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Are We Back to Normal? A Bike Sharing Systems Mobility Analysis in the Post-COVID-19 Era

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Abstract: In recent years, numerous cities around the world have adopted bike sharing systems (BSSs). The increasing popularity of these transportation means is directly related to their eco-friendly and health advantages. Several factors affect how citizens make use of BSS, for instance, the size and configuration of a city, where docking stations are located, the associated prices, and others. Moreover, these systems have different usage patterns that vary according to the month, day, or hour but remain constant when compared yearly. However, the onset of the COVID-19 pandemic modified mobility behaviors as various governments around the world implemented mobility restrictions to avoid the spread of the virus. The objective of this investigation is to determine if the usage patterns of BSSs have changed permanently or if we have recovered pre-pandemic levels and usage patterns. Given the special characteristics of each BSS, this study focuses on Barcelona's BSS, called Bicing. To understand the impact of other BSSs, the further analysis of each system's unique characteristics is necessary. The study employs bike usage information from the public open data service maintained by Barcelona City Hall, namely, the Open Data BCN website, from January 2019 to December 2023, and it covers mechanical and electrical bikes with more than 4 million records per month. The results show that usage patterns were similar before and after the pandemic; the usage increased in 2021 and 2022 and stabilized in 2023, registering a rise of 17.5% in Bicing usage from 2021 to 2023. However, bike type preferences have changed for reasons unrelated to the pandemic restrictions. The main limitation of this investigation is the lack of continuity in the data due to a change in the company that provides the service in Barcelona. For future research, data from other transportation means can be used to analyze all communication behavior in this city. Additionally, if data are available, a study by gender and age can be performed and used to improve the system for certain groups.

Keywords: bicycle sharing systems (BSSs); Bicing; COVID-19 mobility restrictions; inclusive transport system; BSS usage patterns

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1. Introduction

In 1965, bike sharing systems (BSSs) started as a public service program named "white bike" in Amsterdam [1]. These systems were initially provided by local community organizations and currently have become a popular transportation mode thanks to their multiple benefits. BSSs not only provide advantages in the economic sector but also in the social and health aspects of local communities where they have been implemented. Moreover, BSSs contribute to reducing pollution, avoiding traffic congestion, and can be used as a low-cost transportation mode that is environmentally friendly [2–4]. An important aspect that has made this transportation system relevant in the latest years is its flexibility, as there are no fixed routes or scheduled times; therefore, these systems can be adapted to customer travel needs. Zheng and Li (2020) [5] mentioned that BSSs are often implemented as a tool for sustainable transport initiatives to reduce pollution, improve the travel experience and choices, and improve and achieve the strategic goals for the public transport network in a nation. BSSs have been deployed in many large cities around the world, but small and medium cities are also adopting this novel transportation mode. In fact, according to [2], there are approximately 1700 BSS worldwide of different types (public, private, dockless) and of different sizes. These systems have been traditionally used as a replacement for other transportation modes for short- to medium-distance trips, also called last-mile (or first-mile) connections. BSSs are generally complemented with web services or mobile applications where customers of the system can check the status and book bikes for their rides. System operators and managers of BSSs are also interested in the analysis of BSS data to improve the system, as BSSs are an important tool for the construction of sustainable cities due to their impact on the reduction in carbon footprint, their accessible prices, and lower risks compared to owning a bike.

The characteristics of the city, its size, and the "urban configuration" have a big influence on how BSSs are being used [6]. For example, stations with more bike paths close by tend to be used more often [7], as well as those stations that are close to central business districts or with high job or population densities. Other variables such as the size of the system (small, medium, or large), the quality of data, and the type of user (manager, system operator, or regular customer) are also key factors to consider. Given that the characteristics of each BSS varies according to the city where it is located, and the aforementioned variables, we have concentrated on the Barcelona BSS, called Bicing. Barcelona is one of the most touristic cities in Spain, with a population of more than 1.6 million inhabitants. Its BSS opened in 2007, and it has a medium-sized system with more than 500 fixed docking stations around the city. Barcelona has warm Mediterranean weather characterized by soft winters, which can positively influence bike rides, as mentioned by previous studies [8–10]. The data available for Bicing are reliable and of good quality as they are provided by an open data website, as in many other large cities. Finally, considering the type of user, this study focuses on managers and system operators as they can use the outputs of this investigation to understand the commuting patterns in Barcelona before and after the pandemic.

Another key factor to mention in this study is the COVID-19 pandemic and the measures adopted by different governments to control the spread of the virus. The COVID-19 pandemic modified the travel behavior (ways of making trips, places, and frequency) of citizens given the travel restrictions and the suggestion of staying at home, which decreased population movement and dropped the ridership levels of public transit systems. Moreover, many COVID-19 safety measures were implemented in transit spaces, such as the introduction of mandatory face masks, floor and seat markers defining physical distancing, and provision of hand sanitizing materials [11], All these measures were accompanied by emotional responses related to the individual's transportation mode choice given the perception of risk when they shared the transportation mode instead of a private mode [12]. Therefore, BSSs resulted in alternative mechanisms for secure transportation during and later on in the COVID-19 pandemic.

Without any doubt, COVID-19 and all the related measures adopted during the peak of the pandemic have changed many habits for the whole society as we had to quickly adapt to a new situation. The mobility restrictions benefit for the environment was evident in the short term, as mobility patterns reached a minimum during the first month after COVID-19 was declared a pandemic. However, greener transportation modes such as BSSs were also affected. After some of the mobility restrictions were lifted, the world population still had to face other types of measures (face mask use, crowd avoidance, use of hand sanitizing materials) that indirectly affected the use of certain public transportation means.

The main objective of this study is to provide a deep analysis of the usage patterns in the Barcelona BSS known as Bicing before and after the pandemic. The study focuses on a descriptive analysis and visual exploration of the commuting trips made from 2019 to 2023 with different levels of disaggregation and employs a *t*-test to prove if the means between different years are different. The results show consistent usage patterns pre- and post-pandemic, with a notable increase in usage during 2021 and 2022 followed by stabilization in 2023. Moreover, shifts in bike type preferences occurred independently from pandemic-related restrictions. The output of this study can be used by system operators, policymakers, and managers of BSSs to improve the system and motivate regular customers to embrace this type of transport-sharing system, contributing, in the long term, to reducing air pollution and having a greener city.

The remainder of the article is organized as follows. Section 2 presents the literature review and describes the hypothesis development, Section 3 focuses on the data collection and processing and the methodology description, Section 4 presents the empirical findings and discussion. Finally, Section 5 contains the main conclusions.

2. Theory and Hypotheses

2.1. Bike Sharing Systems Analysis

The analysis of BSS data can be performed to fulfill different purposes. One of the main concerns of system operators is to increase customer satisfaction by actively rebalancing the system. This way there should be enough bicycles for rent and docks available to drop off the bikes after their use. Therefore, several authors have concentrated on analyzing effective vehicle routes between stations to optimize the balancing operations [13–15] and smart traffic control [16]. Another area of investigation has been how the influence of urban configuration can affect bike demand. Different authors have investigated how the features and services around bike stations [6,7], the connection with other transportation modes [17], or the elevation of the cities [8,18] can influence the usage of BSS. For the case of Barcelona, [19] have demonstrated, using a visual tool, that stations located in the upper part of Barcelona are used to go downhill; therefore, they are empty most of the day if no balancing operation is performed.

Another area that has been deeply analyzed is the traffic patterns and the characteristics of the trips. For example, several authors found that weather has a big influence on BSS usage, winter months being the ones with fewer trips while spring and summer usually have higher bike demand [8–10]. Moreover, bike traffic patterns can also vary during the day. Some systems like BIXI in Montreal are used more often during the afternoons [6], while others present early morning and afternoon peaks [17]. Bike trips are also different when comparing weekdays versus weekends [17,20,21]. This can happen as during weekdays, bike trips are related to commuting trips while during weekends, bike usage is more recreational. The type of user (occasional or regular) [10], the age, gender, or educational level [22] can also influence BSS trends. The case of gender and age analysis is particularly interesting as there is no consensus. Many studies have found that women tend to make fewer trips than men [23,24]. However, some other authors did not find significant differences between the trips made by both genders [7,25]. When analyzing the age, results show that men older than 34 years old make more trips [7,22]. Unfortunately, information about the customers of Bicing was not available to perform this type of investigation. However, if data are available, it opens new lines of investigation. Other factors such as built environment and land use, public transportation, or socio-demographic attributes have also been analyzed and summarized in Eren and Uz's study [26]. They concluded that bike demand is mainly affected by rainy weather, which had a negative effect in almost all studies. However, other factors that influence bike demand are not clear.

