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Cycling Infrastructure Assessment

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Abstract: The 21st century is called a century of urbanization due to the fast growth of the share of the urban population in the world. Cities often grow into metropolitan areas, which stimulates the development of transport that, due to new technologies, can ensure accessibility of every point in the metropolitan area. While earlier the concentration of production facilities was accompanied by an extra effect (so-called "agglomeration effect"), negative effects arise more and more often now: transport chaos in urbanized territories, water supply and environmental issues. Growing automobilization is the main transportation problem in cities. Cars need space for movement and parking and, per one person, take twenty times more space than a streetcar and ninety times more than the subway. Pedestrian infrastructure public transport, and bikes not only save urban space but also contribute to the establishment of healthy and cost-effective cities. The top priority is to ensure the safety of all road users. In its Global Status Report on Road Safety (2018), WHO points out that currently, road accidents are the primary cause of death of people aged 5 to 29. Cyclists are one of the most vulnerable groups of road users. Ideally, roads should be designed in such a way so that safety was ensured for pedestrians, cyclists and motorcyclists. Since any changes in traffic infrastructure re-quire a feasibility study, including in terms of safety of the transportation system, the risks and consequences of changes in the traffic pattern should be taken into account.

I. INTRODUCTION

Bicycling has become vital for urban transportation worldwide. Numerous transportation agencies have encouraged the increasing trend of bicycling as they recognize the potential benefits of public health, air quality, and traffic congestion. Bicycling helps meet the global recommended daily physical activity and has been associated with reduced risks of all-cause mortality, coronary heart disease, and diabetes. Forecasting and modelling research has also demonstrated that bicycling offers population health benefits that outweigh adverse risks, such as air pollution. Moreover, shifting from motorized transport to cycling for short, regular trips (up to 5 km one way) has yielded significant economic benefits, including annual savings of approximately 1300 euros through improved physical health. Therefore, encouraging cycling can facilitate diverse health and monetary benefits.

Providing infrastructure that supports the needs of cyclists has been considered an important strategy to encourage more cycling in cities. Previous studies suggest that dedicated bicycle facilities are critical to cycling, as potential cyclists strongly desire infrastructure that separates cyclists from motor vehicles. Currently, there are many examples of how bicycle infrastructure is implemented. For instance, in addition to conventional bike lanes, cities in the United States have experimented with buffered bike lanes either as single or combined with European-style cycle tracks, a design known as "separated bicycle facilities" to distinguish motor vehicles and cyclists. European countries like the Netherlands, Denmark, Sweden, and Belgium provide excellent, interconnected bicycle infrastructure to encourage bicycling. Additionally, many countries promote using bicycles as feeders for public transportation. Various bicycle infrastructure conditions result in different levels of perceived comfort and safety. Street design can significantly impact the ability to bicycle, making it crucial for urban planners to consider diverse user needs. Creating visually appealing urban spaces with uninterrupted bicycle ways, smooth pavement, connected and well-planned bicycle facilities can further enhance the experience for those choosing to bike. Various methods, such as the BLOS, BSI, and BI, have been developed to consider these factors in assessing the bicycle environment for bicyclists' safety, comfort, and overall efficiency. A few studies have also been conducted that review the developed methods. A number of review papers have been published in recent years, specifically since 2010, focusing on evaluating bicycle infrastructure assessment methods. It is crucial to note that each review article focused only on a specific type of assessment method; for example, Asadi-Shekari et al. and Kazemzadeh et al, considered only the bicycle LOS concept. Whereas others, for example, Castañon and Ribeiro and Valenzuela et al, focused on bikeability. These review articles provide a comprehensive overview of the methods developed but lack clarity on differentiating and categorizing them. While diverse assessment methods exist for bicycle comfort and safety of the bicycle environment, a critical gap in the literature remains unaddressed: the comprehensive grouping, comparison, and selection of these methods based on specific contexts. Existing studies fail to systematically categorize methods and highlight the key differences in each category. In addition, the review articles fail to provide information on the application of these developed methods. This lack of clarity creates significant challenges for practitioners and policymakers in selecting the optimal assessment method for their specific needs.

II. LITERATURE REVIEW

1) *A Review And Critical Assessment Of Cycling Infrastructures Across Europe*

Authors: A. Vassi & T. Vlastos

Cycling is an old but fast growing component of European cities' mobility planning schemes. Cycling has strategic importance for the mobility management schemes and the sustainable development of European cities. Bicycle infrastructure offers excellent value for money compared with other types of transport. In some cities, the traffic system already offers a large amount of bicycle infrastructures. This paper will be dealing with the categorization of cycling infrastructures across Europe and on its contribution to the mobility management of cities. This study has gathered data concerning the cycling infrastructure across Europe through an online questionnaire, common for all cities. The main benefits and challenges of infrastructures, their effectiveness in mobility management, and their safety performances are presented. The research conducted explored and highlighted the pillars of a cycling city.

The results concern the way to build an optimum environment for cycling. Each city has its own needs, its own culture and its own potential to grow cycling culture. The requirements of a cycle network differentiate a lot between cities, but a variety of solutions is provided in order to establish a complete, safe and integrated cycling network. Each city has different geographical, urban and traffic characteristics. A lot of factors influence the effects of cycling infrastructures. Land use planning, car parking policies, car free zones and speed limits are some of the factors that can strengthen or weaken the effects of infrastructure. Culture, and

habit tend to increase cycling in cities with high levels of cycling but also they decrease cycling, especially among non-cyclists, in cities with low levels of cycling. Non- cyclists in bike-oriented cities can respond differently to infrastructures than non-cyclists in cities with little cycling. Non-cyclists who are surrounded by other cyclists it is more likely to start to use bicycle and thus more responsive to infrastructure establishments. Thus, the same infrastructure provision, program, or policy might have different impacts on cycling in different cities. Each solution must be "tailor made" for each city. Any type of infrastructure in the proper environment can make people think that cycling is a good option.

In recent years great significance is given to shared infrastructures: shared space, bike sharing systems, sharrows, fahrradstrasse, perspective which reduces infrastructure costs, gives space to pedestrians, lowers speeds in town and therefore make it more humane. We could say that there is a world leading tendency not "equip the warrior", if we describe the cyclists as a warrior in the urban environment, but to "improve the equipment". It is a sign that we passed from the policy of protecting the bicycle to more decisive policies which have as pillars the pedestrians and the cyclists. The new policies are targeting at transforming the city into something more civilized and mild, after all cities are places for people. They need human scale constructions, policies, and measures to cultivate social relationships.

2) *Assessing The Impact Of Bicycle Infrastructure On Safety And Operations Using Microsimulation And Surrogate Safety Measures: A Case Study In Downtown Atlanta*

Authors: Katherine Lee, Amirarsalan Mehrara Molan, Anurag Pande, Uijeong Hwang, Subhrajit Guhathakurta, Mirabel Nkanor, Benedetta Sergio

This research assessed the impact of efficiently expanding the biking network in Atlanta, Georgia, using dedicated lanes for bicycles. A total of three different conditions: existing, proposed (by the authors), and alternative (suggested by the City of Atlanta) conditions were modeled to see the effectiveness of bike infrastructure design improvement and expansion. Trajectory data collected from the VISSIM simulation model was used in FHWA's Surrogate Safety Assessment Model (SSAM) to analyze the safety effect on the bike infrastructure improvement and expansion. Based on the results, both the proposed and alternative conditions resulted in safer travel through the network during the peak hour period without any apparent deterioration in delays. For instance, compared to the existing condition, the average stop delays decreased from 190 s to 164 s for the proposed and the alternative conditions. These findings showed that the introduction of bicycle lanes and narrower lanes for automobiles may not adversely affect the peak hour congestion. Also, fewer conflicts were observed in the simulated network of proposed and alternative conditions compared to existing conditions. Conflicts involving bicyclists were also reduced since the bicyclists can use their own lanes and do not have to interact with automobile traffic in the sharrows. The paper examined the effects of complete streets by analyzing the existing bike networks and the potential connections and implementation of new bike infrastructure to form complete networks that improve active mobility. The simulation scenarios evaluated in this study demonstrated the impact of the existing, alternate, and potential bike infrastructure on the operations and safety within the study network.

3) Engineering Condition Assessment Of Cycling Infrastructure: Cyclists Perceptions Of Satisfaction And Comfort

Authors: J.C. Calvey, J.P. Shackleton, M.D. Taylor, R. Llewellyn

The UK National Cycle Network comprises 23,660 km of cycling and walking paths of which a significant percentage is dedicated off-road infrastructure. This represents a significant civil engineering infrastructure asset that currently contributes to the provision of a sustainable transport mode option nationwide. Commuting and recreational cyclists have observed the often hazardous conditions on these paths. There are various simple measures that could be taken to improve the maintenance of such off-road paths. Reliance on walk-over surveys (direct visual inspection) and path users notifying the local authority may not be tackling maintenance in a resource efficient manner. The proposed inspection method includes the use of an instrumented bicycle to examine cycle path condition through user perception of satisfaction and quality. A questionnaire was conducted to identify the attributes of off-road cycling infrastructure people find most important in relation to their personal satisfaction. An exploratory factor analysis was undertaken on perception study data to elucidate the determination of the variables associated with perceived user satisfaction. The study has shown that people find maintenance issues to be of high importance, especially surface issues. From exploratory factor analysis of results, satisfaction has been found to load with comfort and safety. Field testing was then con-ducted using subjective user opinions and objective vibration data. These results were then used to assist the creation of dedicated user perception based surface condition rating-scale.

The primary research objective was to develop a user perception study to identify the pertinent issues that the Intelli Bike would consider. General maintenance and upkeep has been deemed to be important by respondents. Vegetation levels, sur-face quality, surface issues (defects, debris), and night lighting levels will be considered by the Intelli Bike. In addition certain key aspects of the path, specifically width and surface type, will be noted as they have been found to be of importance and relate to maintenance of a path. From the results of exploratory factor analysis, the study has shown five latent variables emerge one of which is satisfaction which links with comfort and safety. This provides a clear definition when using satisfaction as the base for associated user rating scales. From the results of the user perception study it is clear that exploratory factor analysis is a useful tool in elucidating the determination of the variables associated with cycle-path satisfaction. As the sample frame was restricted to University campus members, which was restricted by student and faculty, overall completion numbers have been limited and reduced the scope of current results. Further results from public respondents will be targeted in the future in order to generate a more complete database. However with the number of responses currently agreeing on many factors importance, it may be that the results prove to be similar.

4) Where to improve cycling infrastructure? Assessing bicycle suitability and bikeability with open data in the city of paris

Authors: Laura Wysling, Ross S Purves

This study proposes a method that can help in identifying potential locations for improvements of cycling infrastructures. It addresses the need for simple and effective methods to support decision-making in bicycle planning. The city of Paris is used as a case study area because it has made considerable efforts to improve cycling infrastructures and to become more bicycle-friendly in recent years. The method (1) identifies potential locations for improvements of bicycle infrastructures on a street level and (2) on a city level considering accessibility to important destinations. The main data used in this project is street data from OpenStreetMap (OSM) and cycling infrastructure data from the Atelier parisien d'urbanisme (Apur). The proposed method can be applied with commonly available data, has clear outcomes, is reproducible, and can be applied to different case study areas. We produced a map of bicycle suitability across all of Paris, and validated it for the 30 longest segments in the city with lower bike suitability. Our validation showed that combining OSM and Apur data led to a reliable dataset, with which we modelled bikeability using the underlying network overlain on a 250 m resolution grid and destinations representing leisure activities, education, shopping, city functions and public transport. The resulting map identifies regions of the city with poor bikeability, where improvements to cycling infrastructure should be investigated.

5) Bicycle Infrastructure Safety Assessment From The Perspective Of Urban Development Specialists And Engineers

Authors: Miglė Zabielaitė-Skirmantė, Marija Burinskienė

The safety of bicycle infrastructure is a primary factor influencing bicycle travel. While cyclists' perspectives on infrastructure safety are extensively studied, they are merely the end users. Decisions on infrastructure design are made by engineers and urban development specialists. Therefore, it is crucial to determine if these professionals' safety assessments align with those of cyclists. A qualitative survey was conducted with 5 expert engineers and 5 urban development specialists, each having 5 to 20 years of experience in transportation infrastructure planning. Kendall's coefficient of concordance W was used to assess the compatibility of their opinions.

The results showed significant compatibility: W = 0.697 for engineers and W = 0.511 for urban development specialists. Seventeen cycling infrastructure installation schemes were evaluated. Both engineers (M = 10.0, SD = 0.0) and urban development specialists (M = 9.8, SD = 0.44) indicated the DT_2 option as providing the greatest sense of security, where the bicycle path is physically separated from both the carriageway and pedestrian path. The key findings reveal agreement on the safety of straight-street segments of bicycle infrastructure but diverging opinions at intersections zones. Urban development specialists are influenced by existing practices and legal frameworks lacking detailed cycling infrastructure guidelines at intersections. Engineers align more closely with cyclists' perceptions, emphasising physical separation and speed reduction measures. The study concludes that urban development specialists need to better understand cyclists' needs and prioritize safer infrastructure solutions.

III. METHODOLOGY

This study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines extension and the review framework for scoping reviews.

IV. STUDY DESIGN

Given the diverse study designs and methods employed in the literature, this scoping review explored the comfort and safety evaluation frameworks for various bicycle infrastructure and facility designs. The scoping reviews suit studies with broader aims and objectives [20]. The PRISMA Extension for Scoping Reviews guidelines were followed to ensure the study was systematic and transparent [21]. These guidelines assist in defining research questions, identifying exclusion and inclusion criteria, and assessing relevant and accessible scientific articles while conducting a scoping review.

V. SEARCH STRATEGY AND SEARCH TERMS

Three search engines, Web of Science (WOS), Scopus, and Google Scholar, were employed in this study. The search was limited to studies published between 2005 and 2024. The search terms were broadly categorized as bicycling, infrastructure, and assessment methods. Alternative keywords were permitted for each component as denoted by the Boolean operator "OR." The separator "AND" combines each component with other words. These terms were searched in titles, abstracts, and keywords to minimize the risk of overlooking relevant studies. The detailed search string, developed based on the keywords below, is provided in Appendix 2.

- Retrieval of studies on bicycling.
  - ("bicycle" OR "cycling" OR "bike") AND
- Retrieval of articles related to bicycling infrastructure.
  - ("infrastructure" OR "facility" OR "lanes" OR "path") AND
- To retrieve all relevant studies using assessment methods for bicycle infrastructure.
  - ("assessment" OR "evaluation").

VI. STUDY SELECTION

Specific inclusion and exclusion criteria were considered in the study selection process. Irrespective of the study design, all articles written in English describing assessment methods for bicycle infrastructure were considered. Subsequently, only journal articles and research presented at conferences were considered, while review articles, reports, and book chapters were excluded. Likewise, no further evaluation was conducted for inaccessible articles. The titles and abstracts of all retrieved articles were screened for shortlisting the articles. Studies that used or computed assessment methods using a mathematical index to evaluate either comfort or safety with cycling infrastructure were considered for the final selection. The full text of the selected articles was read only after fulfilling the eligibility criteria. Fig. 1 shows the total number of articles retrieved from the three databases. The number of papers decreased when the filtering criteria, i.e., English language, type of publication, was applied. Seven hundred eighty-two articles from the WOS, 1739 from Scopus, and the first 400 relevant articles based on titles were selected for further screening. The reason to screen the first 400 results in Google Scholar was that relevance significantly declined beyond this point. A limitation of using Google Scholar was its lack of systematic export and filtering options like WOS and Scopus, which required screening online. However, this additional step ensured that no potentially relevant studies were overlooked. The duplicates (n = 664) were removed, and the remaining 2257 articles were screened based on their titles and abstracts. Next, 89 articles were assessed for eligibility or full-text reading. Subsequently, 39 articles were excluded due to irrelevant study designs, unavailable documents, book chapters, and review articles. Finally, five articles were retrieved from the backward and forward reference checks. Overall, 55 articles fulfilled the inclusion criteria and were included in the present study.

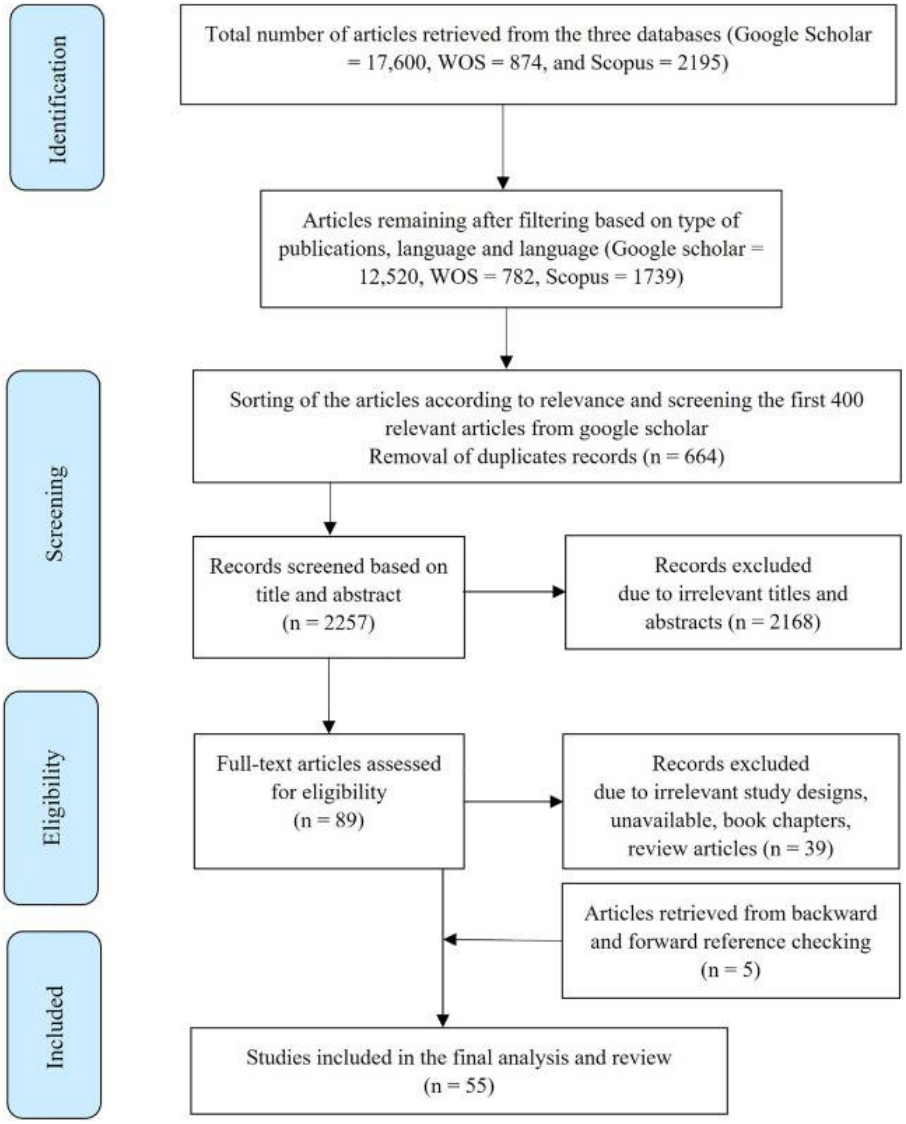

Fig. 1. Literature search and selection process using the extension of the PRISMA guidelines.

VII. DATA SYNTHESIS

The extracted information included the author's information, year and country of publication, tools utilized for data collection (e.g., surveys, interviews), study sample, the scope of the study, and the assessment method used. In addition to general metadata, we extracted data directly relevant to the study objectives, such as the assessment methods' applicability, to analyze its applicability in various contexts. To categorize and synthesize the findings, we employed thematic analysis, a method used to identify, analyze, and report patterns or themes within the shortlisted articles. Themes were generated on the basis of the assessment methods used in the included studies. Thematic analyses have been used in several scoping and systematic reviews on research topics related to bicycling. As this review is exploratory, an inductive approach allows themes to emerge directly from the assessment methods. The papers were examined and scrutinized for data extraction for more familiarity, followed by systematic data coding. Themes were then generated based on the assigned codes. Analyses were performed using Microsoft Excel and NVivo.

The studies were also synthesized to evaluate the time, cost, and technical skills required to execute the methods. These aspects are categorized into three levels, low, medium, and high, to facilitate method selection based on the specific context and resource availability. The time required for a method depends on several factors, including the assessment scale, the volume of data needed, and whether advanced devices like probe bikes or cameras are used for data collection. Methods with extensive data collection or complex execution phases may require significantly more time. These factors also influence the cost, particularly the resources required for devices, infrastructure, and personnel for data collection (if primary data is needed).

The expertise level required varies based on the technical complexity of the method, such as setting up experiments, managing data collection, and analyzing results. Low expertise' indicates that the method can be executed with basic training or general skills, such as simple data collection and processing. Medium expertise refers to methods requiring more specialized skills, such as familiarity with specific software, equipment, or basic statistical analysis. Advanced methods that involve advanced statistical models or machine learning techniques need higher technical skills.

VIII. RESULTS

A. Geographic Location Of The Studies

Studies developing an assessment method for bicycle infrastructure have sharply increased, with 32 of the 55 studies published published in 2019 and onwards. Fig. 2 shows the region where the selected papers were conducted. Assessment methods have received a broad international presence, with many countries (n = 23) contributing to the research landscape. Most of the studies in this scoping review were conducted in Europe (n = 24), followed by Asia (n = 16), and North America (n = 12). One study has examined case studies conducted in the United States and the UK . Almost half of the studies in Asia were conducted in China (n = 7), whereas ten of the twelve studies in North America were conducted in the USA. Fig. 3 shows the journal and conference proceedings that have published the articles reviewed. Most (n = 8) articles were published in Transp. Res. Part A Policy Pract. and Transportation Research Record, followed by Sustainability, which published six articles. Sensors and Case Studies on Transport Policy published two articles each. Five articles were conference proceedings, and Proceedia Engineering published two of the five in the review.

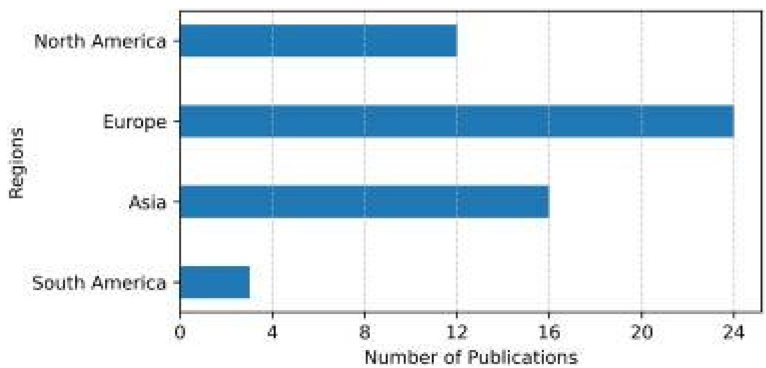

Fig. 2. Distribution of the articles based on the region.

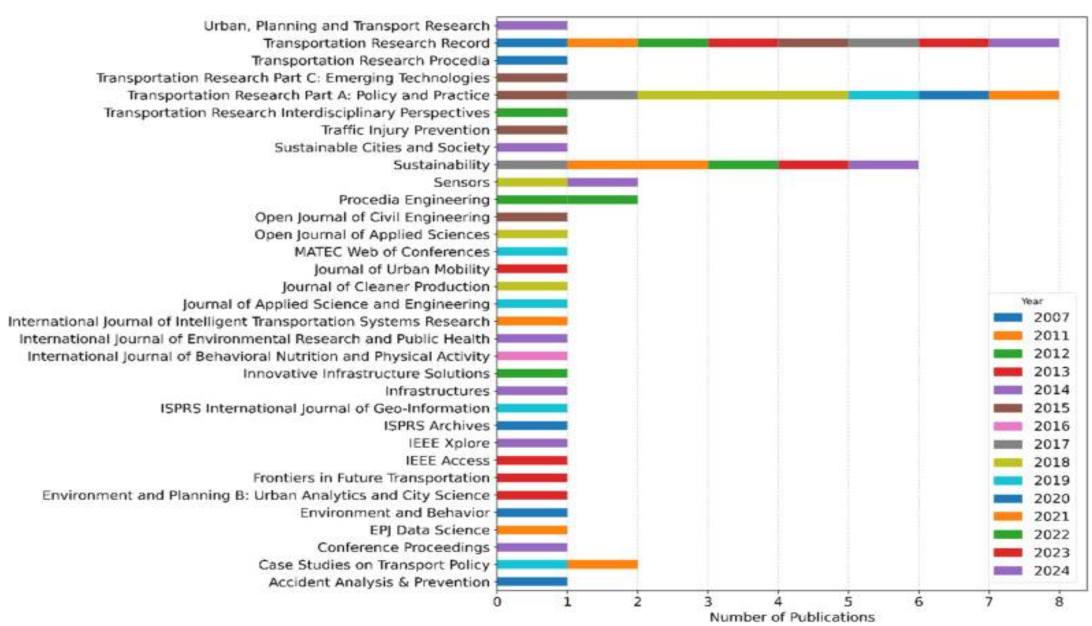

Fig. 3. Number of publications in journals.

B. Bicycle Infrastructure Assessment Methods

The themes synthesized from the review focused on the evaluated aspects of bicycle infrastructure, emphasizing the safety and comfort of the infrastructure for cyclists. The emerging themes were broadly categorized based on evaluation methods: vibration or roughness index, BLOS determination, BI, and BSI. The difference in these assessments is mainly based on the methodologies' scope. The BI assesses the overall quality of cycling conditions within a city network, reflecting on how friendly an urban area's environment is to cycling [24]. Unlike other measures focusing only on one aspect of the network, such as safety or comfort, BI considers multiple factors, including cyclists' safety, comfort levels, convenience, and attractiveness [25]. To capture this comprehensive perspective, we included studies that addressed safety, comfort, and other critical factors contributing to the overall bikeability of urban environments under this category.

Meanwhile, BLOS serves as a framework for assessing the performance of bicycle facilities [26]. The BLOS ranks various bike infrastructures, such as street segments, midblock crossings, nodes, and intersections. The assessment is based on the quality of service provided to bicyclists concerning various factors such as safety, comfort, and efficiency [15,27]. The BLOS can be measured using different indices and variables [17]. It provides an index that helps assess the quality of bicycle infrastructure in a community or city. The studies assessing the bicycle infrastructure's performance based on various metrics or indices are categorized in determining the BLOS theme.

On the other hand, the vibration or roughness index only assesses the bicycle infrastructure based on the vibration or verticle acceleration cyclists face while riding [16]. We considered studies that measure cycling comfort using the surface pavement quality of bicycle paths through vibrations experienced by cyclists as the vibration or roughness index. These measures rely on data collected via instrumented probe bicycles, smartphones, or smart bicycle lights, which capture parameters like vertical accelerations, GPS positioning, and road surface conditions. Lastly, the BSI considers only safety when evaluating the infrastructure through various variables. These studies often employ quantitative models to assess safety risks, including traffic volume, conflict risk, and road geometry. Articles in this category primarily aim to identify hazards, validate safety measures, and recommend infrastructure improvements for safer cycling environments.

C. Research On Vibration Or Roughness Index

Vibration, otherwise known as the roughness index, is a popular method for assessing the comfort quality of bicycle infrastructure. We found sixteen studies that developed the vibration or roughness index for measuring cyclists' comfort on bicycle infrastructure. Several models were used to calculate the vibration or roughness index in the relevant articles, such as the International Roughness Index (IRI), Dynamic Comfort Index (DCI), Dynamic Cycling Comfort (DCC), and Bicycle Environmental Quality Index (BEQI). Nevertheless, acceleration or vibration data is still required to support these models.

Subjective and objective data have been combined in several studies to validate the results of the vibration data. For example, Bil et al. combined the DCI results from GPS data and accelerometers and surveyed cyclists' perceptions of their riding experiences. The results of the DCI and the subjectively assessed evaluations were strongly correlated. Similarly, Gao et al. integrated the objective data collected using a DCC measurement system consisting of a GPS logger, acceleration logger, and smartphone mounted on a bicycle handlebar. The test vibration data (objective data) were also analyzed according to the ISO 2631 vibration standards. Another study utilized the same approach: an instrumented probe bicycle examines cycle-path conditions through user perception of satisfaction and quality. Field testing was conducted using subjective user opinions and objective vibration data, which were then used to assist in the creation of dedicated user perception-based surface condition rating scales. These studies demonstrate the importance of combining these approaches for comprehensive analysis.

D. Determining Blos

The BLOS was the second evaluation method for bicycle infrastructure assessment in this review and was used in sixteen relevant studies. BLOS assesses service quality offered by road segments or bicycle facilities for cyclists. Thus, it was unsurprising as subjective evaluations were performed in twelve relevant studies relating to BLOS. Ten out of sixteen studies used video cameras on the bicycle route or segments for the users and then asked participants to rate infrastructure. This approach addresses the potential evaluation bias in different settings, e.g., traffic, roadway, and weather conditions. Notably, it is argued that the method delivers results as credible as field study. Some BLOS studies performed surveys by intercepting cyclists regarding their comfort perception while riding through specific study areas. In addition, developed BLOS methods address different aspects of cycling, such as road safety, pleasant environment, and sometimes connectivity of cycling areas.

A few alternative terminologies have also been used, e.g., Quality of service (QoS), Level of Traffic Stress (LTS), or Bicycle Compatibility Index (BCI); however, their objectives align with BLOS. In contrast, studies have evaluated the study area using video clips. A video camera is frequently mounted on a bicycle to record video clips of bicycle facilities and their surroundings, and sometimes, the generated sound is recorded for a more realistic scenario.

E. Bikeability Index For Measuring Bicycle Friendliness

The third theme in scoping review studies was BI, which assesses the bicycle infrastructure for its friendliness. Utilizing bicycle infrastructural variables is common among BI studies. The use of scoring, geographically weighted regression analysis, and the Analytic Network Process (ANP) framework in different studies highlights the adaptability of methodologies to various urban contexts. Incorporating users' perceptions through questionnaires adds a subjective dimension to the assessment, emphasizing the importance of considering the human experience in evaluating cycling infrastructure. However, as few studies have adopted an objective approach to BI, relying mainly on open-source data.

F. Bicycle Safety Index

The fourth theme for infrastructure assessment is BSI, which emphasizes both bicycle infrastructure and the presence and volume of vehicles. Motorized traffic volume and traffic speed are consistent indicators in BSI studies. Nine articles evaluate bicycle facilities on urban streets using a BSI. Most BSI studies used mixed techniques; some combined objective data with respondents' perceptions, where the respondents had to rate the selected variables for their safety. In these studies, questionnaire data were collected on the field at the selected locations to collect data from the respondents. One study compared the proposed safety scoring methods with observed safety ratings gathered through an online questionnaire to validate the results. Three studies have also utilized field observations to collect the data for the indicators. Two studies utilized videos for data collection and later used them for ratings.

G. Equipment And Resources Used In The Bicycle Infrastructure Assessment Methods

Fig. 4 shows that various equipment and tools were employed to assess various aspects of bicycle infrastructure in the selected studies. The most commonly used include questionnaires or surveys employed in 31 studies. Bicycles, the second most common tool (n = 18), have been predominantly employed in roughness index research. Other equipment, such as cameras and accelerometers, are often attached to bicycles for data collection purposes. GIS and cameras were vital equipment and resources, with 17 and 15 occurrences, respectively. Some studies have used technological instruments like instrumented bicycles, accelerometers, gyro sensors, and GPS devices. Studies have also employed emerging technologies, such as virtual or immersive technology. Open source data is increasingly utilized, as is evident from OSM (n = 8), Google Maps, open cycle map, and CycleStreet. The use of smartphone applications (n = 8), GPS (n = 8), and accelerometer (n = 6) are prominent technological approaches identified in the studies.

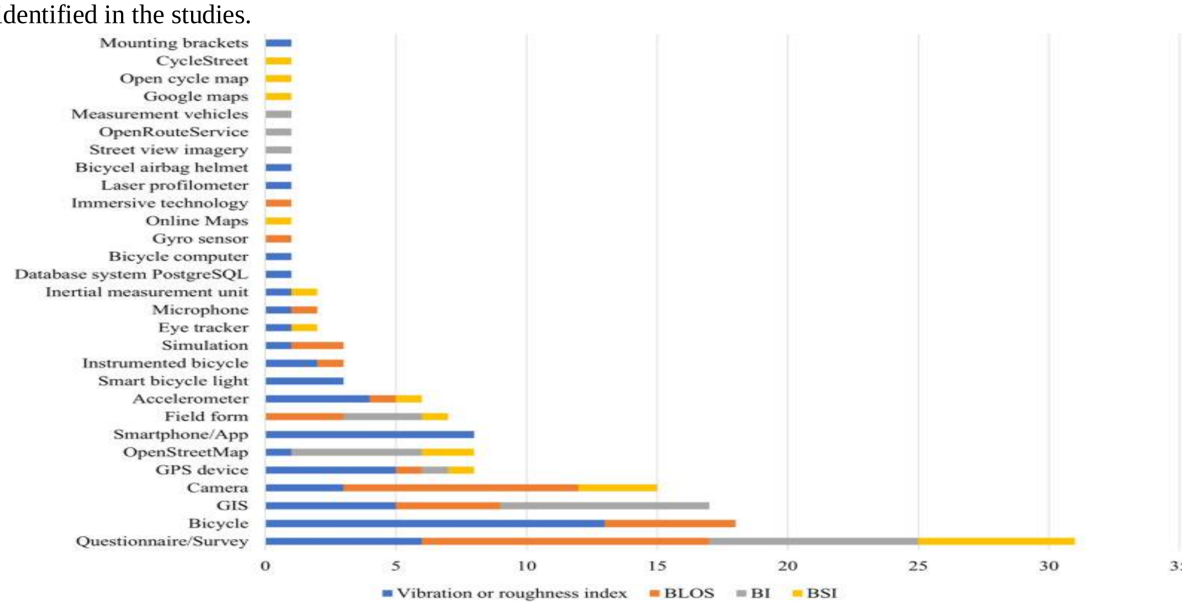

Fig. 4. Equipment and resources used in the evaluation methods for bicycle infrastructure.

IX. CONCLUSION

Bicycle infrastructure conditions strongly influence the perceived comfort and safety of cyclists. Different methods have been developed to assess the aspect of comfort and safety of the bicycle infrastructure. Understanding the scope of assessment methods is essential for evaluating bicycle infrastructure effectively. A clear knowledge of their objectives, limitations, and applicability ensures the selection of the most suitable method to address specific aspects of cycling facility evaluation and improvement. The assessment methods developed vary greatly in scope. Based on common characteristics, this scoping review categorized these methods into four groups (vibration index, BLOS, BI, and BSI).

Some developed methods are generalizable and adaptable; however, it is crucial to consider relevant methods when applying them. For example, the BI method is the most suitable approach when conducting an overall bicycle friendliness of a city because BI includes components like comfort, safety, attractiveness, cohesiveness, and cohesion of bicycle infrastructure. The vibration or roughness index is more appropriate for assessing the comfort levels of bicycle infrastructure, particularly concerning pavement conditions. This technique evaluates the smoothness of cycling routes, making it a pertinent choice for assessing comfort.

Similarly, the BSI index is relevant when assessing the safety of bicyclists on a given route. BSI incorporates a combination of objective data and user perceptions, making it a robust tool for evaluating and suggesting improvements in the safety aspects of bicycle infrastructure. Adapting the assessment method to specific needs ensures a thorough and targeted analysis, contributing to a more customized assessment. This scoping review provides a detailed overview of assessment methodologies, which will help city authorities select appropriate assessment methods tailored to specific contexts. Some methods require advanced technical skills for implementation, which is needed to enhance the accuracy of the findings. This review paper also guides the selection of appropriate methods by categorizing the required technical skills, estimated time, and associated costs from low to high. This information enables urban and transport planners to make informed decisions when choosing and applying the most suitable method for their needs. The availability of infrastructure data is essential for adapting assessment methods to specific contexts. The unavailability of data can significantly limit the range of methods that can be applied. For example, the comprehensive bicycle friendliness (bikeability) of an urban area or neighborhood assessment can be difficult and time-consuming without secondary data availability. However, some methods that utilize OSM data can provide an accessible and efficient alternative for such evaluations.

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