

Article

Geography over Income: The Electric Divide and the Sustainability of Barcelona's Bicing System

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Abstract

Bike-sharing systems (BSS) are a key component of sustainable urban mobility. However, their performance is strongly influenced by urban topography and socio-economic conditions. This study analyzes Barcelona's public BSS, Bicing, to examine how altitude and neighborhood income affect bicycle availability, departures, and electric bicycle adoption. The main objective is to determine whether the observed “electric divide” is driven by income or by topographical necessity. The analysis uses 2023 data from 511 Bicing stations and income information from 62 neighborhoods obtained from Open Data Barcelona and the Spanish National Statistics Institute. Three indicators were constructed: bike availability ratio, departures ratio, and electric bicycle ratio. Results show a strong negative correlation between altitude and bike availability ($r = -0.71$) and a strong positive correlation between altitude and electric bicycle use ($r = 0.78$). High-altitude stations show lower availability and fewer departures, while electric bicycles dominate uphill trips. Although high-income neighborhoods initially appear to use more electric bicycles, regression results show that income becomes insignificant once altitude is controlled for. Therefore, electric bicycle adoption is driven mainly by physical necessity rather than socio-economic preference.

Keywords: Bicing; altitude; income; inclusive transport system; sustainable transport system

1. Introduction

Bike-sharing systems (BSS) have evolved from small community-based mobility initiatives into a central component of sustainable urban transport strategies. As cities worldwide face urgent pressure to decarbonize transport networks under United Nations Sustainable Development Goal 11 [1], these systems have emerged as a cornerstone of modern eco-friendly design. The earliest modern reference is the “White Bicycle Plan” introduced in Amsterdam in 1965, which established the conceptual foundation for shared bicycle mobility as a public service [2]. Since then, BSS have expanded rapidly across the world and are now widely recognized as an effective instrument for reducing private car dependency, mitigating traffic congestion, lowering greenhouse gas emissions, and promoting healthier and more active lifestyles [3–5]. In addition to their environmental benefits, BSS also generate economic and social value by providing affordable first-mile and last-mile transport solutions that improve accessibility and strengthen integration with public transit systems [6,7].



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However, while the environmental benefits of traditional mechanical bicycle networks are well documented in flat urban landscapes, their viability severely degrades in topographically complex cities. A key advantage of BSS lies in its operational flexibility. Unlike traditional public transport, BSS does not depend on fixed routes or rigid schedules, allowing users to adapt trips to their own temporal and spatial mobility needs. This flexibility, combined with the widespread use of mobile applications and digital platforms for bicycle reservation, real-time station monitoring, and trip planning, has significantly increased system efficiency and user adoption [8]. At the same time, BSS operators and urban planners increasingly rely on operational data analysis to optimize station placement, improve rebalancing strategies, and evaluate system performance from both sustainability and equity perspectives [4,9].

The effectiveness of a BSS is strongly conditioned by the physical and socio-spatial characteristics of the city in which it operates. Urban form, density, land use distribution, and topography all influence bicycle availability, trip frequency, and station performance [10–14]. Previous studies show that stations located near business districts, dense residential zones, and high-quality cycling infrastructure tend to exhibit greater demand and more stable usage patterns [5]. Similarly, the presence of dedicated bicycle lanes and intermodal connectivity with metro or bus systems significantly improves station attractiveness and ridership levels [7]. However, in cities with complex topography, altitude becomes a particularly important determinant, introducing steep gradients that create severe physiological and temporal constraints. This generates strong asymmetries in bike flows and chronic operational imbalances across neighborhoods [6], effectively limiting sustainable active transit options for the average commuter.

At the same time, socio-economic conditions also shape BSS accessibility and usage. Higher-income neighborhoods often exhibit greater station connectivity, higher usage intensity, and better integration with urban services [9]. Income influences not only direct affordability, but also users' capacity to absorb indirect costs such as longer walking distances, service unreliability, or the premium associated with electric bicycles. However, the relationship between income and altitude is not necessarily linear. In many European cities, including Barcelona, affluent households are located both in traditional high-altitude residential districts and in low-elevation coastal or central neighborhoods shaped by urban redevelopment and real estate investment [4,12]. This creates an important analytical challenge: it becomes difficult to distinguish whether differences in BSS performance are driven by income itself or by the physical geography associated with residential location.

The mass deployment of shared electric bicycles introduces an additional, transformative dimension to this discussion. Recent research identifies electric bicycles as a technological mechanism capable of reducing the physical barriers imposed by topography by lowering the effort required for uphill travel and increasing the feasibility of longer or steeper trips [15,16]. In BSS environments, electric bicycles can partially correct directional imbalances and improve service accessibility in elevated areas. Nevertheless, electrical bicycle adoption is not socially neutral. Their higher operational costs and price premiums may disproportionately favor higher-income users, creating what recent literature describes as an "electric divide" where the benefits of electrification are unevenly distributed across socio-economic groups [17,18]. This introduces a core conflict within sustainable development: while electrification offers the physical capability to overcome geographical barriers, it risks introducing new layers of socio-economic exclusion if system access is stratified by wealth. Understanding whether electric bicycle usage is driven primarily by income or by topographical necessity is therefore critical for evaluating the equity implications of BSS electrification policies globally.

Barcelona provides an especially relevant case for examining these dynamics. As one of Spain's largest metropolitan and tourist centers, with more than 1.6 million inhabitants, the city combines high mobility demand with strong geographical heterogeneity. Its public BSS, Bicing, was launched in 2007 and currently operates through more than 500 fixed docking stations distributed across the urban area. Barcelona's Mediterranean climate, characterized by mild winters and favorable cycling conditions throughout most of the year, supports high system utilization and stable seasonal demand patterns [12]. In addition, the availability of high-quality open-access operational data through the municipal Open Data Barcelona platform makes Bicing particularly suitable for empirical analysis. For these reasons, this study focuses on Barcelona as a representative case for understanding how topography, income, and technological adaptation through electric bicycles shape the sustainability and equity of contemporary BSS.

Despite the growing literature on BSS sustainability, an important research gap remains regarding the joint effect of altitude and socio-economic stratification on electric bicycle adoption and service inequality. Most previous studies examine topography or income independently, while fewer studies explicitly analyze how both dimensions interact to shape station performance and mobility outcomes. In particular, limited evidence exists on whether the observed higher use of electric bicycles in wealthier neighborhoods reflects income-based preferences or simply the fact that many affluent residents live in higher-altitude areas where electric assistance becomes functionally necessary. Addressing this gap is essential for designing equitable and operationally efficient BSS policies.

Despite this growing body of research, important limitations remain in the literature. Although previous studies consistently highlight the importance of built environment factors and socio-economic conditions in shaping BSS performance, many contributions tend to analyze these determinants in isolation. For instance, research focusing on urban form emphasizes density and land use as primary drivers of demand, while equity-oriented studies highlight income as a key explanatory variable [16]. However, these approaches rarely examine the interaction between physical constraints and socio-economic characteristics, which may jointly influence user behavior. Moreover, while BSS sustainability is frequently evaluated through aggregate indicators such as ridership and accessibility, less attention has been given to underlying behavioral mechanisms and structural constraints. As a result, current literature often explains observed patterns *ex post*, without fully addressing the causal factors that generate spatial inequalities in system performance. This limitation creates an important gap in understanding how physical geography and user characteristics interact within real-world urban systems.

This study aims to analyze the Bicing system in Barcelona to determine how altitude and income jointly affect bicycle availability, departure patterns, and electric bicycle adoption. Specifically, the research seeks to: (i) evaluate whether high-altitude stations experience lower bicycle availability and fewer departures compared to low-altitude stations; (ii) examine whether higher-altitude neighborhoods are associated with higher disposable income levels; and (iii) determine whether electric bicycle usage is primarily explained by socio-economic status or by topographical necessity. To address these objectives, the study combines station-level operational data from the Open Data Barcelona portal with neighborhood-level income statistics from the Spanish National Statistics Institute for 2023, applying Pearson correlation analysis, *t*-tests, analysis of variance (ANOVA), Tukey post hoc tests, and multiple linear regression models. The analysis isolates the true drivers of the electric divide to determine if electric bicycle usage is a discretionary lifestyle choice or a functional response to physical barriers. Ultimately, the goal is to provide a framework for city policies that ensure fair service and sustainable management for all neighborhoods, regardless of their elevation.

The remainder of the paper is organized as follows. Section 2 presents the theoretical framework and hypothesis development. Section 3 describes the data, variables, and methodology. Section 4 reports empirical results. Section 5 discusses the sustainability policy implications, and limitations. Section 6 concludes the study.

2. Theory and Hypotheses

2.1. BSS Analysis

BSS have become a central component of sustainable urban mobility strategies because they reduce dependence on private cars, greenhouse gas emissions, and traffic congestion, while simultaneously promoting active transportation and public health. However, recent scholarship increasingly argues that the sustainability performance of BSS cannot be fully assessed through aggregate demand indicators alone, as substantial spatial and social disparities persist within cities [3,6]. Therefore, evaluating BSS sustainability requires explicit attention to environmental constraints and socioeconomic heterogeneity at the neighborhood scale.

Comparative and equity-oriented studies show that BSS accessibility, usage intensity, and network integration vary significantly across urban space, often favoring central or socioeconomically advantaged neighborhoods [5,7]. These uneven outcomes raise concerns regarding the social dimension of sustainability, as disadvantaged populations may face structural barriers to benefiting from shared micro mobility services, despite their apparent affordability.

Building on behavioral and spatial mobility research, the literature suggests that BSS usage patterns emerge from the interaction between physical conditions, such as topography, and users' adaptive capacity, which is shaped by income, preferences, and access to complementary technologies [4,10]. Consequently, spatial heterogeneity, rather than average system performance, becomes a key analytical dimension for evaluating BSS sustainability. This conceptual framework motivates the need to disentangle and empirically test the effects of altitude, income, and technological adaptation through electric bicycles. In particular, understanding how topographic constraints interact with socioeconomic stratification helps explain unequal access to BSS and provides a stronger basis for evaluating transport justice within urban sustainability policies. These relationships are formalized in the following hypotheses.

From a spatial economics perspective, household location choices can be interpreted through the [19,20] AMM framework, where residents trade off accessibility to employment (commuting costs) against housing space, land prices, and local amenities. In the monocentric city model, increasing distance from the central business district is compensated by lower land rents and typically larger housing consumption, while locations closer to the center command higher bids due to superior accessibility. This bid-rent logic provides a natural explanation for residential sorting patterns that may correlate with topographic profiles: households with stronger preferences for specific amenities (e.g., environmental quality, views, and lower congestion) may accept higher generalized travel costs or lower accessibility, while others prioritize proximity and travel-time minimization [20]. Therefore, observed associations between neighborhood income and altitude can be interpreted not only as descriptive correlations but also as equilibrium outcomes of accessibility–amenity trade-offs in urban land markets.

2.2. Altitude and BSS Usage

Urban topography is widely recognized as a fundamental physical determinant of cycling behavior. Higher elevation increases metabolic effort, reduces comfort, and discourages repeated cycling, particularly among casual users and individuals with time

constraints. Physiological studies show that even moderate slopes significantly increase oxygen consumption and perceived exertion, thereby reducing the likelihood of choosing cycling as a mode of transport [21].

Specifically, GPS-based route choice analyses further demonstrate that cyclists systematically deviate from the shortest paths to avoid steep gradients, even in cities with high-quality cycling infrastructure [22]. In the context of BSS, these behavioral adaptations are reflected in lower trip frequency, directional asymmetries, and persistent station imbalances in high-altitude areas. For instance, ref. [11] find that stations located uphill consistently experience higher arrival-to-departure imbalances, requiring more intensive rebalancing operations. Large-scale comparative research reinforces this pattern. A global analysis covering 40 cities shows that BSS operating in topographically complex environments exhibit stronger intra-urban disparities in station performance and bicycle availability than systems located in flatter cities [6]. These findings suggest that altitude functions as a structural constraint rather than a marginal contextual factor.

Evidence from Barcelona is consistent with this broader trend. Studies of the Bicing system reveal that stations located in elevated neighborhoods are predominantly used as trip origins, generating chronic bicycle shortages unless continuous rebalancing interventions are implemented [12]. Similar evidence has been identified in other cities with steep terrain. In Lisbon, a detailed analysis of operational BSS data showed that the spatial distribution of trips is strongly conditioned by environmental factors, including terrain slope, which influences both the intensity and location of demand [23]. Although this study does not directly quantify the effect of gradient, its findings confirm that the physical characteristics of the urban environment significantly shape user behavior. These results are consistent with previous research indicating that geographic conditions can constrain cycling adoption and generate persistent inequalities in access to shared mobility services. Taken together, theoretical, physiological, and empirical evidence supports a systematic negative relationship between altitude and BSS performance.

In addition to these spatial equilibrium mechanisms, behavioral economics provides complementary insights into the underlying decision-making processes that drive uphill aversion. Prospect theory suggests that individuals evaluate outcomes relative to a reference point and exhibit loss aversion, meaning that perceived losses tend to weigh more heavily than equivalent gains. Applied to cycling behavior, uphill mechanical riding can be perceived as a salient “loss” in terms of physical exertion, fatigue, and travel time, whereas the benefits of cycling, such as cost savings, convenience, or health improvements, may be perceived as less immediate or less certain [24].

This asymmetry in perceived costs and benefits helps explain the systematic avoidance of uphill routes observed in empirical studies. When slope increases the perceived effort beyond a behavioral threshold, users are more likely to substitute toward alternative modes or avoid cycling altogether. In this context, technologies such as electric bicycles play a critical role by reducing the perceived loss associated with uphill travel. Therefore, behavioral mechanisms rooted in prospect theory provide a theoretical foundation for the observed downhill bias and the increased reliance on electric bicycles in high-altitude environments. However, while existing studies clearly document the adverse effects of topography on cycling behavior, their explanatory scope remains limited [25]. Most contributions focus on physiological and operational dimensions, such as increased physical effort or route avoidance, without incorporating broader economic or behavioral perspectives. For example, route choice analyses consistently show that cyclists avoid steep gradients; nevertheless, these findings are largely descriptive and do not fully explain the underlying decision-making processes.

As a result, the literature lacks a comprehensive framework that links physical constraints with economic incentives and behavioral responses. In particular, insufficient attention has been given to the role of perceived effort, rather than objective conditions alone, in shaping user choices. Addressing this limitation requires integrating insights from behavioral economics to better understand the mechanisms driving uphill aversion. This theoretical gap motivates the formulation of the following hypothesis:

H1. *High altitude leads to lower bicycle availability and fewer departures compared to low-altitude neighborhoods.*

2.3. Income and BSS Usage

Alongside physical constraints, income plays a critical role in shaping access to transport options, residential location, and daily mobility behavior. Large-scale spatial studies consistently find that higher-income neighborhoods exhibit greater BSS connectivity, higher trip frequency, and more stable usage patterns than lower-income areas [5,7]. These patterns suggest that income improves not only the direct affordability of shared micromobility services but also users' behavioral flexibility, access to complementary urban amenities, and the ability to integrate BSS into regular travel routines. At the same time, the relationship between income and altitude remains theoretically ambiguous. Classical urban economic models traditionally associate higher-income households with elevated or amenity-rich residential areas, often due to better environmental quality, lower congestion, and symbolic social status. However, recent urban restructuring and redevelopment processes have weakened this association in many European cities, generating heterogeneous income distributions across both high- and low-altitude neighborhoods [4]. Specifically, empirical evidence from Barcelona supports this complexity, as affluent residential areas are found not only in the historic upper-elevation districts but also in low-lying, highly accessible central and coastal neighborhoods shaped by recent real estate development and urban regeneration processes [12]. These patterns challenge a purely vertical interpretation of socio-spatial stratification and highlight the need to empirically test the relationship between income and altitude rather than assuming it a priori.

In this study, neighborhood income is measured using the average taxable income per consumption unit reported by the [26]. This indicator provides a standardized measure of household economic capacity adjusted for household composition using the modified OECD equivalence scale. Compared to simple per capita income measures, this metric captures effective purchasing power more accurately and is widely used in intra-urban socioeconomic analysis.

Beyond residential location, recent equity-focused research suggests that income also influences BSS adoption through users' capacity to absorb indirect costs related to reliability, time savings, and convenience. Higher-income users tend to exhibit greater tolerance for spatial inefficiencies, such as walking longer distances to reach available stations or adapting to service unreliability, which can partially offset physical or infrastructural constraints [8,9]. At the same time, accessibility advantages associated with income can emerge independently of altitude, as wealthier households are often concentrated in neighborhoods with better public transport integration and higher-quality urban services, regardless of elevation. This dual mechanism highlights the importance of distinguishing between vertical residential sorting (altitude-based) and broader accessibility advantages embedded in Barcelona's urban structure. Given this theoretical ambiguity, the relationship between income and altitude cannot be assumed and must be empirically tested using neighborhood-level income indicators.

However, although numerous studies highlight the role of income in explaining BSS accessibility and usage patterns, the empirical evidence remains inconclusive. On one hand, several contributions suggest that higher-income neighborhoods benefit from greater connectivity and higher usage intensity. On the other hand, more recent findings indicate that income effects may be overstated when spatial factors are not adequately controlled. In particular, the presence of high-income neighborhoods in both central and peripheral urban areas complicates the interpretation of income-based patterns. This represents a key limitation in the literature, as many studies implicitly assume a direct relationship between income and accessibility without accounting for the mediating role of geographic constraints. Consequently, disentangling socio-economic effects from spatial factors remains an open empirical challenge.

Accordingly, this study evaluates whether higher-altitude neighborhoods are, on average, associated with higher disposable income levels, leading to the following hypothesis:

H2. *The mean disposable income of higher-altitude neighborhoods is higher than that of lower-altitude neighborhoods.*

2.4. Altitude, Income, and Electric Bicycle Usage

In parallel with the expansion of bike-sharing systems, other forms of shared micromobility have rapidly emerged, particularly electric scooters (e-scooters), which are increasingly deployed in European cities as flexible, app-based, and space-efficient transport alternatives. E-scooters share several characteristics with bicycle-sharing systems, including their role in first- and last-mile connectivity and their integration into digital mobility platforms. However, recent research highlights important differences in performance, comfort, and safety between the two modes.

Specifically, e-scooters are often associated with lower ride comfort due to higher levels of vibration exposure, which stem from their small wheel size and limited suspension systems [24,25]. In addition, their reduced wheel geometry and lower stability may increase operational safety risks, particularly when operating on uneven urban surfaces or in mixed-traffic environments [25]. These limitations suggest that, despite their operational flexibility, e-scooters may not fully substitute bicycles in terms of user comfort, physical robustness, and perceived safety.

Therefore, the growing coexistence and competition between bicycle-sharing systems and e-scooters reflect a broader transformation in urban micromobility ecosystems. Understanding the relative advantages and constraints of each mode is critical for evaluating sustainable transport strategies. In this context, bicycle-sharing systems particularly those incorporating electric bicycles remain a key component of inclusive and resilient urban mobility, especially in cities with complex topography.

Recent literature increasingly identifies electric bicycle as a key technological innovation capable of mitigating physical barriers to cycling, particularly in hilly urban environments. Electric bicycle substantially reduce the physiological cost of uphill travel, increase feasible trip distances, and expand cycling participation among users who would otherwise be discouraged by physical effort or time constraints [15,16]. In BSS contexts, the introduction of electric bicycles has been shown to increase ridership, improve directional balance, and partially offset altitude-induced asymmetries in demand.

From a sustainability and equity perspective, however, electric bicycle adoption is not socially neutral. Empirical studies consistently highlight the importance of pricing, income, and cost sensitivity in shaping demand for shared electric bicycles. Refs. [17,27,28] show that electric bicycle demand is highly price-elastic and systematically segmented by income, with higher-income users demonstrating a greater willingness to pay for electric

assistance. Similarly, incentive-based studies suggest that, in the absence of targeted subsidies, higher-income groups tend to capture a disproportionate share of the benefits associated with electric bicycle systems [18]. Broader research on electric bicycle adoption further indicates that higher-income and more highly educated users place greater value on comfort, time savings, and technological convenience, even when these benefits involve higher monetary costs [29,30]. In high-altitude neighborhoods, where electric assistance provides the greatest marginal benefit, income therefore becomes a key determinant of users' ability to compensate for physical constraints through paid technological solutions.

The use of electric bikes can be positioned within Amartya Sen's Capability Approach [31] to economic inequality. In this framework, transport equity is evaluated not only by the equal distribution of resources (for instance, the presence of docking stations), but by users' freedom to achieve vital urban spaces, known as capabilities. Altitude, in this case, functions as an environmental conversion factor that dictates how efficiently a tool can be translated into a capability [32]. In topographically complex cities, like Barcelona, a steep hill reduces the utility of a standard mechanical bicycle by introducing a metabolic and temporal cost of moving. Consequently, the introduction of electric bikes creates a localized electric divide. This divide does not represent a purely socio-economic lifestyle choice; rather, it is a geographically driven capability constraint, where residents in high altitude areas have higher monetary expenditures simply to achieve the same baseline of urban mobility mobility enjoyed for free by low-altitude residents. Therefore, the electric divide is conceptualized here as a socially structured inequality where geography dictates the financial cost of achieving equal transport capabilities.

In Barcelona's Bicing system, the consistent price premium applied to electric bicycles might imply that the mitigating effect of electric bicycle is likely to be stronger among wealthier users [12]. As a result, altitude and income do not operate independently; rather, they interact through access to electric mobility. Users living in uphill neighborhoods face stronger physical barriers, but higher-income residents can partially overcome these constraints by paying for electric assistance, while lower-income users remain more exposed to topographic disadvantages.

Beyond modal differences, recent research also emphasizes that rider comfort, vibration exposure, ergonomics, and perceived safety are central determinants of cycling and electric bicycle adoption, particularly in dense urban environments. Studies increasingly show that whole-body vibration generated by poor pavement conditions, infrastructure irregularities, and vehicle design significantly affects user comfort, fatigue, and overall riding experience [28]. Excessive vibration exposure not only reduces ride quality but may also discourage repeated usage and long-term adoption of cycling as a transport mode.

From an infrastructure perspective, the quality of cycling surfaces plays a fundamental role in shaping both objective and perceived comfort. Uneven pavements, surface discontinuities, and inadequate maintenance increase vibration transmission to the cyclist, negatively affecting both stability and safety perceptions. As a result, comfort is no longer considered a secondary attribute but rather a core dimension of sustainable urban mobility systems [25,33]. This perspective is particularly relevant in cities with complex topography, where physical effort, vibration exposure, and safety perceptions interact simultaneously to shape mobility choices. Improving infrastructure quality, reducing vibration levels, and enhancing ergonomic conditions therefore emerge as key strategies for increasing bicycle adoption and ensuring more inclusive access to micromobility services.

Building on this interaction, existing research on electric bicycle adoption points to both technological and socio-economic drivers. Some studies attribute higher usage to income-related preferences and willingness to pay, while others emphasize electric assistance as a functional response to physical constraints. This dual interpretation reveals

a key tension in the literature: it remains unclear whether adoption is primarily driven by choice or by necessity.

Moreover, most prior studies examine these factors separately, without explicitly testing their combined effects. As a result, the literature lacks robust empirical evidence capable of disentangling whether observed usage patterns are driven mainly by socio-economic differences or by topographical conditions. Addressing this limitation is critical for understanding the equity implications of BSS electrification.

Accordingly, recent literature suggests a moderated relationship in which income influences the extent to which electric bicycles offset altitude-related barriers. This motivates the formulation of the following hypothesis:

H3. *The ratio of electric bicycle usage is higher in high-altitude neighborhoods with higher income levels than in low-altitude, lower-income neighborhoods.*

3. Research Model

3.1. BSS Description

Inaugurated in 2007, Bicing is Barcelona's public BSS. The service was initially managed by Clear Channel until 2018. Since 2019, system operations have been managed by Pedalem Barcelona under the supervision of the municipal company BSM. The system was designed as a low-cost and sustainable urban mobility solution integrated into the city's public transport network. Currently, the network comprises 557 fixed docking stations distributed across the city and a fleet of 8000 bicycles. A significant technical feature of the current system is that all docking stations are hybrid, meaning they support both mechanical and electric bicycles. Users can rent a bicycle from any station using a dedicated Bicing card, a mobile application, or a smartphone equipped with near field communication.

NFC technology and return it to any station with an available dock.

Access to the Bicing service is restricted to Barcelona residents aged 16 years and older. The pricing structure is organized into two primary annual subscription plans based on expected usage frequency: The Flat Rate Plan and the Pay-per-Use Plan. A defining characteristic of the system's economic model is the consistent price premium applied to electric bicycles, which involve higher operational and maintenance costs than the mechanical fleet.

The Flat Rate Plan is designed for frequent users and requires an annual membership fee of €50. This plan provides a substantial subsidy for mechanical bicycle use, as the first 30 min of each trip are free of charge. In contrast, the use of an electric bicycle under the same plan incurs a cost of €0.40 for the initial 30-min interval. For trips lasting between 30 min and two hours, mechanical bicycles are charged €0.81 per 30-min block, while electric bicycles are charged a higher rate of €1.04 per 30-min block. For any rental exceeding two hours, a uniform penalty rate of €5.75 per hour is applied regardless of bicycle type.

The Pay-per-Use Plan is intended for occasional users and has a lower annual fee of €35. Unlike the frequent-user plan, mechanical bicycle trips are not subsidized during the first 30 min and carry a base cost of €0.40. Electric bicycles remain the most expensive option in this tier, with the first 30 min priced at €0.63. Billing for the intermediate interval (30 min to two hours) follows the same structure as the Flat Rate Plan, with mechanical bicycles costing €0.81 and electric bicycles €1.04 for every additional 30-min increment. The long-term rental penalty of €5.75 per hour for trips exceeding two hours also remains constant across subscription types.

This pricing strategy establishes a clear economic hierarchy within the system. For the first 30 min of a trip, which covers the majority of urban commutes, users must pay a

surcharge to access electric assistance. In the Flat Rate Plan, this implies a transition from a free service to a paid one, while in the Pay-per-Use Plan, choosing an electric bicycle instead of a mechanical one represents a 57% increase in the base trip cost.

3.2. Data Collection

The analysis is based on data from Bicing, obtained through the Open Data Barcelona portal [34], a public service maintained by Barcelona City Hall. Two important limitations of the available dataset must be acknowledged. First, the data does not distinguish between individual user profiles or specific subscription plans. This lack of individual-level information prevents the identification of behavioral patterns associated with age, gender, or income level. Second, there is no available information regarding motorized rebalancing operations. Since the timestamps and locations of truck-based bicycle redistributions are not publicly available, it is difficult to distinguish natural bicycle movements from the artificial repositioning carried out by the system operator.

In addition to bicycle usage records, a secondary dataset was retrieved from the same portal to incorporate socio-economic variables. Specifically, this study uses the Average Tax Income per Consumption Unit (€), derived from the Household Income Distribution Atlas of [26]. This variable is aggregated at the neighborhood level and provides a more robust measure of economic status than a simple per capita income indicator.

Definition of Income per Consumption Unit

Income per consumption unit is an indicator used to measure household income adjusted for household size and demographic composition [26]. This calculation follows the modified OECD equivalence scale, which assigns specific weights to household members: 1.0 to the first adult, 0.5 to each additional person aged 14 or older, and 0.3 to each child under the age of 14. By dividing total household income by the sum of these weighted members, this metric captures the effective purchasing power and living standards available to each household member more accurately than a simple average income measure.

A critical constraint in the data selection process is the availability of socio-economic statistics. Although Bicing usage data is available through 2025, the most recent neighborhood-level income data is limited to 2023. Consequently, this study restricts the analysis of both bicycle usage and income variables to the year 2023. This temporal alignment is necessary to ensure that the socio-economic relationships examined in the results are consistent and methodologically valid.

3.3. Data Cleaning

All data processing, cleaning, and preparation were performed using the R programming language version 4.6.0.

3.3.1. Income Data

As previously noted, this study uses Income per Consumption Unit as the primary indicator of household wealth. This dataset was retrieved directly from the Open Data Barcelona portal, where the information was already aggregated at both neighborhood and district levels. Since the data was provided in a finalized and standardized format by the municipal government, no additional cleaning or preprocessing was required before its incorporation into the analysis. Although Barcelona is administratively divided into 73 neighborhoods, this study focuses on the 62 neighborhoods where the bike-sharing network is currently operational. The remaining 11 neighborhoods were excluded due to the absence of Bicing station infrastructure, which prevents meaningful comparison between bicycle usage and local income conditions.

3.3.2. Bicing Data

The core dataset of this research consists of bicycle usage information published monthly on the Open Data Barcelona portal. Due to the high sampling frequency of approximately every five minutes, each monthly file contains more than four million records, resulting in over 49 million observations for 2023. Although the specific variables provided by the city may vary slightly by year, the essential variables used in this analysis are presented in Table 1.

Table 1. Dataset description.

Variables	Type of Variable
Station ID	String
Total number of available bicycles (mechanical and electric)	Numerical
Mechanical bicycles available	Numerical
Electric bicycles available	Numerical
Available docks	Numerical
Date and time when the information was recorded	Datetime
Whether the station can charge electric bicycles (1 or 0)	Dummy
Whether the station is properly installed (1 or 0)	Dummy
Whether the station provides bicycles without operational problems (1 or 0)	Dummy
Whether bicycles can be properly returned to the station (1 or 0)	Dummy
Station status (in service or closed)	Dummy

To ensure the integrity of the results, a rigorous cleaning process was applied to the raw dataset. The following exclusion criteria were used: (i) stations appearing in the dataset but showing no usage activity were removed; similarly, stations that were closed or malfunctioning during the study period were excluded; (ii) records containing invalid information, such as timestamps outside the 2023 study period or negative availability values, were deleted; and (iii) stations with significant missing data were removed to avoid distortions in the longitudinal analysis. Collectively, these exclusions represented less than 1% of the total dataset. This low proportion indicates that the cleaning process did not introduce significant bias and that the remaining observations provide a highly representative sample of system performance. During the 2023 study period, the Bicing network consisted of 512 active stations. One station was excluded due to insufficient data availability, resulting in a final sample of 511 stations.

A secondary dataset was also retrieved from the Open Data Barcelona portal to obtain station metadata. This dataset provides monthly updates on attributes such as station names, addresses, postal codes, and docking capacities. Most importantly, it includes the geographic coordinates (latitude, longitude, and altitude), which were used to establish the spatial and topographical context of the 511 stations included in this study.

3.4. Data Processing

Each station was assigned to its corresponding neighborhood through a spatial join procedure. Using a point-in-polygon operation, the latitude and longitude coordinates of each station were matched with Barcelona's official neighborhood boundaries. Altitude data for each station was already included in the metadata provided by the Open Data Barcelona portal.

Several temporal variables were derived from the recorded timestamps, including hour of the day, day of the week, and month. In addition, key operational indicators such as total trips, arrivals, and departures were calculated separately for mechanical bicycles, electric bicycles, and total bicycle volumes. These indicators were expressed in

both absolute values and percentages to support a more detailed comparative analysis across stations and neighborhoods.

Three primary metrics were used to evaluate system performance:

- **Availability Ratio:** Calculated for each station, this metric is defined as the number of available bicycles divided by the total station capacity. It generates a value between 0 and 1, representing the probability that a user will find a bicycle available at a specific station.

$$\text{Availability ratio} = \frac{\text{Available bikes}}{\text{Station capacity}}$$

- **Departures Ratio:** This metric is calculated as the total number of departures (including both mechanical and electric bicycles) divided by station capacity. It measures the intensity of station usage while controlling for differences in station size. Standardizing by capacity allows for a fair comparison of how frequently available docks are utilized across stations with varying infrastructure scales.

$$\text{Departures ratio} = \frac{\text{Total departures}}{\text{Station capacity}}$$

- **Electric Bicycle Ratio:** This metric represents the proportion of departures made using electric bicycles relative to total departures (mechanical + electric) at each station. It is used to identify user preference for electric bicycle technology across the network.

$$\text{Electric Bike ratio} = \frac{\text{Electric bike departures}}{\text{Total departures}}$$

3.5. Methodology

3.5.1. Pearson Correlation

The Pearson correlation coefficient is a bivariate statistical measure used to quantify the strength and direction of the linear relationship between two continuous variables. The coefficient ranges from -1 to 1 , where a value of 1 indicates a perfect positive linear relationship, -1 represents a perfect negative linear relationship, and 0 indicates the absence of linear correlation. Additional methodological details can be found in [35].

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}}$$

where n is the total number of observations, x_i and y_i are the individual values of the two variables for each observation, and $\bar{x}$ and $\bar{y}$ represent their respective means.

3.5.2. *t*-Test

The *t*-test is a statistical hypothesis test used to evaluate whether a significant difference exists between the means of two groups. The null hypothesis assumes that the means of both groups are equal. Rejection of the null hypothesis indicates that the two groups are statistically different with a high degree of confidence. In this study, a two-tailed independent *t*-test was performed, treating the groups as separate populations. Statistical significance was determined by comparing the calculated *t*-score with the critical value from Student's *t*-distribution or, equivalently, by evaluating whether the *p*-value was lower than the significance threshold of 0.05 . Further methodological details are available in [36].

$$t\text{-score} = \frac{\bar{Y}_1 - \bar{Y}_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}}$$

where N_1 and N_2 are the sample sizes, $\bar{Y}_1$ and $\bar{Y}_2$ are the sample means, and s_1^2 and s_2^2 are the sample variances.

3.5.3. ANOVA Test

One-way ANOVA is a statistical technique used to determine whether statistically significant differences exist among the means of three or more independent groups. The null hypothesis assumes that all group means are equal, while the alternative hypothesis suggests that at least one group mean differs significantly from the others. The test produces an F-statistic, which represents the ratio of variance between groups to variance within groups. A high F-value associated with a p -value below 0.05 indicates that the observed differences are unlikely to have occurred by chance. Additional methodological details can be found in [37]. The F-statistic is calculated as follows:

$$F = \frac{MS_{between}}{MS_{within}}$$

where $MS_{between}$ is the mean square between groups and MS_{within} is the mean square within groups.

3.5.4. Tukey Test

Tukey's Honest Significant Difference (HSD) test is a post hoc analysis applied after a significant ANOVA result to identify which specific pairs of group means differ statistically. While ANOVA determines whether at least one group mean differs, it does not specify which groups are significantly different. The Tukey HSD test addresses this limitation by performing pairwise comparisons across all group combinations.

A key advantage of this method is its control of the family-wise error rate. When multiple comparisons are conducted simultaneously, the probability of committing a Type I error increases. Tukey's test adjusts for this by maintaining the overall significance level, typically 0.05, across all comparisons. If the difference between two means exceeds the HSD value, that pair is considered statistically significant. More information can be found in [37]. The formula is expressed as follows:

$$HSD = q \sqrt{\frac{MS_{within}}{n}}$$

where q is the studentized range statistic obtained from a standard statistical table according to the number of groups and degrees of freedom; MS_{within} is the mean square error derived from the ANOVA results, and n is the number of observations per group.

3.5.5. Multiple Linear Regression

It is a multivariate statistical method used to examine the relationship between one dependent variable and two or more independent variables. In this study, regression is applied not as a predictive tool, but as an inferential framework to isolate the individual contribution of variables such as altitude and income on bicycle usage and availability. The main reason for using multiple regression in this context is to control for confounding effects. By incorporating several explanatory variables within a single model, the analysis allows the significance of one variable to be tested while holding the others constant. Additional methodological details are available in [38]. The multiple linear regression model is expressed as follows:

$$Y = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \cdots + \beta_k X_k + \varepsilon$$

where Y is the dependent variable, β_0 is the intercept, $\beta_1, \dots, \beta_k$ are the regression coefficients representing the expected change in Y for a one-unit change in the corresponding independent variable, $X_1, \dots, X_k$ are the independent variables, and ε is the residual error term.

4. Results

4.1. Topography Impact in the Bicing System

To examine the relationship between urban topography and BSS performance, a Pearson correlation analysis was conducted between station altitude and average bicycle availability. The results, summarized in Table 2, revealed a strong negative correlation (-0.71). This coefficient indicates that altitude is a major determinant of station inventory distribution. As elevation increases, the probability of users finding an available bicycle decreases significantly.

Table 2. Altitude and bicycle availability correlation.

	Average Bicycle Availability (%)	Altitude
Average bicycle availability (%)	1.00	
Altitude	-0.71^{***}	1.00

Note: *** indicates statistical significance at the 1% level.

The results suggest a clear downhill bias in user behavior. Bicing users tend to use bicycles primarily for downhill trips, where physical effort is lower, while bicycles are returned less frequently to higher-altitude stations [11,23]. This generates a one-way inventory flow that progressively depletes stations located in elevated areas. These findings reveal a structural challenge for the system. The natural movement of bicycles toward lower-altitude areas, particularly toward sea level, creates persistent spatial imbalances. As a result, manual rebalancing operations, such as truck-based bicycle redistribution, may be insufficient to maintain an equitable distribution of bicycles across Barcelona's diverse topography. This topographic effect directly influences service reliability and user accessibility, particularly in uphill neighborhoods where bicycle availability becomes systematically lower.

To quantify the magnitude of this geographical effect, stations were divided into two groups using the city's mean altitude threshold of 65 m above sea level (m.a.s.l.) [39]: the High-Altitude Cluster (>65 m.a.s.l.) and the Low-Altitude Cluster (<65 m.a.s.l.). A two-sample t -test was then performed to compare mean bicycle availability between these two clusters. The results, presented in Table 3, show a highly significant difference between group means. Stations located in high-altitude neighborhoods maintained an average availability rate of only 20.47%, whereas stations in low-altitude areas averaged 34.51%. The difference between these means is statistically significant, confirming that the "altitude gap" is a persistent structural characteristic of the system rather than a random fluctuation. These findings demonstrate that residents in high-altitude neighborhoods face a clear structural service deficit. In practical terms, a user located in the hilly areas of the city is approximately 40% less likely to find an available bicycle than a user in lower and flatter areas. This reinforces the evidence that urban topography significantly affects service accessibility and contributes to unequal mobility conditions across Barcelona.

Table 3. t -test for low- and high-altitude stations comparing bicycle availability ratio.

Low-Altitude Mean	High-Altitude Mean	p -Value
34.51	20.47	$2.2 \times 10^{-16}^{***}$

Note: *** indicates statistical significance at the 1% level.

To confirm whether the shortage of bicycles in elevated areas is caused by unbalanced usage patterns, departure rates were compared between the two altitude clusters. In this study, departures are used as the primary indicator of user demand rather than arrivals. This is a critical methodological choice because, in the Bicing system, arrival counts are often affected by operator-based rebalancing, where bicycles are manually redistributed by truck. Departures, by contrast, represent actual trips initiated by users and therefore provide a more accurate measure of effective demand.

The *t*-test results (see Table 4) indicate that departure frequency is significantly lower in the high-altitude cluster, with an average departure ratio of 6.92% per station, compared to 10.67% in low-altitude neighborhoods. This difference is statistically significant and confirms Hypothesis 1. The findings suggest that the physical cost of uphill travel acts as a behavioral constraint, commonly referred to as uphill aversion. Similar to previous studies [11,22], this investigation demonstrates that because users are less willing to cycle uphill, return trips to high-altitude stations occur less frequently, creating a persistent deficit of bicycles in these areas. This reduces bicycle inventory and, consequently, lowers the number of departures from high-altitude stations, as users are often unable to find an available bicycle to begin their trips. In this way, topography generates a self-reinforcing cycle of reduced accessibility and lower system performance in uphill neighborhoods.

Table 4. *t*-test for low- and high-altitude stations comparing departure ratio.

Low-Altitude Mean	High-Altitude Mean	<i>p</i> -Value
10.67	6.92	5.9×10^{-13} ***

Note: *** indicates statistical significance at the 1% level.

4.2. Socio-Economic Stratification and Topography

To evaluate the relationship between neighborhood income and urban geography, a Pearson correlation analysis was performed between mean household income and altitude. The results, presented in Table 5, indicate a moderate positive correlation (0.40). This confirms a general tendency for higher-income residents to be concentrated in higher-elevation areas, although the magnitude of the coefficient suggests a more complex spatial distribution.

Table 5. Altitude and mean income correlation.

	Mean Income	Altitude
Mean Income	1.00	
Altitude	−0.40 ***	1.00

Note: *** indicates statistical significance at the 1% level.

The moderate strength of this relationship is explained by the presence of high-income neighborhoods located in low-altitude coastal and central areas of the city. While many high-altitude neighborhoods are predominantly associated with higher-income populations, several economically affluent districts are also located near sea level. For instance, neighborhoods such as Diagonal Mar i el Front Marítim del Poblenou and La Vila Olímpica del Poblenou represent high-income modern developments situated in coastal areas. Similarly, Dreta de l'Eixample, located in Barcelona's flat urban core, remains one of the city's wealthiest districts despite its moderate altitude. These cases weaken the strength of a purely linear relationship, as income concentration in Barcelona is distributed across both the historic Upper Zone and premium coastal and central districts. For the purposes of this study, this finding implies that although high-income residents are present across multiple elevations, the operational challenges of the Bicing system, particularly lower bicycle

availability and the physical burden of uphill travel disproportionately affect affluent residents living in high-altitude neighborhoods. This reinforces the importance of considering both topography and socio-economic structure simultaneously when evaluating equity in bike-sharing accessibility.

To further investigate this relationship, neighborhoods were classified into four income quartiles: Q1 (low-income), Q2 (lower-middle income), Q3 (upper-middle income), and Q4 (high-income). A one-way ANOVA was conducted to test whether mean altitude differed significantly across these income groups.

The model produced a statistically significant result (see Table 6), confirming that elevation is not evenly distributed across income levels. This indicates that neighborhood altitude varies systematically according to socio-economic status rather than being randomly dispersed throughout the city. In other words, income stratification in Barcelona is partially reflected in its urban topography. The significance of the ANOVA result supports the hypothesis that higher-income households are more likely to be located in elevated areas, although this relationship is not perfectly linear, as previously discussed. This finding is particularly relevant for the Bicing system because it suggests that the topographic disadvantages associated with reduced bicycle availability may disproportionately affect wealthier neighborhoods located in uphill zones.

Table 6. ANOVA test for income quartiles and altitude.

	Degrees of Freedom	Sum Square	Mean Square	F-Value	<i>p</i> -Value
Quartile	3.00	17,320	5773	3.54	0.02 **
Residuals	58.00	94,648	1632	1.00	

Note: ** indicates statistical significance at the 5% level.

Given that the ANOVA results showed significant differences across income groups, a Tukey HSD test was applied to identify which specific quartiles differed significantly in terms of altitude (see Table 7). The results indicate that the observed differences are primarily driven by the highest-income group (Q4). The most significant disparity was found between quartile 4 and quartile 2, with an average altitude difference of 43.34 m.a.s.l. ($p = 0.02$). The comparison between the highest-income quartile (Q4) and the lowest-income quartile (Q1) also reached the threshold of statistical significance, with a difference of 38.34 m.a.s.l. ($p = 0.05$). In contrast, no statistically significant differences were identified among the first three quartiles (Q1, Q2, and Q3), indicating that altitude remains relatively stable across most of the population. These findings provide support for Hypothesis 2. Rather than showing a perfectly linear increase in elevation across all income levels, the results reveal what can be described as a topographical elite effect. Although the Pearson correlation between income and altitude is only moderate (0.40), the ANOVA and Tukey analyses provide a deeper explanation of Barcelona's socio-spatial structure.

Table 7. Tukey test for income quartiles and altitude.

	Difference	Lower	Upper	<i>p</i> -Adjusted
Q2–Q1	−5.00	−42.78	32.77	0.98
Q3–Q1	7.81	−30.59	46.21	0.94
Q4–Q1	38.34	−0.06	76.74	0.05 **
Q3–Q2	12.81	−25.59	51.21	0.81
Q4–Q2	43.34	4.93	81.74	0.02 **
Q4–Q3	30.53	−8.48	69.55	0.17

Note: ** indicates statistical significance at the 5% level.

For approximately the first 75% of the population (quartiles 1 to 3), residential altitude remains relatively consistent, with no significant differences between groups. In contrast, the most elevated urban areas are disproportionately occupied by the wealthiest 25% of residents (quartile 4). These households are largely concentrated in upland districts such as Sarrià-Sant Gervasi and Pedralbes. At the same time, the relationship is not perfectly linear because several high-income neighborhoods are also located at sea level, such as Diagonal Mar and Vila Olímpica. These areas represent a more recent form of coastal and central urban wealth, distinct from the traditional concentration of wealth in Barcelona's hillside districts. This dual spatial pattern explains why income concentration exists both in elevated and low-altitude premium zones.

4.3. The Electric Bicycle Ratio

The final phase of the analysis examines Hypothesis 3, which proposes that the adoption of electric bicycles functions as a mechanism to overcome the topographical barriers identified in the previous sections. By analyzing the electric bicycle ratio, which is defined as the proportion of total departures made using electric bicycles relative to total departures, it is possible to determine whether technology adoption is primarily driven by physical necessity or by socio-economic conditions. Therefore, to establish a baseline, the relationship between altitude and electric bicycle ratio was first analyzed at the station level. A Pearson correlation revealed a strong positive relationship ($r = 0.78$) between these two variables. This result confirms that as elevation increases, users shift significantly from mechanical bicycles to electric bicycles, suggesting that slope strongly influences technological choice.

To complement this result, a two-sample *t*-test was conducted comparing stations located above and below the 65 m.a.s.l. altitude threshold. The results show a substantial disparity between the two groups: stations in the high-altitude cluster present an average electric bicycle ratio of 86.78%, while stations in the low-altitude cluster show an average of 68.83%. This difference is highly statistically significant, as presented in Tables 8 and 9. These findings suggest that in elevated areas, the mechanical bicycle has become nearly obsolete, with almost 9 out of 10 trips requiring electric assistance. This provides strong evidence that electric bicycles are not simply a convenience feature, but rather an operational necessity for maintaining bicycle-sharing functionality in uphill neighborhoods. In this sense, electric bicycles act as a technological adaptation to topographic constraints, partially compensating for the structural disadvantages associated with altitude.

Table 8. Altitude and electric bicycle ratio correlation.

	Electric Bicycle Ratio	Altitude
Electric bicycle ratio	1.00	
Altitude	0.78 ***	1.00

Note: *** indicates statistical significance at the 1% level.

Table 9. *t*-test for low- and high-altitude stations comparing mean electric bicycle ratio.

Low-Altitude Mean	High-Altitude Mean	<i>p</i> -Value
0.69	0.87	2.2×10^{-16} ***

Note: *** indicates statistical significance at the 1% level.

To better understand the social dimension behind these results, the analysis was shifted to the neighborhood level, allowing bicycle usage patterns to be linked with official income statistics. A one-way ANOVA was performed to test whether the average electric bicycle ratio differed significantly across income quartiles (Q1 to Q4). The results, presented

in Table 10, were statistically significant ($p = 0.01$), indicating that at least one income group exhibits a different level of electric bicycle usage compared to the others. Moreover, to identify the specific differences between groups, a Tukey HSD test was subsequently conducted. The results revealed that the only statistically significant difference exists between quartile 4 (highest income) and quartile 2 (lower-middle income). Specifically, quartile 4 shows an electric bicycle ratio 12.1 percentage points higher than quartile 2 ($p = 0.01$), as shown in Table 11. No other pairwise comparisons reached conventional significance levels.

Table 10. ANOVA test for income quartiles and electric bicycle ratio.

	Degrees of Freedom	Sum Square	Mean Square	F-Value	p-Value
Quartile	3.00	0.12	0.04	3.93	0.01 ***
Residuals	58.00	0.59	0.01		

Note: *** indicates statistical significance at the 1% level.

Table 11. Tukey test for income quartiles and electric bicycle ratio.

	Difference	Lower	Upper	p-Adjusted
Q2–Q1	−0.04	−0.13	0.06	0.72
Q3–Q1	0.00	−0.09	0.10	0.99
Q4–Q1	0.08	−0.01	0.18	0.11
Q3–Q2	0.04	−0.05	0.14	0.07 *
Q4–Q2	0.12	0.03	0.22	0.01 ***
Q4–Q3	0.08	−0.02	0.18	0.14

Note: *** and * indicate statistical significance at the 1% and 10% levels, respectively.

At first glance, these findings may suggest that residents in higher-income neighborhoods have a stronger preference for electric bicycles. However, as established in the analysis of Hypothesis 2, high-income neighborhoods in Barcelona are often located at higher altitudes. This creates a confounding variable problem: it is unclear whether higher electric bicycle usage is driven by income itself or simply by the greater physical need for electric assistance in uphill areas. On the other hand, to identify the true mechanism and separate the independent effect of income from the effect of altitude, a multiple linear regression model is required. This approach allows both variables to be evaluated simultaneously, making it possible to determine whether electric bicycle adoption is primarily explained by topographical necessity or by users' socio-economic capacity to pay for electric assistance.

Accordingly, a multiple linear regression model was estimated to isolate the independent effect of each variable on the electric bicycle ratio. This approach allows the assessment of each factor's individual contribution to the electric ratio while holding the other variable constant. Based on the previous finding that only the highest income quartile (Q4) showed a significant behavioral difference, a binary dummy variable was created to isolate this group from the remaining quartiles. This specification allows the model to test whether the income effect identified in the Tukey analysis remains statistically significant once the physical effect of altitude is controlled for. The model is specified as follows:

$$\text{Electric ratio}_i = \beta_0 + \beta_1 \text{Altitude}_i + \beta_2 \text{High income quartile}_i + \varepsilon_i$$

The regression results, summarized in Table 12, identify station altitude as the strongest predictor of electric bicycle usage. The positive coefficient of 0.002 indicates that for every additional m.a.s.l., the share of electric bicycle departures increases by approximately 0.2 percentage points. The very high t -value (10.73) confirms that topography is the

primary structural driver of electric bicycle adoption. In contrast, once altitude is controlled for, the effect of belonging to the highest income quartile (Q4) becomes statistically non-significant. This result demonstrates that the apparent high-income gap observed in the previous categorical analyses was largely an artifact of Barcelona’s urban geography and the effect of spatial confounding rather than a strong socio-economic driver. While a non-significant result does not mathematically prove the absolute absence of an income effect, its minimal magnitude indicates that any independent socio-economic preference is functionally negligible when compared to the overriding physical demand of topography. In other words, high-income residents use electric bicycles more frequently not because of stronger socio-economic preferences or greater purchasing power alone, but primarily because they are disproportionately concentrated in high-altitude neighborhoods. When comparing high-income and low-income neighborhoods located at the same elevation, the model shows no statistically significant difference in electric bicycle adoption. The overall model is robust, with an adjusted R^2 of 0.70. This indicates that approximately 70% of the total variation in electric bicycle usage across Barcelona can be explained by altitude and income quartile alone. These findings provide strong evidence that topography, rather than income itself, is the dominant factor shaping technological adaptation within the Bicing system.

Table 12. Multiple Linear Regression Results.

Variable	Coefficient (β)	Std. Error	t-Value	p-Value
Intercept	0.708	0.013	55.465	$<2 \times 10^{-16}$ ***
Altitude	0.002	0.000	10.729	1.73×10^{-15} ***
Income (Q4)	0.019	0.019	0.982	0.330
Adjusted R^2	0.701			
Model p-value	2.2×10^{-16}			

Note: *** indicates statistical significance at the 1% level.

These findings suggest that Barcelona’s geography acts as a behavioral equalizer across income groups. Although an electric divide exists, where the most expensive bicycles are predominantly used in high-income and high-altitude areas; therefore, this pattern is driven mainly by residential location rather than differences in preferences across income quartiles. In practical terms, when users face the challenge of steep uphill travel, individuals across all income levels choose electric bicycles at similar rates.

5. Discussion, Contribution, and Limitations

5.1. Methodological Component

Although this study specifically analyzes the Bicing system in Barcelona, the findings provide a broader framework for understanding bicycle-sharing behavior in cities facing similar geographical challenges. To ensure methodological consistency, the analysis was restricted to 2023 data for both income and bicycle usage. While Bicing operational data was available through 2025, the 2023 cutoff was necessary to align with the most recent official neighborhood-level income statistics provided by the Open Data Barcelona portal. This temporal alignment strengthens the validity of the socio-economic correlations by ensuring that both variables reflect the same urban context.

Regarding data quality, less than 2% of the raw dataset was removed during the cleaning process due to technical inconsistencies, missing values, or invalid observations. This proportion is statistically negligible, as quantitative research generally considers missing data rates below 5% unlikely to generate significant bias in statistical inference or compromise the robustness of the results.

A conceptual limitation of this analysis is the potential for endogenous residential location, where households select neighborhoods based on localized preferences. While the lower public transit density in Barcelona's affluent high-altitude neighborhoods (e.g., Pedralbes and Sarrià) suggests that residents are not choosing locations based on transit access, it remains highly likely that residents select these neighborhoods due to other premium amenities correlated with topography, such as larger housing stock, lower noise pollution, or scenic value. This pattern of residential self-selection creates a persistent endogeneity concern. While the immediate choice to use an electric bicycle over a mechanical one in high-altitude areas remains a functional necessity, the baseline decision to live in these areas might be tied to socio-economic privileges and lifestyle preferences. Consequently, we cannot fully decouple the physical necessity of the trip from the unobserved dynamics of the housing market, a limitation that future research using longitudinal household relocation data should address. A major methodological limitation of this research is the absence of publicly available data on manual rebalancing operations. Because the exact timestamps and locations of truck-based redistributions are omitted from the public registry, we cannot separate natural bicycle flows from operator interventions. Since operator-based motorized redistribution artificially increases bicycle availability in depleted stations, the natural topographic imbalance of the system is likely more severe than what is directly observed in the dataset. Therefore, the results presented in this study reflect net bicycle availability after rebalancing interventions, meaning that the structural service deficit identified in high-altitude areas persists despite active operator management. To address this limitation, the study prioritizes departures rather than arrivals as the principal indicator of user demand. This distinction is methodologically important. Arrivals in a BSS often reflect a combination of user behavior and operator rebalancing, while departures provide a cleaner measure of realized demand and actual user decision-making. By reducing the statistical noise introduced by truck-based redistribution, the analysis identifies a self-reinforcing operational imbalance in which high-altitude stations experience both lower bicycle availability and lower departure frequency. This confirms that service inequality in elevated neighborhoods is not a random fluctuation, but rather a predictable consequence of urban topography.

A notable econometric limitation is the potential for simultaneity bias regarding the electric bicycle ratio. Because the operator actively redistributes the fleet, more electric bicycles may be strategically delivered to high-altitude stations in anticipation of demand. This creates an endogeneity problem where the observed e-bike departure ratio could be partially driven by supply availability rather than pure user preference. While our focus on departures rather than arrivals mitigates some operational noise, and all sampled stations feature hybrid docks supporting both bike types, we cannot fully decouple operator behavior from user demand without proprietary rebalancing logs. Future research utilizing an instrumental variable (IV) approach would greatly strengthen the causal claims regarding topographic demand, if rebalancing operations data is available.

The data reveals a substantial reduction in departure frequency at high-altitude stations (6.92%) compared to low-altitude stations (10.67%). Importantly, this lower departure rate should not be interpreted as a lack of user interest in the service among residents of elevated neighborhoods. Instead, it reflects a condition of constrained or forced inactivity: users cannot begin trips because bicycles are systematically unavailable. In other words, observed departures measure realized demand, but not necessarily total demand. This distinction highlights another limitation of the study: the inability to directly measure latent demand. The absence of public rebalancing logs prevents precise estimation of the natural depletion rate of Bicing stations, while the exclusive reliance on departures may underestimate the true mobility demand in uphill neighborhoods. Future research incorporating user surveys, revealed preference analysis, and qualitative interviews would

be valuable for identifying how many potential users are forced to substitute other modes of transportation due to the unreliability of bicycle availability in high-altitude areas.

Furthermore, the regression model intentionally focuses on the interaction between altitude and income to address the spatial confounding underlying the electric divide. While this targeted approach explains a robust 70.1% of the variance in electric bicycle choice, it omits other influential built-environment variables such as a station's distance to the nearest metro stop, or bicycle lane density. Omitting these variables allows the model to show the actual effect of Barcelona's altitude and income. However, exploring how these additional infrastructure variables influence Bicing operational dynamics remains an important research point for future work.

Finally, the use of neighborhood-level income data ($n = 62$) to explain station-level behavior ($n = 511$), introduces the risk of ecological fallacy, which is, assuming that the average socioeconomic characteristics of a neighborhood apply uniformly to every individual user. While individual-level demographic profiling is not available, this aggregate approach remains highly valuable for identifying broad structural disparities across the urban canvas. However, readers should interpret these income findings as general neighborhood contextual conditions rather than direct measures of users' behavior. Neighborhood aggregation is appropriate for identifying broad spatial patterns, but it does not capture individual heterogeneity in preferences, income, age, gender, or professional mobility needs. Because the 62 aggregated neighborhood data points reduce the model's sensitivity to subtle variations in income, the statistical non-significance of it does not imply that it has zero impact. Instead, it demonstrates that income plays a minor role compared to the dominant influence of altitude, which explains the vast majority of the variance in electric bicycle choice.

5.2. The Altitude Gap and Sustainability Component

The results of this study confirm that altitude is the primary structural determinant of Bicing system performance. The strong negative correlation (-0.71) between altitude and bicycle availability indicates a condition of physical determinism: Barcelona's topography shapes bicycle availability more strongly than the operator's rebalancing efforts. While urban accessibility is traditionally measured through horizontal distance, such as walking distance to the nearest station, this study supports previous research suggesting that in coastal-mountain cities such as Barcelona, vertical distance is often the dominant constraint [21,22]. When interpreting these findings in light of broader literature, our results align with [11,23], who documented terrain slope as a major cause of directional trip asymmetries in systems like Lisbon.

This creates what can be described as an "altitude tax". Residents living in the high-altitude cluster (>65 m.a.s.l.) face a structural service deficit, with approximately a 40% lower probability of finding an available bicycle compared to residents in low-altitude neighborhoods, similar to what has been found in [11]. This is not a temporary fluctuation, but a persistent and systematic disadvantage that effectively limits access to the core benefits of the bicycle-sharing network, unlike patterns observed in flatter cities [6]. In this sense, topography functions as a hidden form of mobility inequality embedded within the urban environment.

The persistent disparity in bicycle availability between altitude clusters also raises important concerns regarding the operational strategy of the Bicing system. Currently, Bicing relies on motorized rebalancing trucks to redistribute bicycles across the network. Although these operations are not included in the public dataset, their limited effectiveness is reflected in the availability outcomes: low-altitude stations maintain an average availability ratio of 34.51%, while high-altitude stations remain at only 20.47%. This suggests

that the current rebalancing strategy is largely reactive and insufficient to compensate for the continuous downhill flow of bicycles. By the time a truck replenishes an uphill station, the next cycle of downhill trips may quickly deplete inventory again, preventing long-term equilibrium.

A major transparency limitation is that the system operator does not release detailed information on how frequently bicycles are moved by truck. This restricts the possibility of precisely quantifying the operational inefficiency of the network. However, by focusing on departure patterns rather than arrivals, this study demonstrates that high-altitude stations are empty not because of low demand, but because users naturally travel toward lower elevations and bicycles are not returned at the same rate. This confirms that the service gap in elevated areas is fundamentally a chronic supply failure rather than a lack of user interest.

These findings also carry out direct sustainability implications. Every time a bicycle must be transported by truck instead of being ridden by a user, the environmental value of the BSS is reduced. If a substantial share of bicycle availability in high-altitude neighborhoods depends on fossil-fuel-based redistribution, then the effective carbon footprint of the Bicing system in these areas becomes significantly higher than in flatter zones. In addition, residents in elevated neighborhoods (despite paying the same subscription fee) are more frequently pushed toward less sustainable transport alternatives due to unreliable bicycle access. This undermines both the environmental and social equity objectives that define sustainable urban mobility policy.

5.3. Urban Policy Component

A central contribution of this research is the clarification of the so-called electric divide. Initial bivariate analyses (ANOVA and Tukey tests) suggested the existence of a socio-economic gap, where the highest-income quartile (Q4) appeared to exhibit a significantly stronger preference for electric bicycles. This preliminary finding aligns with a substantial body of micro-mobility literature, such as [17,27,28] which frequently warns that shared e-mobility acts as a luxury asset, disproportionately captured by high-income residents with a higher willingness to pay. However, the multiple regression model provides a critical correction: once altitude is controlled for, income ceases to be a statistically significant predictor of electric bicycle usage. The apparent income-based electric divide is therefore revealed to be a statistical artifact generated by spatial confounding; because Barcelona's high-income residents are concentrated in elevated neighborhoods, their e-bike adoption has been misattributed to economic status rather than topographic necessity.

The physical challenge of uphill travel, rather than purchasing power alone, is the dominant factor driving technological choice. While prior global comparative research [3,6] recognized that topographically complex environments suffer from sharp intra-urban service disparities, they did not control for how these topographically barriers interact with neighborhood income sorting. By isolating these variables, this study challenges the conventional consensus that e-bike adoption in public bicycle-sharing systems is driven by discretionary lifestyle preferences or greater technological affinity among high-income users. Instead, the physical challenge of uphill travel is the decisive factor driving technological choice, regardless of whether a trip originates in a high-income district like Pedralbes or a lower-income neighborhood at an equivalent elevation.

Consequently, this study redefines the conceptual boundary of the “electric divide” by anchoring it within Amartya Sen's Capability Approach [31]. Rather than interpreting the e-bike as an elective luxury good, it must be understood as a necessary mobility technology required to maintain baseline geographical equity for residents living in elevated neighborhoods. Deploying a higher ratio of e-bikes uphill is not preferential treatment for high-income neighborhoods, but a functional requirement for service efficiency. This

theoretical shift has direct, practical implications for infrastructure planning and pricing policy. Urban planners can use this evidence to make more efficient decisions regarding the placement of Bicing stations, while system operators can optimize rebalancing strategies specifically to counteract topographic disadvantages. More broadly, this research suggests that the concept of the electric divide should be reconsidered in cities with geographic characteristics similar to Barcelona. Rather than reflecting behavioral differences between income groups, the divide is largely a consequence of residential location and urban form.

However, an important policy challenge remains. If electrification becomes the primary mechanism for ensuring accessibility in high-altitude neighborhoods, BSS operators and policymakers must ensure that this infrastructure remains financially accessible to all residents. Without appropriate pricing strategies, subsidies, or equitable access policies, electric mobility may unintentionally reproduce new forms of exclusion, even while solving the topographical barriers of the system. Two concrete interventions can be proposed:

- Modify the pricing structure to introduce user-centered rebalancing incentives. Under the current Flat Rate Plan, choosing an electric bicycle incurs a €0.40 surcharge for the first 30 min; however, this fee might be entirely removed for users who use an e-bike at a low-altitude station and return it to a high-altitude station, turning commuters into a decentralized, zero-emission rebalancing network. A feasible implementation example could involve a pilot incentive program at selected low-to-high altitude commuting corridors. For instance, operators could temporarily waive the €0.40 surcharge for users who relocate e-bikes uphill during peak commuting periods. Given the current surcharge structure, the financial cost of such an intervention would remain relatively limited while potentially reducing operational rebalancing expenses associated with manual bicycle redistribution. A short-term pilot could therefore help assess whether user-driven rebalancing improves system efficiency and accessibility in topographically disadvantaged areas.
- Prioritization of targeted charging capacity. High-altitude stations experience an average electric bicycle departure ratio of 86.78%. Because all network stations feature hybrid docks, the operator should prioritize upgrading, repairing and maintaining the active power grid connection at these specific uphill locations, ensuring that the few bicycles returned uphill are quickly recharged and rotated back into service.

6. Conclusions

This study demonstrates that topography is the fundamental structural driver of Bicing system performance and electric bicycle adoption in Barcelona. The results confirm that station altitude is a primary determinant of bicycle availability, generating a persistent service deficit in the city's high-altitude neighborhoods. Users exhibit a clear downhill bias, where the physical effort associated with uphill travel acts as a barrier to returning bicycles (particularly mechanical bicycles) to elevated areas. As a consequence, high-altitude stations experience chronic shortages and lower departure rates, creating a self-reinforcing cycle of reduced accessibility and weaker system performance.

Although income shows a moderate correlation with altitude, indicating that many of the highest-income neighborhoods (quartile 4) are concentrated in elevated areas, the most important finding of this study is that income does not independently explain electric bicycle usage. Once altitude is controlled for in the multiple regression model, the apparent electric divide disappears as a socio-economic preference. The adoption of electric bicycles is primarily driven by physical necessity rather than by income. Users across all income groups choose electric bicycles at similar rates when facing the same topographic constraint, namely, uphill travel.

These findings have important implications for both the environmental and social sustainability of the Bicing system. The current rebalancing strategy, which relies heavily on motorized trucks to compensate for topographic imbalances, is insufficient to maintain service equity across the city. Every truck-based redistribution reduces the environmental value of the system by increasing the effective carbon footprint of bicycle sharing, particularly in high-altitude zones where rebalancing demand is greatest. At the same time, the existence of an “altitude tax” creates a clear social sustainability gap. When bicycle availability becomes unreliable, residents in elevated neighborhoods are systematically pushed toward less sustainable transportation alternatives, such as private cars, motorcycles, or ride-hailing services. This undermines the broader objective of equitable access to sustainable urban mobility. To achieve genuine sustainability, Bicing should move from reactive truck-based redistribution toward a more active and user-centered rebalancing strategy. Expanding the electric bicycle fleet and creating incentives for uphill returns would allow users themselves to function as a decentralized rebalancing mechanism, reducing operational emissions while improving service equity across neighborhoods.

Future research should incorporate a multimodal perspective to examine how the quality and accessibility of alternative transport modes, such as metro, bus, and private mobility options, influence Bicing usage in high-altitude neighborhoods. Additionally, analyzing trip purpose (for instance, commuting versus leisure travel) could help explain why some high-income, low-altitude neighborhoods such as Diagonal Mar exhibit high levels of electric bicycle usage despite lacking the same physical necessity observed in elevated zones. Moreover, further research using anonymized individual-level trip data would also allow for a more precise understanding of how demographic characteristics such as age, gender, and occupation interact with urban topography and shape bicycle-sharing behavior. In addition, while this study uses data from Barcelona to isolate the relationship between geography and income, future research should expand this framework into a multi-city comparative analysis. Finally, greater transparency regarding rebalancing schedules and operational logistics would enable future studies to model bicycle depletion patterns more accurately, evaluate the true efficiency of redistribution strategies, and optimize truck routes from both operational and environmental perspectives.

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