (95.5 %) are categorized as "Highly Suitable" or "Suitable" for bicycle use.

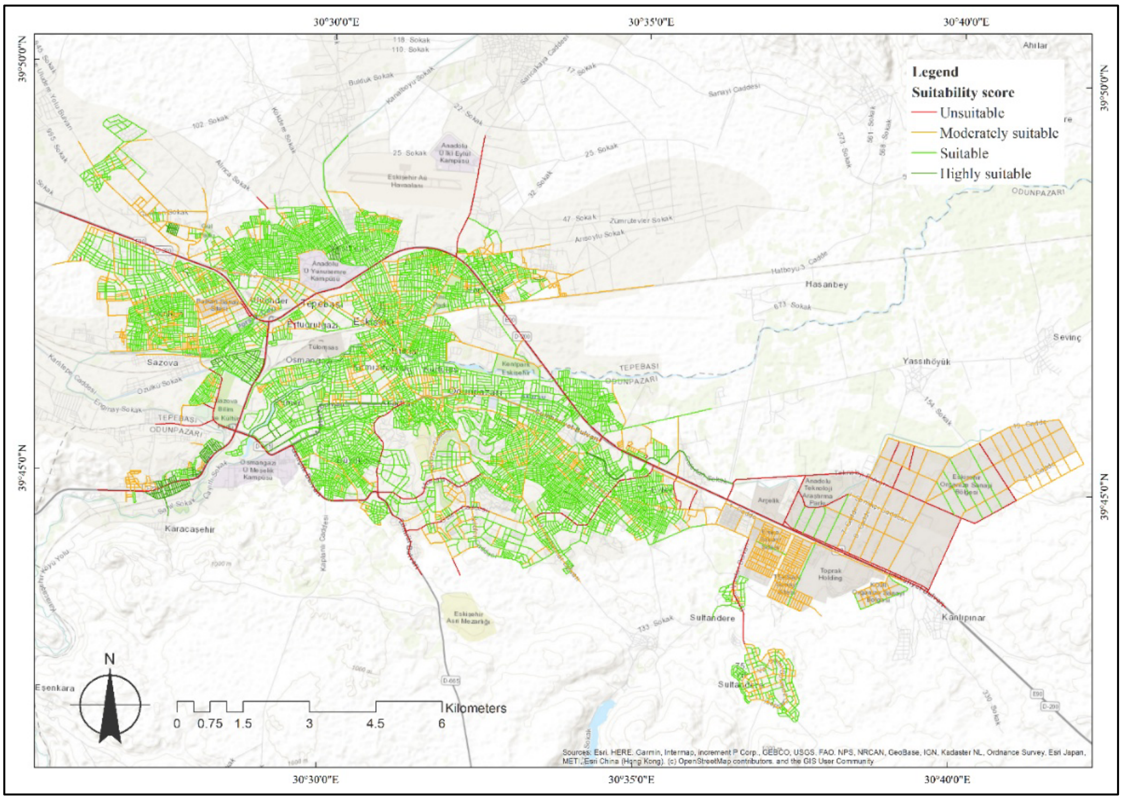

Fig.7 BSS values of the road network in the study area

The results of the BSS analysis including existing and planned bicycle roads, are presented in Tab.12.

		BSS Score			
		Unsuitable	**Moderately Suitable**	**Suitable**	**Highly Suitable**
Share in the urban road network	km	80.20	46.40	2,598.50	55.10
	%	2.90	1.70	93.50	2.00
Share in existing bicycle roads	km	7.80	18.90	29.80	8.00
	%	12.10	29.30	46.20	12.40
Share in planned bicycle roads according to ETMP 2035	km	2.40	10.80	16.60	0.50
	%	7.90	35.60	54.70	1.60

Tab.12 Results on BSS

It was noted that the road segments classified as "Highy Suitable" within the four suitability categories utilized for the BSS assessment account for 2.9 % (80.2 km) of the entire urban road network. Among these, 12.1 % (7.8 km) of the existing bicycle paths in the city are situated on these roads. This situation is believed to arise from the presence of one or more factors in the identified road segments, including bicycle paths that fail to meet legal standards, pavements with physical conditions unsuitable for cyclists, and vehicle speed values exceeding legal limits. Additionally, it was found that roads rated as "Unsuitable" represent 1.7 % (46.4 km) of the total urban road network, with 29.3 % (18.9 km) of the existing bicycle paths located on these segments.

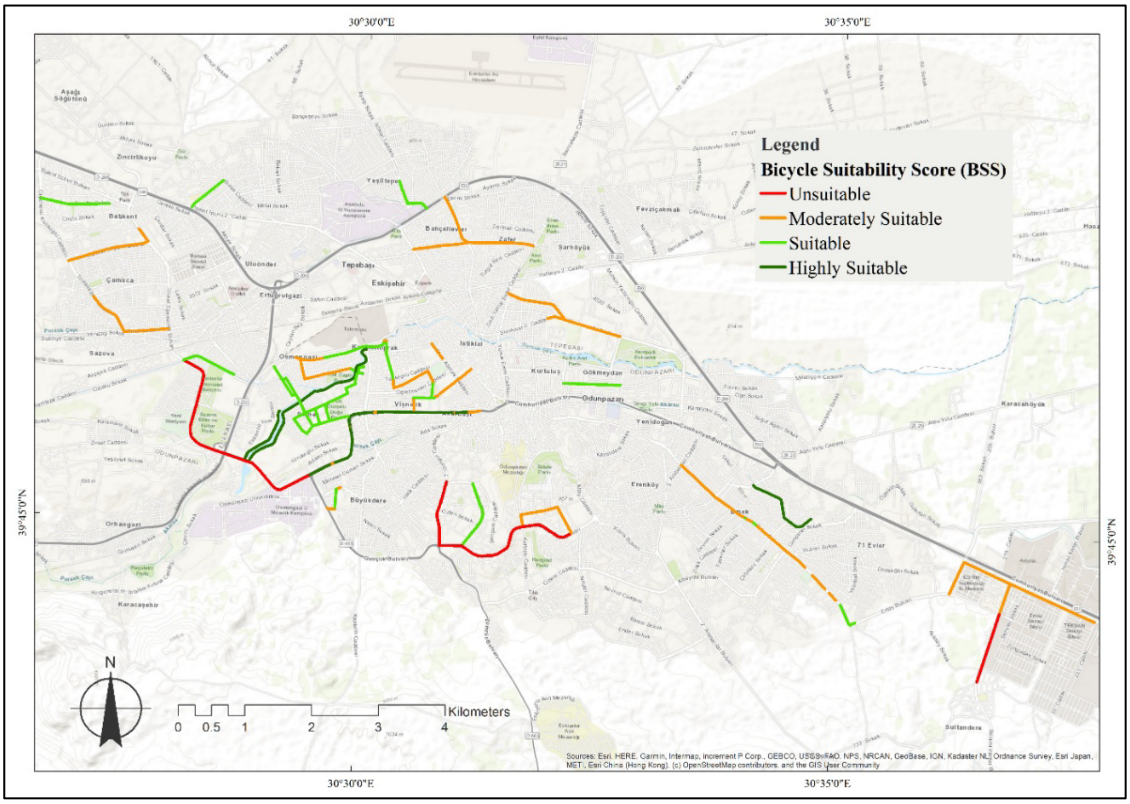

Fig.8 BSS values of existing bicycle roads in the study area

The relatively high traffic volumes and inadequate pavement conditions for cyclists contribute to this classification. Conversely, roads classified as "Highly Suitable," which constitute the largest proportion of the urban road network, cover 93.5 % (2,598.5 km) of the total network. Similarly, 46.2 % (29.8 km) of the existing bicycle paths fall within this category. It is posited that these bicycle paths are deemed "Highly Suitable" because, despite the pavement conditions being insufficient for cyclists, the vehicle speeds and traffic volumes create adequate conditions for cycling. It was observed that the roads defined as "Highly Suitable", which are the most ideal class for cycling, cover only 2 % (55.1 km) of the urban road network, with 12.4 % (8 km) of the existing bicycle roads situated on these roads. The factors contributing to the suitability of these roads for cyclists include dedicated bicycle paths that comply with legislative standards, roads that prohibit vehicle access, and roads characterized by very low traffic volumes. When the bicycle paths proposed for construction in accordance with ETMP 2035 are analyzed using the Bicycle Suitability Score (BSS), the following results are obtained. It was found that 2.4 km (7.9 %) of the planned bicycle paths, which are set to be built between 2015 and 2035, were classified as "Unsuitable." In total, the roads deemed "Unsuitable" amounted to 10.8 km, representing 35.6 % of the planned bicycle paths. Conversely, the classification of "Suitable" exhibited the highest proportion among the planned roads, with a length of 16.6 km and a share of 54.7 %. In contrast, the roads categorized as "Highly Suitable" had the lowest representation, measuring only 0.5 km and accounting for 1.6 % of the total.

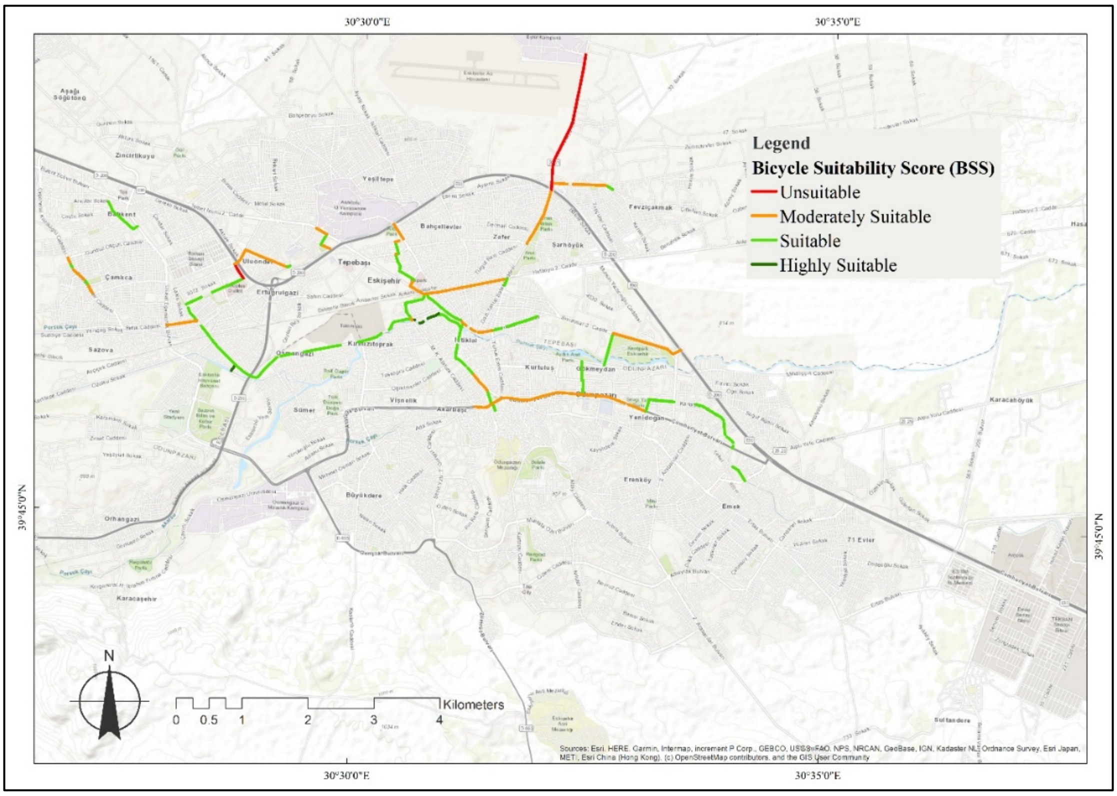

Fig.9 BSS values of bicycle roads planned according to ETMP 2035 in the study area

3.3 Results on BLOS

Upon evaluating the urban road network in terms of the Bicycle Level of Service (BLOS), it can be asserted that a substantial segment of the Eskisehir urban road network (76.3 %) attains a "B" service level. This classification signifies that the cycling experience is deemed acceptable for a diverse range of users, encompassing both "novice" and "experienced" cyclists.

It was observed that road segments classified as Level A, described as providing an excellent environment for cycling, and those classified as Level F, described as unsafe for cycling, were not exist. The lack of Level A roads across the city is thought to stem from several factors: the majority of bicycle paths are not dimensioned in accordance with standards, the proportion of on-street parking is remarkably high, the widths of outer lanes are insufficient for safe cycling, and the poor physical condition of sidewalks.

Road segments classified as Level B, described as providing a good environment for cycling, account for 76.3 % (2,122.6 km) of the total urban road network. Of the existing bicycle paths in the city, 65.7 % (42.4 km) are located on these roads. Key variables influencing the designation of these Level B bicycle paths include traffic volume and the utilization rates of on-street parking spaces. The Bicycle Level of Service (BLOS) values for roads with restricted vehicular access further support this classification.

The results of the BLOS analysis including existing and planned bicycle roads, are presented in Tab.13

		BLOS Score					
		Level A	**Level B**	**Level C**	**Level D**	**Level E**	**Level F**
Share in the urban road network	km	0	2,122.60	349.60	235.80	72.20	0.00
	%	0	76.30	12.60	8.50	2.60	0.00
Share in existing bicycle roads	km	0	42.40	8.10	12.80	1.20	0.00
	%	0	65.70	12.60	19.80	1.90	0.00
Share in planned bicycle roads according to ETMP 2035	km	0	25.50	3.20	1.60	0.00	0.00
	%	0	84.10	10.50	5.20	0.00	0.00

Tab.13 Results on BLOS

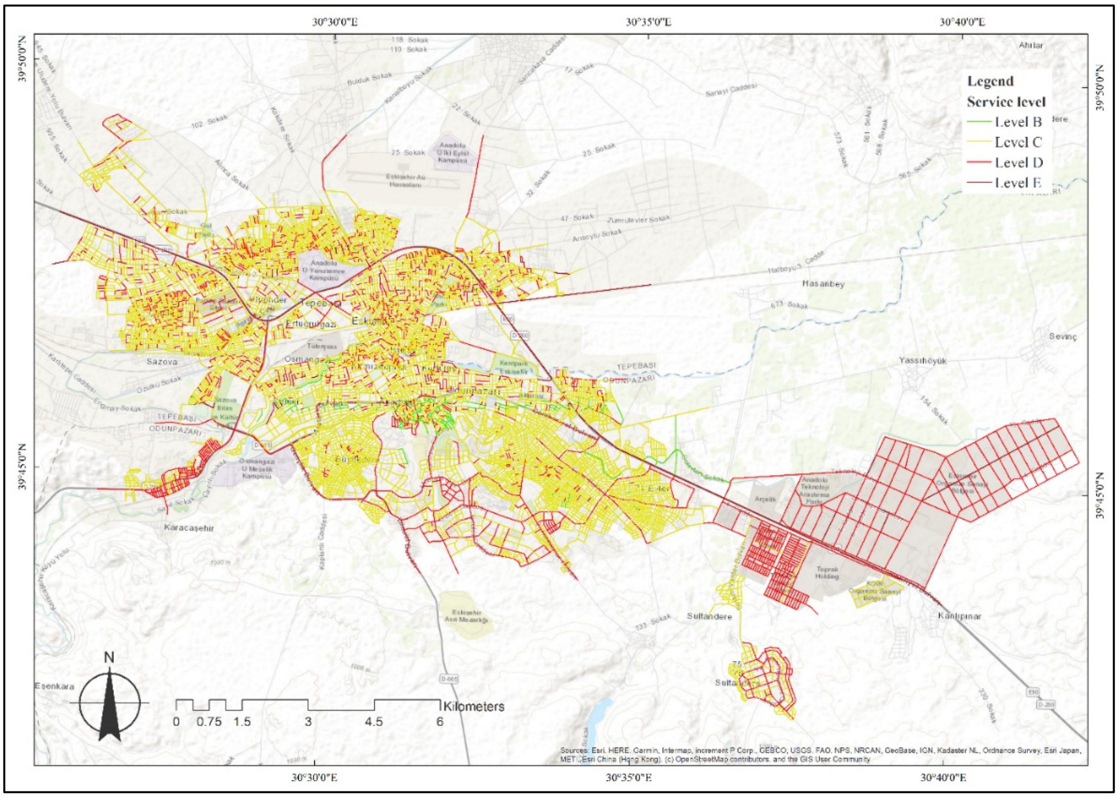

Fig.10 BLOS values of the roads in the study area

Level C road segments, described as providing a reasonable environment for cycling, constitute the largest share of the urban road network, covering 12.6 % (349.6 km). The existing bicycle paths within the city that fall into this category represent 12.6 % (8.1 km) of the total. Variables such as traffic volume, sidewalk conditions, and changes in the on-street parking utilization rates significantly contribute to the emergence of this classification.

Road segments classified as Level D, described as providing a poor environment for cycling, make up 8.5 % (235.8 km) of the total urban road network. Of the existing bicycle paths, 19.8 % (12.8 km) are located on these roads. On roads at this level, where cycling is particularly challenging, bicycle path widths are inadequate, and outer lane widths are insufficient to allow for shared-use arrangements.

Level E Road segments, described as providing an inadequate environment for cycling, account for 2.6 % (72.2 km) of the total urban road network. Only 1.9 % (1.2 km) of the existing bicycle paths are situated on these roads. The external lane widths, bicycle path dimensions, and the physical condition of sidewalks on these road segments fail to meet necessary standards, while the utilization rates of on-street parking spaces remain high.

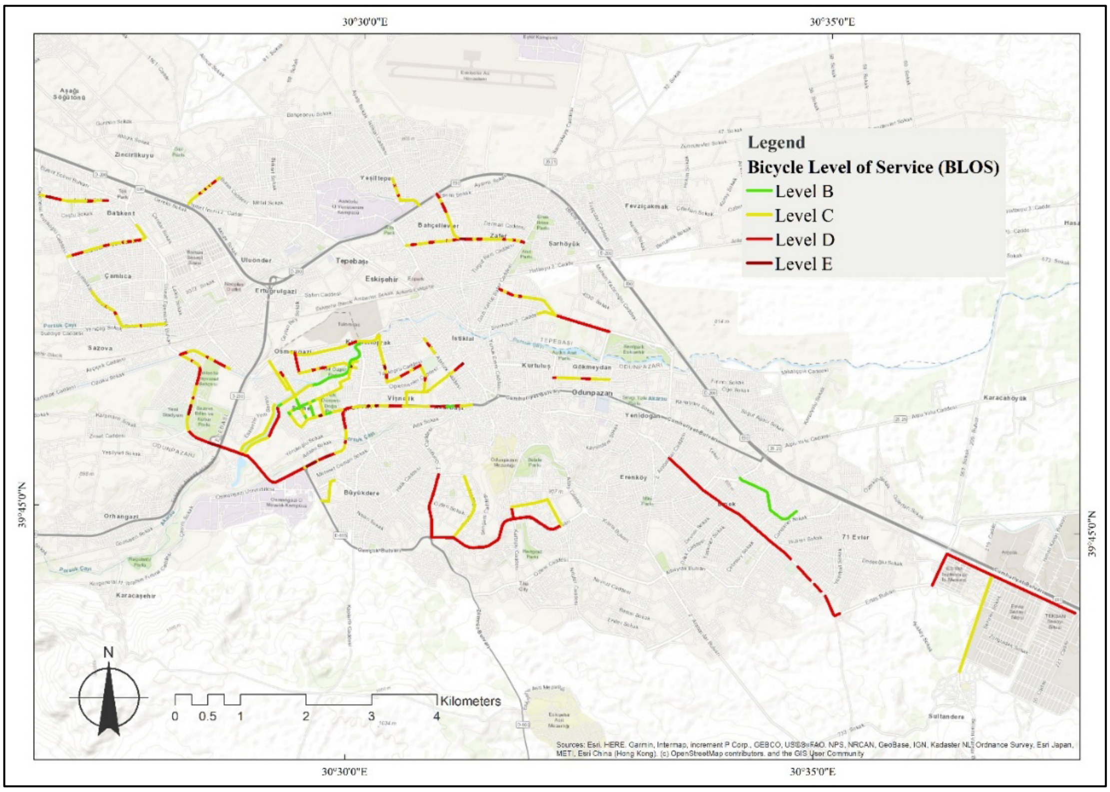

Fig.11 BLOS values of existing bicycle roads in the study area

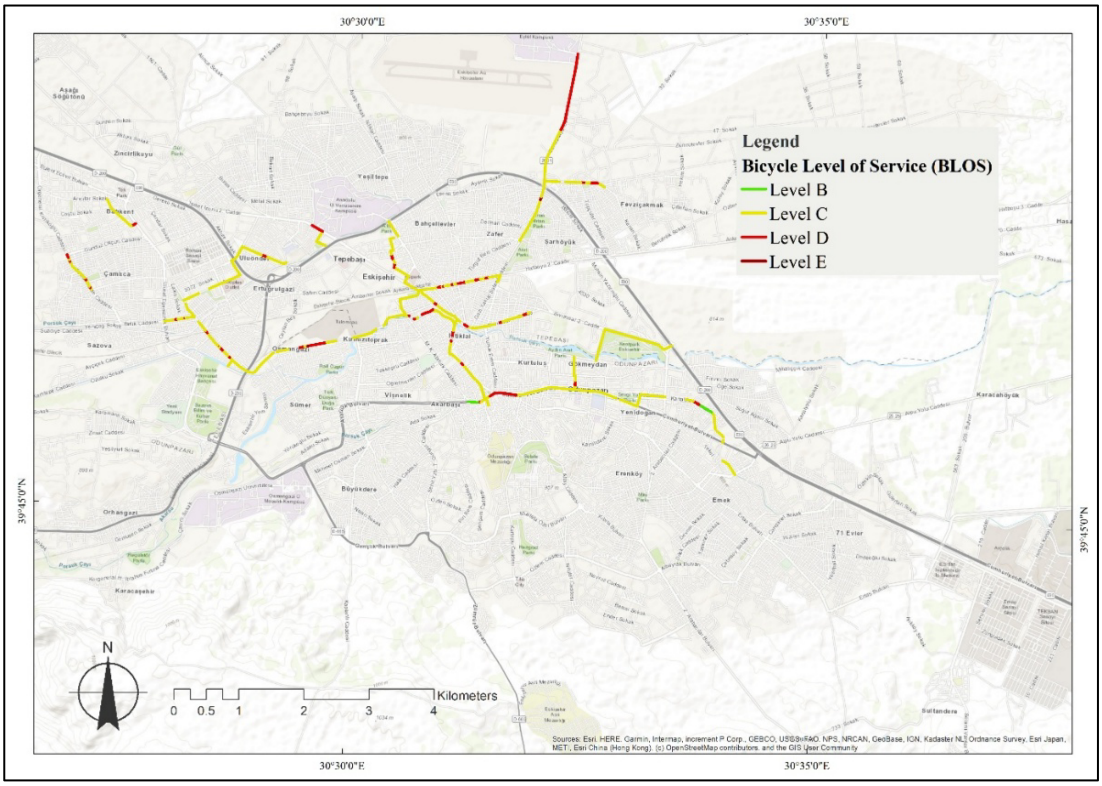

Fig.12 BLOS values of bicycle roads planned according to ETMP 2035 in the study area

When the planned bicycle path routes for 2035, as outlined in the ETMP, are analyzed based on the BKHS approach, it is observed that there are no routes classified at levels A and F among the planned bicycle paths during the plan period. Routes at level B constitute the highest proportion, accounting for 84.1 % (25.5 km) of the total planned paths. Routes at level C have a total length of 3.2 km, representing 10.5 % of the planned bicycle paths, while level D routes have the lowest share, with a total length of 1.6 km, corresponding to 5.2 % of the planned routes.

3.4 The paradox of physical suitability and perceptual stress

The methodology of this study has revealed that the urban road network in the study area has a contradictory structure. While a large portion of the road network (93.5 %) is classified as "Suitable" or "Highly Suitable" according to the BSS, the BSL identifies significant "High Stress" areas (69.1 %). Similarly, although the BLOS analysis shows that most of the network operates at "Level B" (76.3 %), this contradicts the high stress levels indicated by the BSL.

This paradox points to a fundamental problem: even when infrastructure appears to meet physical standards or satisfies basic service level criteria, it can still create significant challenges and stress for cyclists. The primary reason for this is that conventional indices, such as BSS and BLOS, which measure physical parameters, are unable to adequately capture the perceptual and social factors experienced by cyclists. This study fills this perceptual gap with survey data from cyclists, which helps explain the reason for the paradox. The fact that Eskisehir's car ownership rate (23.5 %) is higher than the national average (17 %) creates a negative situation for cyclists in terms of sharing urban infrastructure and increases stress levels. Furthermore, the lack of compliance of existing and planned bicycle roads with national standards (TS 9826, TS 10839) and the absence of fundamental safety measures like intersection layouts, signaling, and marking, cause even physically present infrastructure to create an unsafe and stressful environment for cyclists. This finding proves that there is no direct correlation between a road's physical width or surface quality being rated as "suitable" and a cyclist feeling "safe" on that road. Therefore, a comprehensive assessment requires both quantitative physical data and qualitative data on cyclists' experiences.

3.5 Policy implications and the path to cultural change

The study's findings reveal critical challenges in the implementation of Eskisehir's strategic plans for bicycle transportation. The city has taken determined steps to promote cycling; the Eskisehir Transportation Master Plan (EUAP 2035) aims to expand the bicycle network, and concrete initiatives like the "Bicycle Paths and Parking Stations Project" have been launched. Furthermore, by organizing workshops like "Come on Turkey, Let's Cycle!", the city supports the "cultural change" needed for the widespread adoption of bicycle transportation.

However, the data obtained in our study shows that the implementation of these well-intentioned plans faces a fundamental problem: a significant portion of the existing and planned infrastructure does not comply with national standards, making physically present roads stressful and unsafe for cyclists. For example, BSL results show that 58.6 % of existing bicycle roads are located in high-stress areas. This proves that a quantitative increase in infrastructure investments does not always qualitatively enhance cyclist comfort and safety.

Our GIS-based approach offers a valuable tool for urban planners to identify this critical divergence. By mapping specific road segments that the BSS and BLOS have marked as "suitable" or "reasonable" but the BSL has identified as "high-stress," the GIS analysis clearly shows the areas where investment will genuinely improve the cyclist's experience. This will allow for a more efficient use of resources and will close the gap between policy goals and on-the-ground realities. In conclusion, for Eskisehir to achieve the desired cultural change in bicycle transportation, the planning and implementation processes must be handled with an integrated approach, prioritizing the quality and compliance of existing infrastructure with standards, rather than simply increasing the length of bicycle paths. This approach will not only increase the number of cyclists but also foster a safer, healthier, and more sustainable life in the city.

4. Conclusions and limitations

4.1 Key findings and contributions

The methodology adopted in this study has shown that the urban road network in the study area has a paradoxical structure. While it is largely classified as "Suitable" according to the Bicycle Suitability Score (BSS), the infrastructure also contains significant "High Stress" areas as identified by the Bicycle Stress Level (BSL). Similarly, although the Bicycle Level of Service (BLOS) shows that most of the network operates at "Level B," this contradicts the high stress levels observed in the BSL. Existing bicycle paths follow a similar trend; although they are classified as "Suitable" in the BSS, a large proportion of them are located in "High Stress" areas in the BSL. This recurring theme indicates that a significant portion of both existing and planned bicycle infrastructure is classified as "Moderate" or "Level B," yet still experiences significant challenges in "High Stress" areas. These findings suggest that while the infrastructure may meet basic suitability and level of service criteria, it still poses challenges for cyclists.

The main contribution of this study is that using three different bikeability assessment indices together provides a comprehensive analytical view that a single assessment cannot. This proves how critical not only physical data but also user perceptions are in urban bicycle transportation planning. The quantitative results obtained clearly show that a single model can be misleading and that a multi-criteria approach is essential to get a complete picture. With its GIS-based approach, this study provides a valuable tool for urban planners to identify areas that require infrastructure improvements and to help create a more bicycle-friendly urban landscape.

4.2 Limitations and quantitative significance

This study has some limitations. The data used, such as traffic volume, is static for some variables and may not fully reflect the dynamic changes that occur at different times of the day or on different days of the week. In addition, adherence to the standard formulas of the quantitative indices used (BSL, BSS, BLOS) has limited the direct integration of perceptual data into the formulas. However, these limitations also highlight the study's most important finding and its quantitative significance.

The quantitative significance of the study lies in the striking differences between the results obtained. For example, the fact that 58.6 % of existing bicycle roads have "High Stress" according to BSL, but 46.2 % are "Suitable" according to BSS, numerically proves how misleading traditional single-index evaluations can be. This contradiction shows that a new paradigm is needed at the core of bicycle transportation planning. Future research could overcome these limitations by combining dynamic data from GPS trackers or by developing a new, hybrid index that directly incorporates perceptual factors into the calculation mechanism. In conclusion, this study underscores the need for a comprehensive approach that goes beyond basic suitability and service level assessments and effectively addresses the factors that create stress for cyclists.

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