Clustering stations to understand their common patterns and facilitate the rebalancing operations has also been analyzed in several investigations [19,27–29]. The analysis of BSS traffic patterns has evolved to the prediction of trip destination and duration [30] and the forecasting of bike demand by using different machine learning models, such as linear regression [31,32], multiple additive regression trees [30], or generalized ordered response [22]. The authors have tested prediction algorithms for different scenarios, for instance, demand forecast at cluster level [33], at station level [34], in small cities [35], and in large cities [36,37]. Different models have also been tested with the same BSS to evaluate its performance [9,36,38] or the features that influence bike demand [26,39–41]. In the case of the Barcelona BSS, Bicing, [27] have analyzed the data and compared four prediction models, while [42] have predicted the status (empty, almost empty, bikes and slot available, almost full, and full) in the Barcelona BSS system. The authors of [43] have also studied the performance of different forecasting methods in Barcelona, Logroño, and New York BSSs.

The visual analysis of the BSS data has been also widely studied in the latest years, in some cases as static views [10,44] or as fully dynamic tools [2,19,45]. The individual customers' journey has been studied to understand the commuting behaviors [46]. Other authors focused on the study of multiple BSS systems [2,47,48] to be able to identify the characteristics that define the demand for bikes. The influence of other transportation modes has been also investigated [29,49], as well as clusters of stations with similar usage patterns [28,44]. For the selected BSS in this study, Bicing, ref. [27] analyzed 13 weeks of data and 370 docking stations to understand the usage patterns during weekdays. Its analysis revealed an increase in usage during morning, lunch, and evening. Similar results were found in [19,45]'s studies. However, this research focused on creating visualization tools that help managers, system operators, and regular customers of Bicing to explore the data and create their conclusions. In these Bicing studies, the data employed do not reflect any possible changes in commuting behavior due to COVID-19 measures, as the selected data period is different from the one proposed in this study.

The COVID-19 pandemic had a big influence on the urban transportation system due to the travel restrictions to reduce the spread of the virus around the world. Ref. [50] mentioned that a fifth of the virus' propagation occurs when using public transportation. Therefore, transport alternatives that reduce face-to-face contact can help contain the virus, promoting BBSs as a resilient and sustainable transportation mode with physical distance, supporting the premise of cycling as an important, versatile, and flexible method of transportation with a significant role in meeting the need of mobility [51]. Several studies have been conducted to understand the impact of COVID-19 restrictions on urban mobility. These investigations show that each public transport mode was affected to a different degree: public transport like the metro or bus had a drastic decrease in demand [52], while cycling activities increased. For example, the Budapest [53] BSS was affected to a lower degree than other public transportation modes. In Thessaloniki (Greece) [54], a survey among users demonstrated that even when the COVID-19 measures did not substantially affect the number of bike trips, this transportation mode became more attractive for users. A literature review work carried out by Rotaris et al. [52] showed that bike trips were reduced at the initial phase of the pandemic. However, when the lockdown measures were gradually lifted, bike rides increased but the usage patterns were changed. For instance, bike rides were longer in time and leisure trips increased, especially on weekends. This rebound in the number of trips after the lockdown measures were lifted has also been mentioned by other authors in [55,56].

In some cases, and depending on the period of analysis, the number of trips has reached or exceeded the pre-pandemic levels of usage [57,58]. For Barcelona, Bustamante et al. [59] analyzed data from 24 June to 31 December of 2019 and 2020 and discovered that the total number of trips increased in 2020. However, this can also be explained by more docking stations being available in 2020. These authors also used a set of relevant features to predict the use of Bicing and demonstrated that before and after the pandemic variables like bike-related built infrastructure, trip distance, and the income levels of neighborhood residents were the most relevant. In Valencia (Spain), Seifert et al. [60] analyzed a sample of 4355 regular commuters of Valencia's BSS to understand the changes in their usage behavior. Their results showed a reduction of approximately 40% in bike rides during the pandemic that started to recover at the end of 2020 without reaching pre-pandemic levels. This manuscript shares with these authors the goal of describing and analyzing the changes in bike rides caused by the lockdown measures of the COVID-19 pandemic. However, this study analyzes different data granularity and a longer period to understand pre-pandemic levels and long-term changes in the Barcelona BSS.

2.2. Barcelona Bike Sharing System Description

The Barcelona urban mobility plan (PMU) [61] was designed to evolve the urban space and contribute to having a city where residents have several transport modes (private car, bus, metro, train, tram, and bikes) that coexist together. At the same time, the citizens benefit from a more efficient, safer, and healthier model of mobility that promotes public transport, focusing on walking and cycling. Bicing is the public bicycle sharing system in Barcelona (Spain) that was inaugurated in 2007, and since then, it has provided a low-cost bike rental service. It was initially operated by Clear Channel until 2018; since 2019, Pedalem Barcelona has been the company responsible for providing the service under the supervision of the public company Barcelona de Serveis Municipals (BSM). Currently, there are 519 fixed docking stations distributed around the city for approximately 4000 mechanical bikes and 3000 electrical bikes. Figure 1 displays the Bicing docking stations around Barcelona.

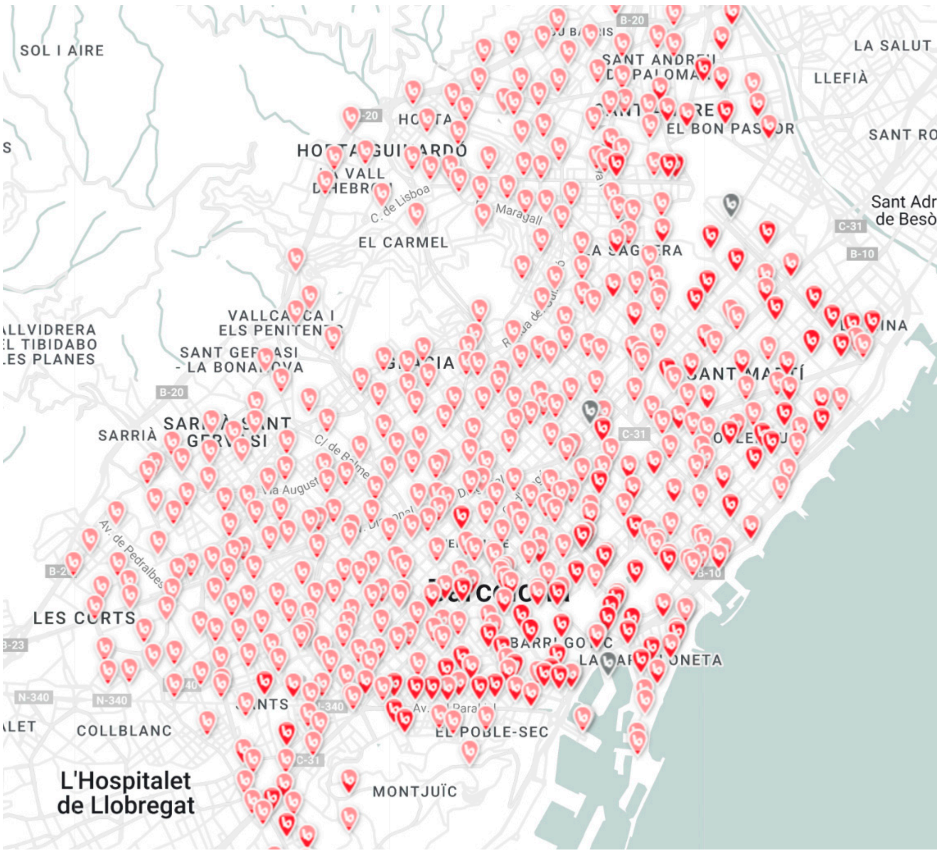

Figure 1. Bicing docking stations. Source: bicing.barcelona webpage.

All docking stations in Bicing support both mechanical and electrical bikes, giving customers the freedom to rent and drop off bikes in any part of the city. Bicing users can rent a bike in any station in the city using their Bicing card, mobile app, or smartphone with near field communication (NFC) and return it to the same or any other station with available docks. Only residents in Barcelona older than 16 years old can use the service. The price varies according to the selected subscription. For frequent users, there is a subscription called "Plain", and for occasional customers, the "Payment by use" subscription. In the first case, the use of mechanical bikes is free for the first 30 min, after which there is a cost of 0.70 euros during the first 2 h and 5 euros per hour if it exceeds the 2 h of use. For electrical bikes, the first 30 min cost 0.35 euros, 0.90 euros for up to 2 h of use, and 5 euros per hour for more than 2 h of renting. The cost of this plan is 50 euros per year. The second subscription plan costs 35 euros per year and has the same prices for both types of bikes when the use exceeds 30 min. For the first 30 min of use, the cost is 0.35 euros for mechanical and 0.55 euros for electrical bikes [62].

Unfortunately, there is no information about the type of user, and an analysis that includes this information is not possible to perform in this study. However, there is information concerning bike type that allows an understanding of the price influence on bike type selection.

Barcelona is also a friendly city for cycling. Most of the city is designed to provide spaces that are suitable for cycling. According to Barcelona City Hall, this city has nearly 1150 km of cycling routes [63]. If only the bike lane network is considered, the City Hall's objective is to provide 95% of permanent residents with a bike lane in a 300-m radio from their homes [63]. In fact, since 2015, the bike lane infrastructure has doubled its size, and the target for 2023 was to reach 272.6 km in the bike lane network. Figure 2 displays the bike lane network in 2023. Considering the bike-related infrastructure, [59] mentioned that bike lanes and bike-friendly streets have increased in 2020, and a maximum speed limit of 30 km/hour has been set in certain populated neighborhoods.

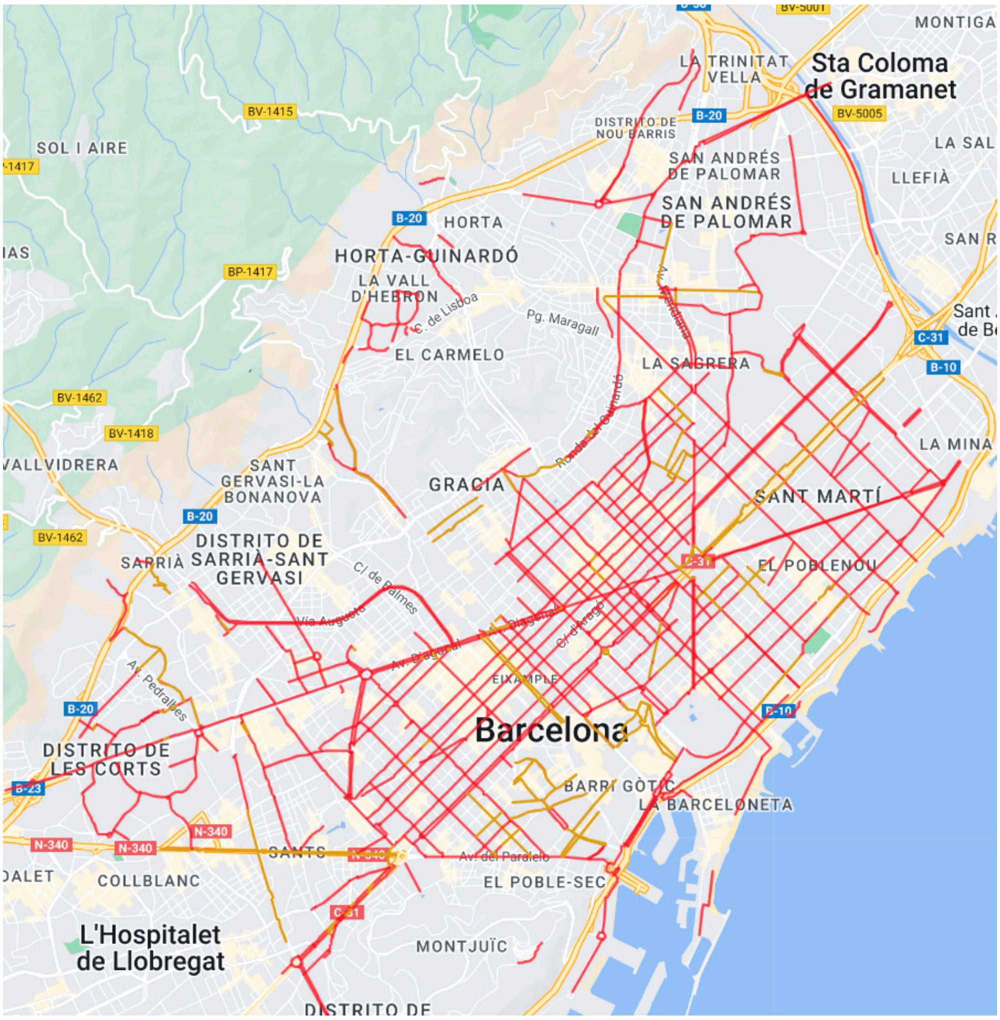

Figure 2. Barcelona's bike lane network in 2023. Source: Barcelona.cat webpage.

2.3. COVID-19 Measures in Barcelona

During 2020, as an impact from the COVID-19 pandemic, several mobility restrictions were imposed in Barcelona and in all of Spain to prevent the spread of the virus. During the third weekend of March, around 14 March 2020, the official lockdown measures started and reached a historical minimum in mobility from 30 March to 6 April [64]. All these restrictions affected mobility and the use of all transportation networks, including BSS. The Bicing system was closed during this period.

The Generalitat de Catalunya [64] described two types of mobility restrictions: One, called forced, that was mainly related to job mobility, as remote work was imposed in all sectors, except on those considered essential. The second one, called non-forced, was related to recreational activities. The lockdown lifting was carried out gradually and in phases, starting on 13 April 2020 [64], and the force mobility started to recover, but the non-forced restrictions maintained their pandemic levels. During the week of 29 July 2020, without any further official lockdown measures, both types of mobility recovered almost their "normal" levels, which means their levels previous to the pandemic. However, there were still other measures such as the mandatory use of masks and the maximum number of people that could be together in certain areas like gyms, health centers, and other spaces. All these restrictions influenced in an indirect manner the mobility and the use of certain transportation systems, as people preferred to use private cars or stay at home. The uncertainty of the virus spread, the job losses, and the remote work affected citizens' habits, schedules, organization, recreational activities, and in general, their mobility patterns.

On 29 October 2020, new mobility restrictions were imposed due to the increase in COVID-19 cases. This situation caused a decrease in non-forced mobility close to the levels seen in March 2020 [64]. These restrictions lasted until January 2021. However, they were a bit more relaxed during Christmas and New Year's festivities. Going forward to 2021, in October, there were still restrictions not in the mobility area but in social interaction. For example, the mandatory use of masks, security distance in bars or restaurants, the limited number of people allowed in public or private events, or the prohibition of attending certain events without the complete COVID-19 vaccination [65]. Without any doubt, citizens were afraid to get sick. This situation and all the policies applied to avoid the spread of the virus affected in an indirect manner mobility and the use of BSS. However, these effects on mobility were only seen during the period of lockdown, and according to different studies [51,66–68], these effects disappeared after COVID-19 measures were lifted.

Considering that, the hypotheses of the study are the following:

H1. *There are no significant differences in Bicing usage patterns during and after the COVID-19 pandemic.*

H2. *Bicing recovered its pre-pandemic usage levels by 2023.*

The transition of service providers for Bicing during 2019 led to a series of disruptions as stations were replaced, making the usage patterns of that year atypical. As such, relying on 2019 data for pre-pandemic benchmarks is not advisable. Instead, comparisons for usage patterns during and post-COVID-19 were used in this study.

3. Research Methodology

3.1. Commuting Trips in Barcelona

Commuting trip patterns provide crucial information for urban planning and sustainable development. Barcelona's case showed that its commuting habits made a shift over the past few years moving into sustainable transportation means. In 2019, the commuting patterns were dominated by traditional modes of transportation such as private vehicle usage (60% of all trips) with a small percentage combination of public transportation (public transit system: buses, metro, and trams), cycling (30%), and walking (10%) [69]. However, the COVID-19 pandemic significantly impacted commuting patterns in Barcelona, showing a notable decrease in the number of daily commuters, given the work-from-home measure employed for the majority of citizens, while the use of bicycles and other sustainable modes of transportation rose. In 2021, as the pandemic continued, Barcelona implemented various measures to promote sustainable transportation, such as the introduction of the on-demand bus service or demand responsive transport, allowing passengers to request buses in real-time and optimize routes based on passenger demand [70]. Moreover, the usage of public transportation increased by 12% from 2019 to 2021, given the implementation of dedicated bus lanes and the improved metro connectivity, while the Bicing system contributed to a 7% reduction in private vehicle usage for commuting purposes [69]. From 2022 to 2024, Barcelona showed a gradual return to pre-pandemic commuting patterns. The shift to normality includes the continued usage of sustainable transportation as public service transport and cycling paid off.

3.2. Data Collection

As mentioned before, this analysis is based on data from the Barcelona BSS called Bicing. The information is available in a public open data service maintained by Barcelona City Hall, named Open Data BCN [71]. To understand the trends and patterns of Bicing trips before and after the COVID-19 mobility restrictions, the data collection period is from January 2019 to December 2023. However, the analysis can be influenced for the following reasons:

- The company that provided the bike service in Barcelona was changed in 2019. This change took place gradually from March 2019. The bikes were replaced, and the stations resized during 2019, causing a lack of continuity in the data. The service was also affected as some stations were closed for a few days during this change.
- With the previous company operator, there were specific stations where Bicing users could rent electrical bikes, while others were used only for mechanical bikes. This situation changed with the new company as the current stations can support both types of bikes.

3.3. Data Processing

Data processing, cleaning, and preparation procedures were performed in R version 3.6.3, using a Windows 10 machine with an Intel Core i5-6200U CPU, 2.30 GHz, 16GB RAM.

The bike usage information is used for this study. The data from the previous period are uploaded to the Open Data BCN website at the beginning of each month. Each monthly file can contain more than 4 million records since data collection occurs approximately every 5 min. The variables in each file could vary depending on the year, but common variables used to clean and process the data are listed in Table 1.

Table 1. Dataset description.

Variables	Type of Variable
Station ID	String
Total number of bikes (mechanical and electrical) available	Numerical
Mechanical bikes available	Numerical
Electrical bikes available	Numerical
Docks available	Numerical
Date and hour when the information was captured	Datetime
If the station can charge electrical bikes (1 or 0)	Dummy
If the station is properly installed (1 or 0)	Dummy
If the station provided bikes without problems (1 or 0)	Dummy
If bikes can be properly returned to the station (1 or 0)	Dummy
Station status (in service or closed)	Dummy

Docking stations that appeared in the dataset but were not being used were removed, as well as those stations that were not working properly or were closed (less than 2% of the total data set). Garbled data like dates outside the selected period, negative data availability, or stations without data were also filtered (less than 1% of data). Missing information was not imputed, as the study focuses on understanding the commuting patterns in Barcelona, and imputing data can lead to misinterpretation of the patterns. Additional extra information was derived to develop the descriptive analysis. For example, the day of the week, month, time interval, and the total number of trips and by which bike type (electrical or mechanical).

3.4. Methodology

The study employs the *t*-test for equality of means for several combinations of pairs of variables. The *t*-test is a statistical hypothesis test used to check if there is a significant difference between two groups. Its null hypothesis indicates that the two groups considered are equal. If it is rejected, one can say that both groups have a high probability of being different. Moreover, the groups to be compared in this study were considered to be different populations; therefore, a two-tailed test was performed. The null hypothesis is accepted if the *t*-test values are significant. In this case, the *t*-score (see Equation (1)) is compared against the Student's *t*-table to determine if the *t*-score is greater than the expected value. Another way to reject the null hypothesis or not is using the *p*-value when this is lower than the critical value considered. A critical value of 0.05 is generally accepted. More information can be found in [72].

$$t\text{-score} = \frac{\overline{Y_1} - \overline{Y_2}}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \quad (1)$$

where N_1 and N_2 are the sample sizes, $\overline{Y_1}$ and $\overline{Y_2}$ are the sample means, and s_1^2 and s_2^2 are the sample variances.

4. Results and Discussion

In this section, the descriptive analysis of the trips taken during the period 2019–2023 is reported. During the whole period, there is a continuous growth in the Bicing trips, as is shown in Figure 3. The trips in 2020 increased 9.5% compared with 2019 (less than 1 million trips). The previous studies have also found similar patterns, i.e., the number of trips reached and increased pre-pandemic levels [52,55,56]. However, as we mentioned before, in Barcelona, this can also be influenced by the change in the operator, resulting in some stations being closed for periods during this transition and affecting the commuting behavior of customers of the Bicing system during 2019. From 2020 to 2021, there is a clear increase in the number of trips (31%), or approximately 2 million trips during that period. This is the biggest percentage increase during the period considered, followed by the increase in 2022 (16%). During 2023, trips seem to stabilize as the number of bike rentals is similar to the previous year, only increasing by 1%. When looking at the type of bikes being used, the patterns presented a clear transformation. The use of electric bikes has constantly increased while mechanical bike use has dropped. Since 2022, electric bikes have been the most popular means of transportation in this BSS. This difference is more notorious in 2023, when users took more than 2 million trips on electrical bikes compared to mechanical bikes.

Figure 4 displays the total number of trips by month during the selected period, while Figure 5 shows the monthly trips by type of bike. Analyzing the data from 2019 and 2020 does not show a clear pattern. In 2019, the trips dropped during the first months and increased from April, reaching a peak in October. This can be explained by the change in the company that operated the service, as mentioned in the last section. During 2020, the usage behavior was also abnormal due to the COVID-19 mobility restrictions and additional measures adopted by the Spanish government. There was a drop between February and April 2020 that coincided with the lockdown measures imposed during these months. A similar situation was experimented with by other BSSs in Spain, as mentioned in [60]. The service started to recover after this but had other usage reductions that also matched with the periods when the COVID-19 cases were increasing, and new measures were adopted [64]. However, as mentioned in [59], bike rides in the second semester of 2020 were higher than in 2019. On the other hand, trips made from 2021 to 2023 showed a different pattern. They usually increased at the beginning of the year but dropped in April, to rise again in May and start slowly decreasing until August. Another usage peak was reached in October to start decreasing again during winter. These patterns were related to variations in weather and seasons. As explained by previous investigations [8–10], the usage behavior tends to decrease during winter months and in the hottest months of summer. Rainy days are also a variable that negatively affects the number of trips. An interesting finding was the drop in the number of trips in August 2023. Unfortunately, we could not find any information about the reason for this usage drop.

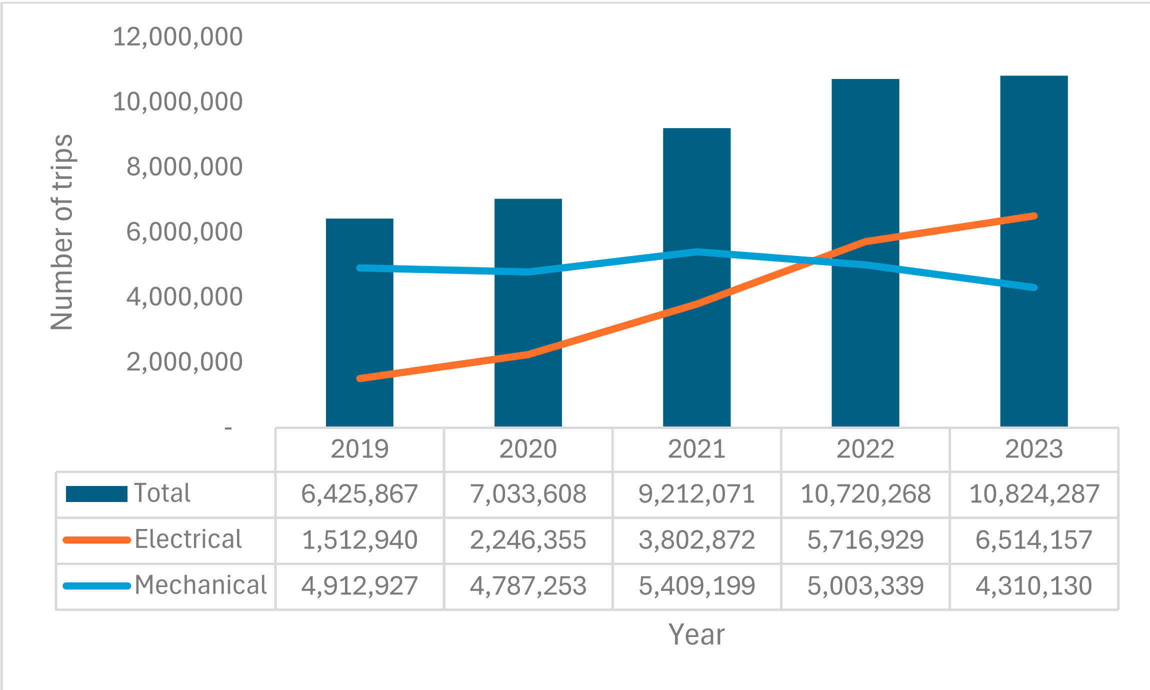

Figure 3. Bicing: Yearly trips by bike type, period: 2019–2023.

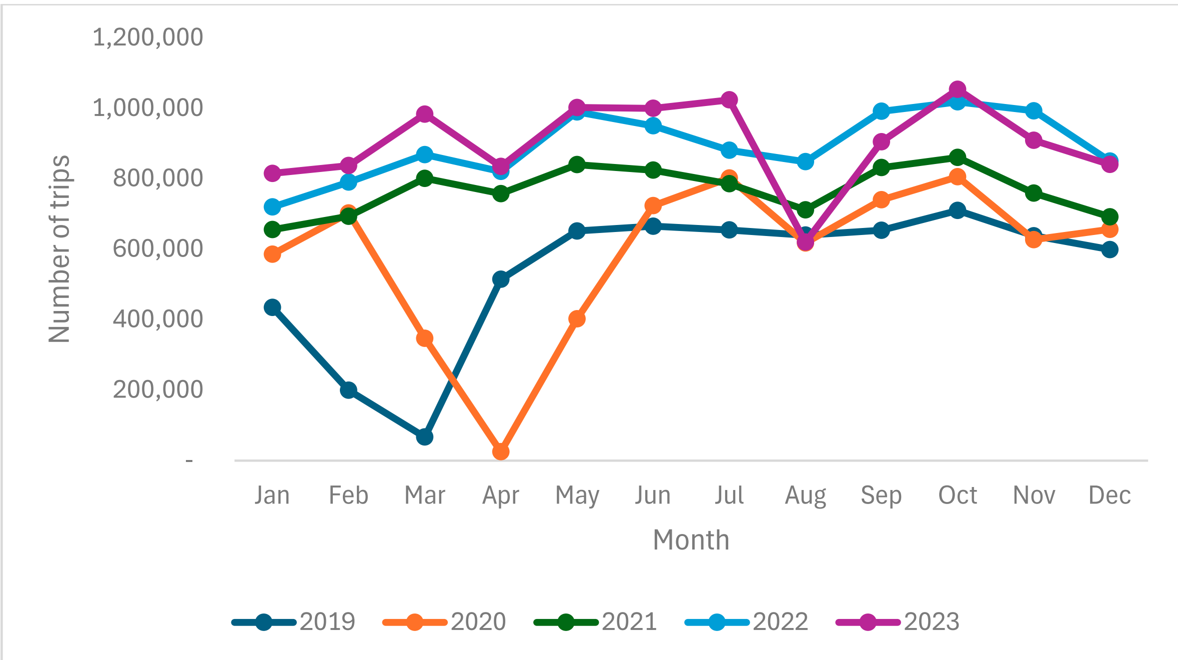

Figure 4. Bicing: Total trips by month, period: 2019–2023.

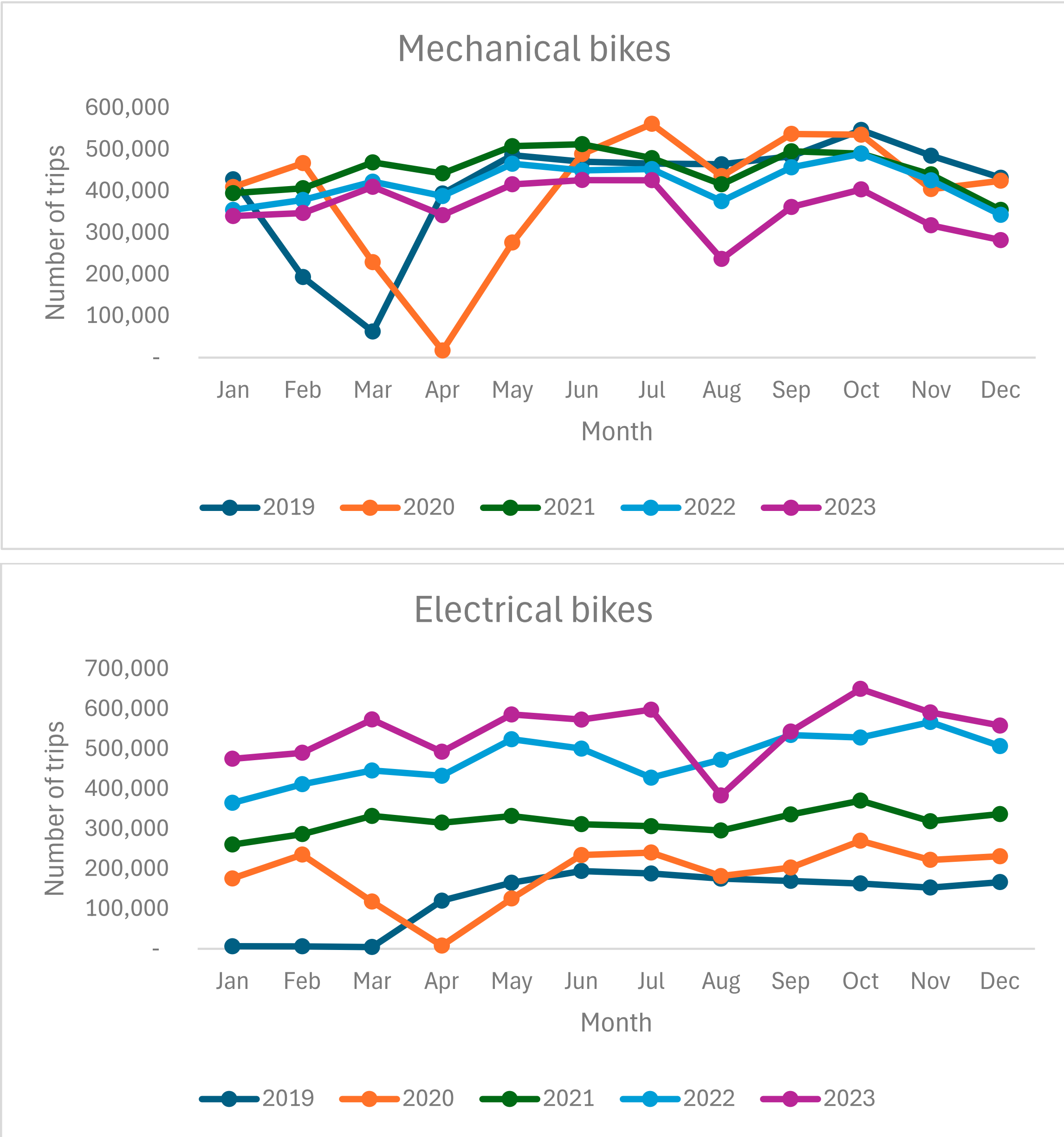

Figure 5. Bicing: Total trips by month and bike type, period: 2019–2023.

The analysis of monthly trips (Figure 5) by bike type also showed a similar pattern as the total number of trips (Figure 4). However, there was a clear difference in the number of trips made with mechanical and electrical bikes. The usage of mechanical bikes has decreased in the last years; 2021 was the year with the highest number of trips taken on this type of bike, and a minimum was reached during all months of 2023. On the other hand, trips made with electric bikes constantly increased each year, reaching a maximum in all months of 2023, except August. This can be explained by the change in the company operator that manages the system. Before this change, the number of electrical bikes was lower and users only had the option to drop off the bikes at certain selected stations adapted for electrical bikes, which were limited around the city. With the change in the company operator, all docking stations were replaced to support both types of bikes and users had more flexibility to rent and drop off electrical bikes in any station in Bicing. Considering that Barcelona has some big slopes in certain neighborhoods [19], it was expected that the use of these bikes would increase with time, even when the cost of renting them was a little bit higher.

Figure 6 shows the average daily rides taken during 2019–2023. As before, the number of trips has progressively increased since 2019. In 2023, the usage tended to stabilize; however, during this year, users took fewer trips (on average) on weekends when compared with 2022. There was a clear pattern of use, which also can be observed when analyzing the number of trips made by bike type, displayed in Figure 7. The Bicing system was used more during the weekdays, especially during central days like Wednesdays and Thursdays. During weekends, the average number of trips sharply decreased, 27% on average, compared with the days with maximum use (usually Thursdays). These findings were similar to the ones found in the previous investigations [17,20,21], which highlighted that bike trips might be related to commuting trips on weekdays and recreational trips during weekends. Nevertheless, to confirm this, a more in-depth study involving data from other transportation means in Barcelona, as well as interviews with customers to understand their preferences and commuting habits, is needed.

Finally, the average number of trips by hour during weekdays is presented in Figure 8, while weekend data are shown in Figure 9. The trips made by bike type (electrical and mechanical) were not presented, as the hourly patterns were similar to Figures 8 and 9, with the difference that electrical bike use has significantly increased in the last two years. Therefore, analyzing these figures did not add substantial value. The usage pattern was different when comparing weekends and weekdays. During weekdays, there was a peak in usage around 7.00 to 9.00, which can be related to the commuting needed for work or school-related activities. Then, the usage dropped and increased again from 13.00 to 15.00, i.e., lunchtime in Spain. From 18.00 to 20.00, the usage reached its maximum peak. The trips made on weekends presented a different trend, with only two peaks. From 8.00, the rides progressively increased until reaching a peak at 15.00. The usage decreased at 16.00, but not so sharply as during weekends, and started increasing again at 21.00. Another finding was that the number of trips made during the early morning on weekends was a little bit higher than on weekdays, which can be associated with the leisure activities on weekdays, as Bicing is a system that is open 24 h a day. These patterns were similar to the ones found by other studies in different BSSs [6,17].

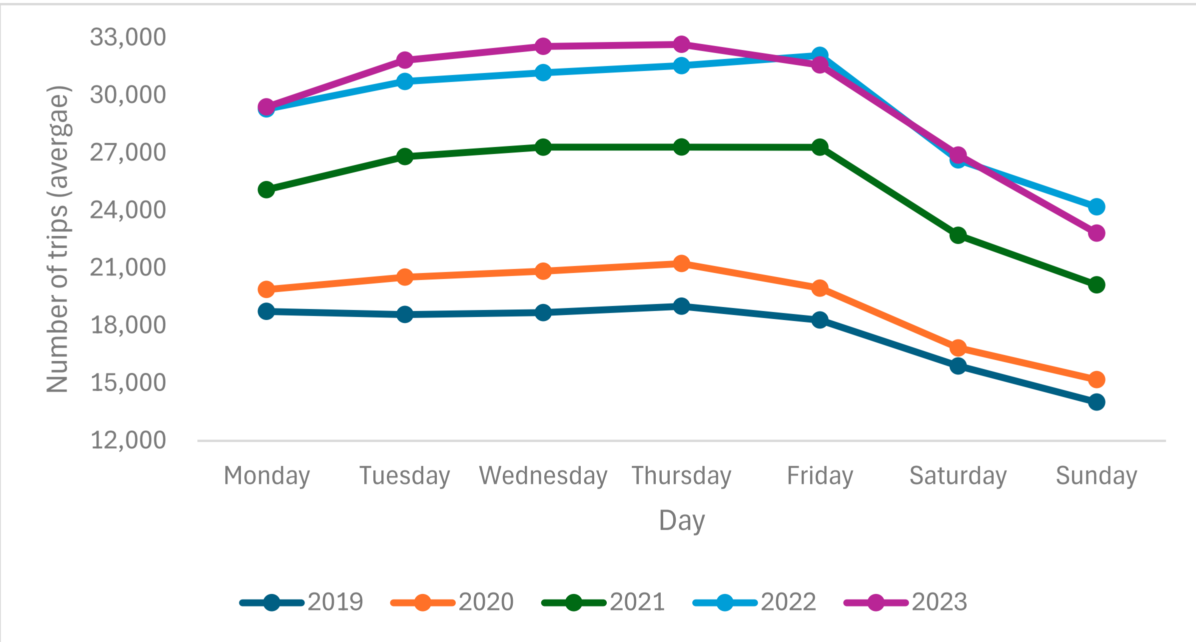

Figure 6. Bicing: Average trips by day, period: 2019–2023.

The visual analysis performed in this section has demonstrated that even when the number of trips has progressively increased since 2019, the patterns remained similar, which indicated that the COVID-19 pandemic had not changed the commuting behavior of Bicing users, contrary to the evidence found by other studies and summarized in [52]. However, during August 2023, monthly trips dropped drastically, reaching 2020 levels, as is shown in Figure 4. To assess the statistical parity of means for the trips taken in 2020 and 2023, *t*-tests were conducted for monthly, daily, and hourly trip data sets. Across all these comparisons, statistically significant differences in means were found. Due to space constraints, only the monthly results are presented as they have interesting insights. Table 2 contains the *t*-test for equality of means for monthly trips taken in 2020 and 2023. The results show that the August 2020 and 2023 average trips did not have a significant difference, with a *p*-value of 0.98. For the other months, there were significant differences, as the *p*-values are closer to 0.

Figure 7. Bicing: Average trips by day and bike type, period: 2019–2023.

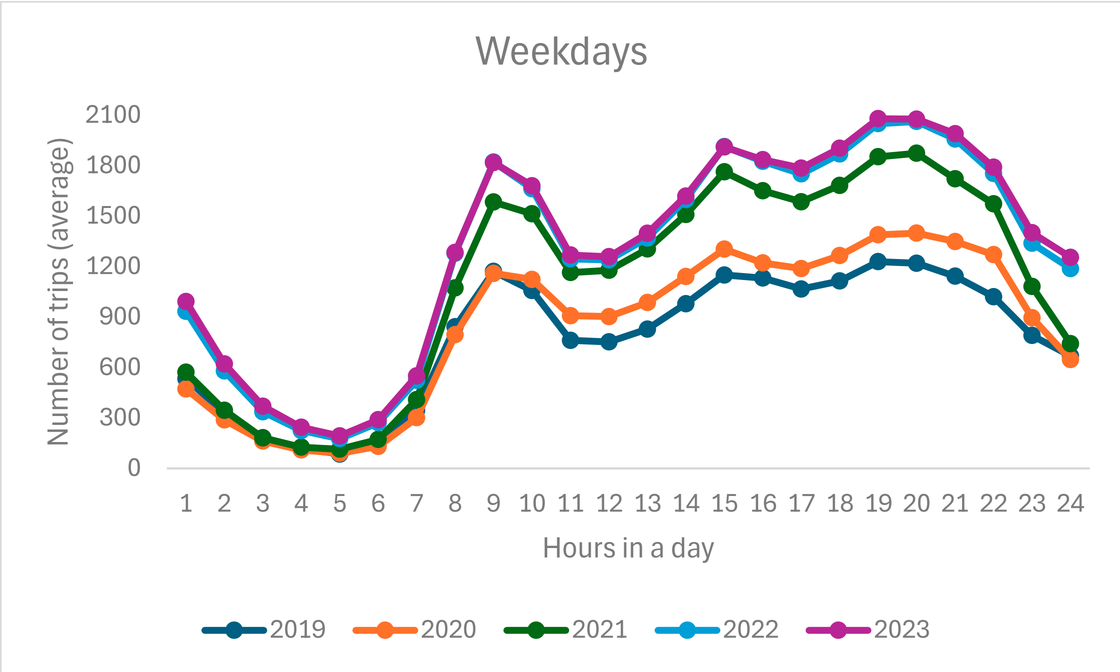

Figure 8. Bicing: Average trips by hour—Weekdays, period: 2019–2023.

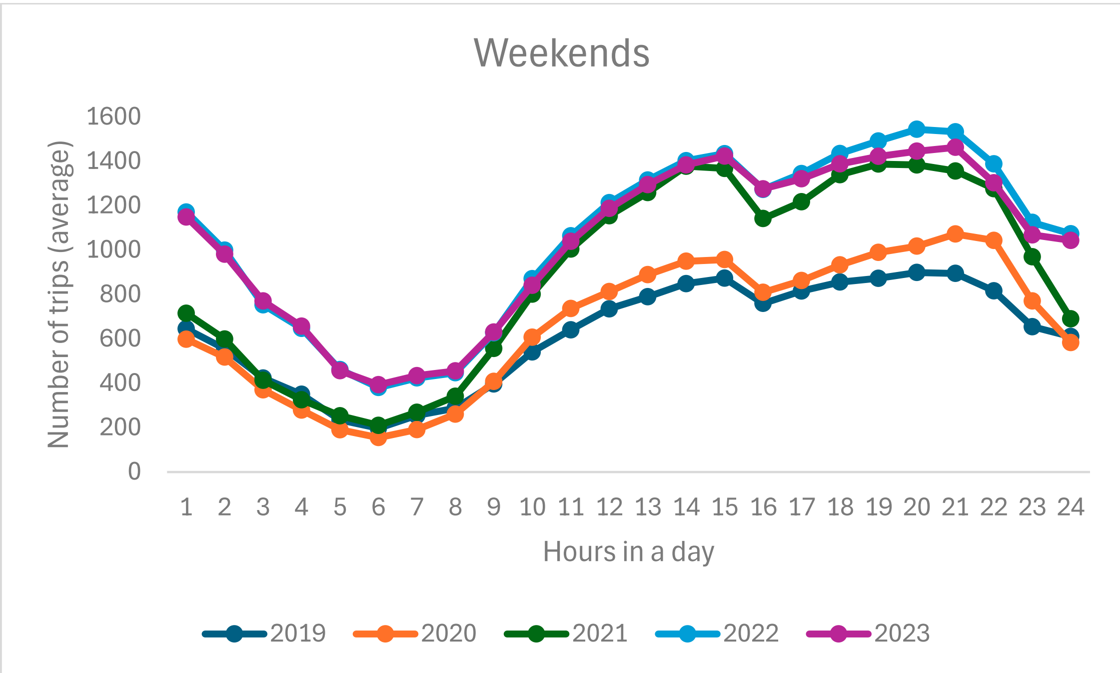

Figure 9. Bicing: Average trips by hour—Weekends, period: 2019–2023.

Our findings are aligned with the results of previous studies given that BSSs promote healthier lifestyles and modify traffic congestion patterns, as well as demonstrating flexibility, affordability, and environmental benefits, aligning with global efforts to reduce carbon footprints and improve urban air quality. The COVID-19 pandemic underscores the BSS's importance, and these urban transportation means have garnered significant attention from policymakers as sustainable alternatives to traditional modes of transportation. Specifically, post-pandemic studies highlighted enduring changes in urban mobility patterns and policy responses. Our results concerning BSS usage in the post-COVID-19 era are similar to [73]'s findings given the continued preference for cycling as a signal of a cultural shift towards sustainable and healthier transportation choices over urban populations. Ref. [74] mentioned advancements in BSS technologies, such as electric-assist bikes and smart docking stations, enhanced user convenience and accessibility, as shown in our study.

Table 2. Bicing: *t*-test for equality of means for monthly trips taken in 2020 and 2023.

	2020	2023	Difference	*t*-Value	*p*-Value
January	18,893.87	26,293.94	−7400.07	−3.74 ***	0.0004
February	24,222.72	29,903.68	−5680.96	−6.24 ***	1.04×10^{-7}
March	11,191.13	31,723.10	−20,532.00	−8.22 ***	1.42×10^{-10}
April	829.06	27,821.40	−26,992.30	−12.28 ***	3.3×10^{-13}
May	12,969.03	32,325.87	−19,356.80	−11.65 ***	2.2×10^{-16}
June	24,109.37	33,323.20	−9213.83	−8.72 ***	1.17×10^{-11}
July	25,871.35	33,026.13	−7154.78	−9.44 ***	2.38×10^{-13}
August	19,923.45	20,001.00	−77.55	−0.03	0.978
September	24,669.27	30,163.70	−5494.43	−2.32 **	0.026
October	25,979.97	33,996.84	−8016.87	−9.11 ***	6.55×10^{-13}
November	20,895.47	30,295.13	−9399.66	−5.91 ***	5.09×10^{-7}
December	21,172.94	27,113.16	−5940.22	−4.69 ***	1.61×10^{-5}

Note: *** and ** indicate statistical significance at the 1% and 5% levels, respectively.

5. Conclusions

In this study, an analysis and exploration of Barcelona BSS called Bicing has been performed using data from the trips made during the period 2019–2023. The data were obtained from the Barcelona Open Data website, cleaned, and processed to obtain the number of trips taken during this period. The previous literature in this area varies according to the BSS under analysis and the period considered [52]. The visual and descriptive evaluation of the Barcelona BSS showed that the commuting habits of Bicing users have not changed before and after COVID-19. When comparing the total number of trips, this has progressively increased since 2019, especially in 2021 (31% compared with 2020). However, it seemed that the usage started to stabilize in 2023, as the number of trips taken during this year only increased by 1% in comparison with 2022. The monthly, daily, and hourly patterns have remained similar and did not show any particular change, contrary to the evidence found by other studies and summarized in [52]. Of course, during 2020, the system was closed during the lockdown period, and the trips dramatically dropped during March and April, but after the mobility measures were gradually lifted, Bicing usage started to recover. These results are in line with previous investigations [52,60]. Therefore, we did not reject our first hypothesis, **H1:** There are no significant differences in Bicing usage patterns during and after COVID-19. In the case of the second hypothesis, **H2:** Bicing recovered its pre-pandemic usage levels by 2023, the *t*-test performed for the yearly, monthly, daily, and hourly trips demonstrated that average trips were significantly different between 2020 and 2023. Therefore, Bicing not only recovered its pre-pandemic levels but also exceeded the number of trips during the pandemic year, similar to what happened in other cities [55,56,59,60]. Only during August 2023, the trips drastically dropped to 2020 levels. Unfortunately, there was no information available that explains this particular situation.

Moreover, even when the general commuting behavior patterns were similar during the period considered, there were some changes in the user preferences. The number of trips made using electrical bikes has significantly increased since 2020, and it was more evident during 2022 and 2023. Electrical bikes have become the most preferred bike type in the Barcelona BSS, even when they were associated with a slightly higher price. In 2023, electrical bike users have taken 2 million more trips than mechanical bikes, a difference of 51%. However, this change in the preferences was not related to COVID-19. During 2019, a change in the company that operated Bicing took place. During the first months of 2019, the docking stations of this BSS were replaced to support both electrical and mechanical bikes. Before 2019, there were a limited number of stations around the city that supported electric bikes. This can explain why this type of bike has become the preferred one in Barcelona. However, a more in-depth analysis involving Bicing users is needed to understand the reasons behind this change.

There were some limitations to this study. As was mentioned before, the company that operates Bicing changed during 2019. All docking stations were gradually replaced, affecting commuting habits as users had to look for different transport options during the time their preferred stations were closed. There was also a lack of continuity in the data due to this change. Therefore, 2019 commuting patterns might not represent real users' behavior and preferences. Unfortunately, there are no data available from previous years to extend the period of analysis and corroborate the usage behaviors with different BSS operators. Another limitation is related to the change in habits when using electric bikes. Interviews with Bicing users are needed to understand their preferences and correlate with the data analyzed.

Finally, several development lines can be considered. For example, data from other transportation means can be used to perform a complete analysis of the commuting behaviors in Barcelona and study how Bicing supports other transportation modes. Other variables such as the bike infrastructure, population, or job density can also be analyzed to understand their influence in the commuting patterns. Moreover, data from Bicing customers (age, gender, and type of subscription) would also be helpful to study in detail the usage patterns in each group. This information can be later used by managers of Bicing to create and evaluate different campaigns related to increasing the use of this BSS among certain groups of users, contributing, in the long term, to having a greener city. In this line, authorities and possible stakeholders must understand and analyze the bike route usage patterns. This analysis contributes to an integrated evaluation of BSS user preferences and provides them an appropriate service, ensuring optimal bike distribution and station placement. Moreover, this information can be used by urban developers to assess user demands, evaluate system financing, and build urban bike routes, taking into account external phenomena such as pandemics and adverse weather conditions.

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References

1. Kamargianni, M.; Li, W.; Matyas, M.; Schäfer, A. A Critical Review of New Mobility Services for Urban Transport. *Transp. Res. Procedia* **2016**, *14*, 3294–3303. [CrossRef]
2. Meddin, R.; DeMaio, P.; O'Brien, O.; Rabello, R.; Yu, C.; Seamon, J. The Meddin Bike-sharing World Map. Available online: https://bikesharingworldmap.com/#/all/5.3/103.96/1.17/ (accessed on 24 November 2020).
3. Fuller, D.; Gauvin, L.; Kestens, Y.; Daniel, M.; Fournier, M.; Morency, P.; Drouin, L. Use of a new public bicycle share program in Montreal, Canada. *Am. J. Prev. Med.* **2011**, *41*, 80–83. [CrossRef] [PubMed]
4. Ricci, M. Bike sharing: A review of evidence on impacts and processes of implementation and operation. *Res. Transp. Bus. Manag.* **2015**, *15*, 28–38. [CrossRef]
5. Zheng, L.; Li, Y. The Development, Characteristics and Impact of Bike Sharing Systems:. A Literature Review. *Int. Rev. Spat. Plan. Sustain. Dev.* **2020**, *8*, 37–52. [CrossRef]

6. Faghih-Imani, A.; Eluru, N.; El-Geneidy, A.M.; Rabbat, M.; Haq, U. How does land-use and urban form impact bicycle flows: Evidence from the bicycle-sharing system (BIXI) in Montreal. *J. Transp. Geogr.* **2014**, *41*, 306–314. [CrossRef]
7. Faghih-Imani, A.; Eluru, N. Analysing bicycle-sharing system user destination choice preferences: Chicago's Divvy system. *J. Transp. Geogr.* **2015**, *44*, 53–64. [CrossRef]
8. Kim, I.; Pelechrinis, K.; Lee, A.J. The Anatomy of the Daily Usage of Bike Sharing Systems: Elevation, Distance and Seasonality. In Proceedings of the ACM SIGKDD workshop on Urban Computing, San Diego, CA, USA, 24 August 2020.
9. Wang, B.; Kim, I. Short-term prediction for bike-sharing service using machine learning. *Transp. Res. Procedia* **2018**, *34*, 171–178. [CrossRef]
10. Talavera-Garcia, R.; Romanillos, G.; Arias-Molinares, D. Examining spatio-temporal mobility patterns of bike-sharing systems: The case of BiciMAD (Madrid). *J. Maps* **2021**, *17*, 7–13. [CrossRef]
11. Navarrete-Hernandez, P.; Rennert, L.; Balducci, A. An evaluation of the impact of COVID-19 safety measures in public transit spaces on riders' Worry of virus contraction. *Transp Policy* **2023**, *131*, 1–12. [CrossRef]
12. Ozbilen, B.; Slagle, K.M.; Akar, G. Perceived risk of infection while traveling during the COVID-19 pandemic: Insights from Columbus, OH. *Transp. Res. Interdiscip. Perspect.* **2021**, *10*, 100326. [CrossRef]
13. Papazek, P.; Raidl, G.R.; Rainer-Harbach, M.; Hu, B. *A Pilot/Vnd/Grasp Hybrid for the Static Balancing of Public Bicycle Sharing Systems*; Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics); Springer: Berlin/Heidelberg, Germany, 2013; Volume 8111. [CrossRef]
14. Raidl, G.R.; Hu, B.; Rainer-Harbach, M.; Papazek, P. Balancing bicycle sharing systems: Improving a VNS by efficiently determining optimal loading operations. in International Workshop on Hybrid Metaheuristics. *Hybrid Metaheuristics* **2013**, *7919*, 130–143, Lecture Notes in Computer Science.
15. Shu, J.; Chou, M.C.; Liu, Q.; Teo, C.-P.; Wang, I.-L. Models for effective deployment and redistribution of bicycles within public bicycle-sharing systems. *Oper. Res.* **2013**, *61*, 1346–1359. [CrossRef]
16. Xie, X.-F.; Wang, Z. Combining Physical and Participatory Sensing in Urban Mobility Networks. In Proceedings of the Workshop on Big Data and Urban Informatics (BDUIC), Chicago, IL, USA, 11–12 August 2014. [CrossRef]
17. Xie, X.-F.; Wang, Z. Examining Travel Patterns and Characteristics in a Bikesharing Network and Implications for Data-Driven Decision Supports: Case Study in the Washington DC Area. *J. Transp. Geogr.* **2018**, *71*, 84–102. [CrossRef]
18. Frade, I.; Ribeiro, A. Bicycle sharing systems demand. *Procedia-Soc. Behav. Sci.* **2014**, *111*, 518–527. [CrossRef]
19. Cortez, A.; Vázquez, P.-P. Advanced Visual Interaction with Public Bicycle Sharing Systems. *J. WSCG* **2021**, *29*, 207–216.
20. Borgnat, P.; Fleury, É.; Robardet, C.; Scherrer, A. Spatial analysis of dynamic movements of Vélo'v, Lyon's shared bicycle program. In Proceedings of the ECCS'09, Warwick, UK, 21–25 September 2009.
21. Borgnat, P.; Abry, P.; Flandrin, P.; Robardet, C.; Rouquier, J.-B. Fleury. Shared bicycles in a city: A signal processing and data analysis perspective. *Adv. Complex. Syst.* **2011**, *14*, 415–438. [CrossRef]
22. Bhat, C.R.; Astroza, S.; Hamdi, A.S. A spatial generalized ordered-response model with skew normal kernel error terms with an application to bicycling frequency. *Transp. Res. Part. B Methodol.* **2017**, *95*, 126–148. [CrossRef]
23. Cortez-Ordoñez, A.; Tulcanaza-Prieto, A.B. The Effect of Gender and Age in Small Bicycle Sharing Systems: Case Study from Logroño, Spain. *Sustainability* **2023**, *15*, 7925. [CrossRef]
24. Wood, J.; Beecham, R.; Dykes, J. Moving beyond sequential design: Reflections on a rich multi-channel approach to data visualization. *IEEE Trans. Vis. Comput. Graph.* **2014**, *20*, 2171–2180. [CrossRef]
25. Wang, K.; Akar, G. Gender gap generators for bike share ridership: Evidence from Citi Bike system in New York City. *J. Transp. Geogr.* **2018**, *76*, 1–9. [CrossRef]
26. Eren, E.; Uz, V.E. A review on bike-sharing: The factors affecting bike-sharing demand. *Sustain. Cities Soc.* **2020**, *54*, 101882. [CrossRef]
27. Froehlich, J.E.; Neumann, J.; Oliver, N. Sensing and predicting the pulse of the city through shared bicycling. In Proceedings of the Twenty-First International Joint Conference on Artificial Intelligence (IJCAI'09), Messe Wien, Vienna, Austria, 23–29 July 2022; pp. 1420–1426.
28. Shi, X.; Wang, Y.; Lv, F.; Liu, W.; Seng, D. Lin. Finding communities in bicycle sharing system. *J. Vis.* **2019**, *22*, 1177–1192. [CrossRef]
29. Noussan, M.; Carioni, G.; Sanvito, F.D.; Colombo, E. Urban mobility demand profiles: Time series for cars and bike-sharing use as a resource for transport and energy modeling. *Data* **2019**, *4*, 108. [CrossRef]
30. Zhang, J.; Pan, X.; Li, M.; Philip, S.Y. Bicycle-sharing system analysis and trip prediction. In Proceedings of the 2016 17th Ieee International Conference on Mobile Data Management (MDM), Porto, Portugal, 13–16 June 2016; pp. 174–179.
31. Holmgren, J.; Aspegren, S.; Dahlströma, J. Prediction of bicycle counter data using regression. *Procedia Comput. Sci.* **2017**, *113*, 502–507. [CrossRef]
32. Holmgren, J.; Moltubakk, G.; O'Neill, J. Regression-based evaluation of bicycle flow trend estimates. *Procedia Comput. Sci.* **2018**, *130*, 518–525. [CrossRef]
33. Li, Y.; Zheng, Y.; Zhang, H.; Chen, L. Traffic prediction in a bike-sharing system. In Proceedings of the 23rd International Conference Advances in Geographic Information Systems (SIGSPATIAL '15), Seattle, WA, USA, 3–6 November 2015; pp. 1–10. [CrossRef]

34. Lin, L.; He, Z.; Peeta, S. Predicting station-level hourly demand in a large-scale bike-sharing network: A graph convolutional neural network approach. *Transp. Res. Part. C: Emerg. Technol.* **2018**, *97*, 258–276. [CrossRef]
35. Lozano, Á.; De Paz, J.F.; González, G.V.; De La Iglesia, D.H.; Bajo, J. Multi-agent system for demand prediction and trip visualization in bike sharing systems. *Appl. Sci.* **2018**, *8*, 67. [CrossRef]
36. Yin, Y.; Lee, C.; Wong, Y. Demand Prediction of Bicycle Sharing Systems. *Engineering* **2014**, 1–5. Available online: https://api.semanticscholar.org/CorpusID:3333800 (accessed on 11 July 2024).
37. Feng, Y.; Wang, S. A forecast for bicycle rental demand based on random forests and multiple linear regression. In Proceedings of the Proceedings—16th IEEE/ACIS International Conference on Computer and Information Science, ICIS 2017, Wuhan, China, 24–26 May 2017; pp. 101–105. [CrossRef]
38. Hulot, P.; Aloise, D.; Jena, S.D. Towards station-level demand prediction for effective rebalancing in bike-sharing systems. In Proceedings of the 24th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining, London, UK, 19–23 August 2018; pp. 378–386. [CrossRef]
39. Scott, D.M.; Ciuro, C. What factors influence bike share ridership? An investigation of Hamilton, Ontario's bike share hubs. *Sustain. Cities Soc.* **2019**, *54*, 101882. [CrossRef]
40. El-Assi, W.; Mahmoud, M.S.; Habib, K.N. Effects of built environment and weather on bike sharing demand: A station level analysis of commercial bike sharing in Toronto. *Sustain. Cities Soc.* **2019**, *54*, 101882. [CrossRef]
41. Rixey, R.A. Station-Level Forecasting of Bikesharing Ridership: Station Network Effects in Three U.S. *Syst. Transp. Res. Rec.* **2013**, *2387*, 46–55. [CrossRef]
42. DIas, G.M.; Bellalta, B.; Oechsner, S. Predicting occupancy trends in Barcelona's bicycle service stations using open data. In Proceedings of the 2015 SAI Intelligent Systems Conference (IntelliSys), London, UK, 10–11 November 2015; pp. 439–445. [CrossRef]
43. Cortez-Ordoñez, A.; Vázquez, P.-P.; Sanchez-Espigares, J.A. Scalability evaluation of forecasting methods applied to bicycle sharing systems. *Heliyon* **2023**, *9*, e20129. [CrossRef]
44. Vogel, P.; Greiser, T.; Mattfeld, D.C. Understanding bike-sharing systems using Data Mining: Exploring activity patterns. *Procedia Soc. Behav. Sci.* **2011**, *20*, 514–523. [CrossRef]
45. Cortez-Ordoñez, A.; Sanchez-Espigares, J.A.; Vázquez, P.-P. A visual tool for the analysis of usage trends of small and medium bicycle sharing systems. *Comput. Graph.* **2022**, *109*, 30–41. [CrossRef]
46. Beecham, R.; Wood, J. Bowerman. