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From equitable access to equitable usage – moving towards data-driven, evidence-based cycling assets management

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ABSTRACT: Cycling is increasingly recognized for its wide range economic, environmental, and health benefits as a mobility option. However, disparities in the provision and the quality of bicycle infrastructure persists. Ensuring fair access and usage of these benefits for all presents a significant challenge. As a result, establishing effective methodologies to evaluate cycling equity is critically important. This paper synthesizes research on infrastructure asset management with a focus on equity considerations in bicycle infrastructure. A systematic review of 19 North American studies critically examines how existing research categorizes vulnerable populations and assesses fairness. The results reveal that most existing analyses focus on equitable access – that is, facility coverage, distribution, and basic reachability – while largely overlooking aspects of equitable usage, such as infrastructure quality, connectivity, quantitative user-experience metrics, and real-world facility utilization across different socioeconomic groups. Moreover, factors like car dependency and road conditions are seldom integrated into equity discussions, leading to incomplete assessments of how well cycling infrastructure serves diverse users. While geospatial analyses, GIS-based modeling, and smartphone-based sensing have started to offer new methods for assessing the cycling experience by identifying pavement distress and evaluating cyclists' comfort, these approaches have not been fully adopted as equity-focused metrics. Instead, current assessments often rely on subjective feedback or user perceptions, which fall short of providing data-driven, evidence-based decision support for maintenance based on actual comfort measurements. To address these gaps, we propose a data-drive evaluation approach that consider not just access, but also usage, safety, and comfort.

1. INTRODUCTION

Cycling has become a key part of sustainable urban travel. It encourages environmentally friendly transportation, eases traffic congestion, and improves public health. It is more than a healthy leisure activity: cycling offers an economical option that strengthens community ties, especially for groups with lower car ownership such as low-income households, refugees, and new immigrants. Despite the benefits of cycling, particularly for the disadvantaged without access to private vehicles or those living in area with underdeveloped public transportation, evidence repeatedly shows that investments in bicycle infrastructure are often concentrated in economical advantaged urban centers or regions with certain demographic characteristics. As a result, the communities with the greatest need are frequently overlooked. Studies have shown that lower car ownership rates are typically associated with higher cycling rates. However, Ferenchak and Marshall (2021), analyzing data from 29 U.S. cities, found that low-income communities

and neighborhoods generally have high percentages of residents lacking adequate cycling infrastructure. This pattern is not unique to the United States. Cunha and Silva (2022) observed that even in well-planned Global North cities, bicycle facilities usually cluster where cycling is already popular, while in many Global South cities, planners often overlook the needs of groups that depend heavily on bicycles. The associations between cycling as a mobility option and cycler's socioeconomic conditions highlight that discussions on bicycle infrastructure equity need to go beyond accessibility metrics (e.g., network connectivity) and include indicators representing residents' actual needs, such as car ownerships and other socio-economic factors.

On the other hand, although many studies and plans mention the concept of "transportation equity," practical tools for measuring and addressing the experience of disadvantaged groups – by metrics such as trip distances and safety – are often missing (Doran et al. 2021). Cyclists' experience like safety and comfort concerns should be included as key indicators when evaluating equity in cycling infrastructure. Safety and comfort, both of which are underpinned by good cycling assets conditions, play key roles in making cycling an appealing option. Existing cycling safety studies dominantly rely on ex-post or indirect measures, such as accident data or speed reductions (Braun 2024; Lee et al. 2021; Pritchard et al. 2019). However, these measures focus on "effects" instead of "causes", failing to capture vital details such as pavement conditions, lane width, or real-time traffic flow. Lee et al. (2017) and Yu (2014) attempted to link crash risks with socioeconomic factors, but they did not explore a more direct reason contributing to crashes – infrastructure facility conditions. New technologies that use smartphone sensors, GPS data, and wavelet analysis have emerged as effective ways to track road quality and spot issues (e.g., potholes), but they have not been integrated into equity-focus discussions (Calvey et al. 2015; Gadsby et al. 2022; Ho et al. 2024; Li et al. 2019).

Many existing equity assessments rely only on counts or proximity of cycling facilities while overlooking whether those facilities are safe, comfortable, and well-maintained enough to be genuinely usable by all. Therefore, by drawing on research produced over the past decade, this article offers a critical review and systematic analysis of how to evaluate equity of cycling infrastructure. We particularly investigate equitable usage instead of equitable access, that is, not only having equal opportunities to access cycling infrastructure, but also having equal opportunities to safely and comfortably utilize cycling infrastructure

2. METHODOLOGY

This study systematically reviews the peer-reviewed articles published between 2015 and 2025 to examine how equity issues have been studied in pertinent to cycling infrastructure. The search was performed using Web of Science, with key words including "bicycle infrastructure", "cycling infrastructure", "equity", "disparity", and "inequalities". Keywords explicitly related to infrastructure condition (e.g., "road condition") were eventually not included due to their limited representation in previous equity-oriented studies, highlighting a notable gap identified during the analysis. The scope focuses on North America, particularly the United States, due to its high level of automobile dependency, which significantly influences infrastructure planning, including cycling facilities. Consequently, evaluating equity through the lens of car ownership provides a critical perspective on how certain groups (e.g., low-income or carless households) may be disadvantaged in accessing safe and comprehensive cycling networks. However, the results show that the number of studies focusing on U.S. contexts is disproportionately low compared to those in Canada, highlighting the long road ahead to promote active mobility in the United States.

After screening papers that explicitly addressed the topic, 32 articles were initially deemed eligible. Studies conducted on college campuses, where the impact of car ownership on equity was minimal and did not align with the overall objectives of this review (even within the U.S.), were excluded. Research centered on transit accessibility rather than cycling infrastructure was also removed. The final selection included 19 publications that meet all the criteria. Content analysis was conducted to systematically and thoroughly examine the themes of each paper. For these papers, we analyzed how each study defines and segments vulnerable or disadvantaged groups – such as low-income individuals, immigrants, women, and carless households—while also considering the different cycling purposes, needs, and activities of these groups. This categorization directly influences the metrics and methods used to evaluate equity. Our review begins

by addressing the cycling purposes, needs, and types of disadvantaged groups, followed by an analysis of the equity assessment methodologies identified in these studies.

3. BICYCLE INFRASTRUCTURE EQUITY

3.1 Cycling purposes, needs, and disadvantaged groups

As shown in Figure 1, among the reviewed studies, low-income or impoverished groups were considered in nearly all studies (around 18), followed by ethnic minorities (around 10). Only Ermagun et al. (2023) explicitly focused on carless households. This distribution reflects the current research emphasizing on economic disadvantages and racial diversity, leaving some important factors not being thoroughly discussed. Examples include age groups and car ownership. While many existing studies are based on common classifications of demography (e.g., low-income or ethnic groups), some studies use synthesized, comprehensive indices which encompass multiple demographic factors. For example, Bonsma-Fisher et al. (2024) apply the Ontario Marginalization Index, which combines factors like income, education, work status, and ethnic background, to pinpoint neighborhoods in Toronto that face hardship. This index offers an overall measure instead of singling out low-income families from other forms of disadvantage. A limitation of the study is that it does not separate households that mostly ride for day-to-day needs, such as commuting, from those that bike for leisure. This separation is crucial for transportation equity studies, because the issue becomes much more prominent if it were a mobility choice rather than a recreational option.
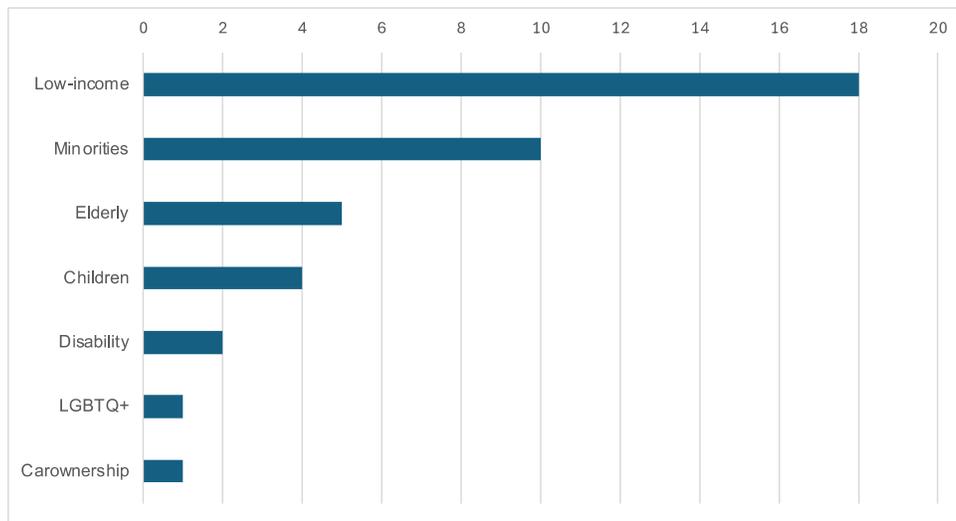
Figure 1: Different Disadvantaged Groups in the Reviewed Papers

Ermagun et al. (2023) made good efforts to separate mobility needs and recreational purposes. The researchers proposed a detailed approach called the Bike Access Risk Gap (BARG) index. Their research specifically looks at African American and Hispanic communities, low-income families, and households without cars. The authors argued that for these car-free households, not owning a car means safe, direct, and connected bike routes to jobs become essential. The researchers stated that for these people, fairness in bike facilities means low-stress, well-linked networks, rather than routes built mainly for recreation. The researchers supported their viewpoint by analyzing commuting paths and potential risks.

With similar mindsets, Doran et al. (2020) reviewed transportation plans in Canada with focus on low-income people, immigrants, women, and seniors. They highlighted fairness in the context of providing better access to people who do not own cars. Although the review does not describe the needs of each individual group in detail, it suggests that seniors and immigrants, for instance, are expected to benefit from routes that are short, safe, and direct, in contrast to more leisure-focused biking paths found in affluent neighborhoods.

Additionally, Barajas and Braun (2021) explored the interrelationships between active travel, health results, and socioeconomic conditions. They specifically mentioned "racial or ethnic minority communities" and "low-income groups" as having limited access to high-quality bike networks. Their work also points out that areas going through gentrification may experience a change in biking habits, shifting from commuting to recreation. The study highlights that in places where people depend on cycling as their main mode of transport, bike routes must be designed for safety and for easy travel to important destinations.

Following the same school of thoughts, Zhao et al. (2024) made in-depth examination on the biking experience of children, seniors, new immigrants, and visible minorities in Canadian cities. The researchers used census data to measure how close these groups are to bike facilities. Their findings show that even though seniors and newcomers may enjoy better access overall, a significant number of children and other at-risk groups live in areas with very few bike lanes. The results suggest the necessity and urgency to provide children with safe, low-stress routes for short trips (such as going to school).

In another study, John Barneson, Grisé, and El-Geneidy (2018) proposed a step-by-step system for deciding where to build new bike lanes in Quebec City. They divide places into two types: those where bike lane improvements mainly help people ride for everyday tasks and those where biking is more about recreation. They pointed out that in low-income neighborhoods, the top priority should be connecting people to job centers and vital services, not adding features that encourage casual riding. Their position is based on the idea that practical cycling is crucial for those who have fewer transportation options.

Overall, existing studies tend to distinguish between recreational biking and bike commuting when discussing fairness or equity issues. There are clear patterns in biking purposes among people with different demographic or socioeconomic backgrounds, such as low-income, ethnic minority, households without cars, seniors, and minors. For people who have limited mobility options, a safe, connected cycling network for commuting is the key. And the equity issue becomes more prominent. Considering the mixed functions of biking facilities and the mixed purpose of cycling, a clear distinguishment is important for research design and discussions.

3.2 Evaluation method for cycling infrastructure equity

As shown in Table 1, the methodological approaches to evaluating cycling infrastructure equity in literature vary widely, reflecting differences in study objectives, geographic contexts, and data availability. Many studies use density or coverage measurements. For example, Winters et al. (2018) calculated the length of cycling routes per square kilometer within specific areas, then compare the density values across neighborhoods with different average income levels. Hosford and Winters (2018) examined whether public bike-share services exist in a certain area, using a yes-or-no measure to capture to what extent these services are available. This type of study typically uses GIS tools and spatial statistics to measure infrastructure coverage, density, and reach. For example, Hosford & Winters (2018) and Winters et al. (2018) used mapping software to calculate the density of bike-share stations or bicycle lanes in certain areas, then comparing how these facilities are spread out in different regions by looking at income quintiles or deprivation indexes. Although these density (or existence) evaluations provide information on facility locations using objective and consistent standards, they fail to reveal the quality of cycling infrastructure and thus cannot reflect if an accessible lane can deliver significant functions of if it is actually usable. It is contestable that these evaluations only scratch the surface of equity discussions.

Table 1 Evaluation Methods

Evaluation method	Details	Number of studies using this method

GIS analysis	Use GIS to analyze the geographical distribution of bike lanes or shared bike stations, involving the measurement of total infrastructure length, the number of stations, and the density within a given area	12
Accessibility analysis	Assess the improvement in accessibility to jobs or destinations for a specific group or an area. Analyze the coverage of low-/high-stress networks	6
Regression analysis	Construct a multiple regression or logistic regression model with bicycle infrastructure coverage as the dependent variable and demographic factors (e.g., race, income) as independent variables.	6
Group-based comparative analysis	Group populations or areas based on income levels, poverty index, or marginalization index, then compare differences in bicycle infrastructure coverage, network length, and other relevant indicators across these groups.	7
Crash/safety analysis (crash-based analysis)	Measure safety equity based on the distribution of traffic crashes and fatalities, examining whether vulnerable groups experience higher accident rates	2
Text/policy document analysis	Conduct systematic review or content analysis on relevant planning documents to examine whether and how equity is addressed	4

*A single study may employ multiple methods.

Beyond simply assessing the existence of bicycle facilities, Bonsma-Fisher et al. (2024) made a more in-depth analysis on accessibility by highlighting the importance of low-traffic-stress (LTS) roads in ensuring accessibility. These roads, designed with lower traffic volumes, slower speeds, and safety-enhancing features, serve as the foundation of a high-quality bicycle network. Recognizing this, the researchers developed a composite scoring system and an optimization model that integrate job accessibility with improvements to the LTS (levels 1–2) network. By adjusting weights to prioritize areas with poor accessibility, their method addresses the shortcomings of traditional approaches that focus solely on facility coverage. Similarly, Ermagun et al. (2023) introduced the Bike Access Risk Gap (BARG) score, which combines the LTS indicator with socioeconomic factors to highlight disparities in commuting risks across different communities. This integrated framework not only reveals inequities in cycling infrastructure but also demonstrates how targeted improvements can enhance both safety and convenience for residents.

Researchers have also tried using statistical methods to evaluate the relationship between facility coverage and neighborhood demographics. For instance, Braun (2021) and Braun et al. (2019) applied multi-layer mixed-effects models and take the presence, length, and connectivity of bike lanes as responsive variables. Census-block data such as income, education, and race were used as explanatory variables. Although this type of evaluation features more robust quantitative methods, it still focuses on spatial coverage and does not consider what riders actually experience when riding on these lanes.

Some studies further supplement crash data and health risk indicators to their numerical models to reveal unequal conditions in traffic safety publications, such as Barajas & Braun (2021) and Younes et al. (2023). These studies use accident rates and fatality rates to measure the threats faced by low-income and minority communities, which indirectly indicates where infrastructure fails to protect vulnerable groups.

Qualitative evaluations or mix-method evaluations have also been applied. Doran et al. (2020) and Jasso et al. (2024) examined policy documents and planning files to see how many state plans or city plans

highlight fairness. They searched for keywords such as "equity," "low-income," "racial/ethnic," and "youth" to decide whether policies consider the unique needs of diverse groups. Although this evaluation approach can reveal how agendas are set during planning phases, it provides no information on if the equity considerations claimed on paper have been delivered through actual infrastructure development efforts.

Davidson (2023) and Lemon et al. (2018) used mixed methods that combine GIS analysis and regression analysis with surveys and interviews. By doing so, they gathered the views of policymakers and the views of bikers on safety, comfort, and facility usefulness. Even though the use of survey data provides multifaceted insights into those studies, this mix-method itself has limitations in terms of transferability. Survey samples are often limited to few cities or regions, and it is hard to synthesize resident inputs using a standardized approach across different areas or over different time periods.

Unlike traditional quantitative analyses that rely on crash or fatality data to infer where infrastructure may be failing vulnerable populations or cyclists' personal perceptions, Zhao et al. (2024) adopt an infrastructure-centered approach. They developed a comfort-based ranking system for bicycle infrastructure using the Canadian Bikeway Comfort and Safety (Can-BICS) metrics, which are derived from standardized OpenStreetMap data. The system categorized facilities into three comfort levels: high-comfort facilities – such as separated bike paths, cycle tracks, and dedicated street bikeways that provide a low-stress riding environment; medium-comfort bikeways – typically comprising paved multi-use paths that are comfortable for some cyclists; and low-comfort bikeways – generally consisting of painted bike lanes that many riders find stressful. This categorization was quantitatively established by assessing the physical attributes of cycling routes within a one-kilometer buffer of each dissemination area's population-weighted centroid, thereby reducing subjectivity. The rankings were then integrated with 2016 census data to standardize comparisons of access across different demographic groups (e.g., children, seniors, new immigrants, and visible minorities), offering a robust tool for analyzing equity in cycling infrastructure access.

4. CONCLUSIONS AND FUTURE RESEARCH

A critical review of the cycling infrastructure equity literature reveals that existing works mainly employ quantitative, GIS-based methods and statistical analyses to evaluate facilities' spatial distribution (e.g., existence or density) and accessibility. Disparities among neighborhoods with various socioeconomic conditions are discussed. However, it is worth reflecting on whether these number-based studies remain superficial and fail to consider more in-depth details beyond mere existence. Without accounting for asset conditions, car ownership, and mobility needs, the lack of access for disadvantaged groups could be underestimated. For example, the same density of cycling infrastructure in an affluent neighborhood versus a low-income neighborhood has distinct implications for residents' quality of life. In neighborhoods where people lack access to cars, biking plays a crucial role in fulfilling daily mobility needs and is often less viewed as a leisure activity. Additionally, the same length of biking infrastructure, coupled with varying asset conditions, has different impacts on residents' willingness to bike, their comfort, and safety. However, these nuances are often overlooked in number-based studies, which could lead to misleading recommendations for decision-making.

The use of composite indices (e.g., the Bike Access Risk Gap) and the use of optimization models that integrate job accessibility with equity weighting represent more holistic approaches. These evaluation approaches attempt to quantify not only the physical presence of cycling infrastructure but also the functions that the cycling infrastructure could deliver. Despite the advancement from number counting, these methods fall short of directly tackling many quality-related factors, such as facility conditions. The condition of cycling infrastructure assets is at the center of delivering planned functions and promoting travel safety. Asset conditions should be an integral part of facilitating equitable access to cycling as a mobility option, but it has always been missing in the body of knowledge.

Overall, the proposed equity evaluation approach aims to assess how equally people with different socioeconomic backgrounds can enjoy biking infrastructure – not just in terms of access, but also safety and comfort. The new framework is expected to stand out due to its comprehensive evaluation of biking

facilities (covering both quantity and quality), its holistic approach to road safety (incorporating both road conditions and accident records), and its exceptional transferability (not relying on input solicitation or archived records).

The advancement of curated sensing methods for cycling facilities makes it possible to incorporate asset conditions into equity analysis. A notable example is the instrumented bike developed by Ho's team (Ho et al. 2021), which uses smartphone built-in sensors to detect pavement defects like potholes, severe cracks, and bumps on cycling paths. The research not only assesses road quality using computing algorithms but also quantitatively maps the location of pavement defects using ArcGIS Pro, offering a potential solution to assess cycling equity across neighborhoods with varying socioeconomic conditions.

Future research will focus on the following three areas:

1. Quantitatively assess cycling assets conditions: employ instrumented bicycles for systematically evaluating pavement conditions and comfort levels within medium-to-high demand areas of a medium-sized American city.
2. Incorporate demographic and multimodal mobility factors: perform geospatial statistical analyses using a combination of demographic data, car ownership data, cycling asset condition data, and cycling asset inventories to identify equity gaps in usability and accesses.
3. Analyze cycling safety by exploring the relationship between accidents and infrastructure: investigate correlations between cycling-related traffic accidents and the condition of bicycle facilities, considering factors commonly involved in crash analyses, such as accident severity, time, traffic control, facility type, and location.

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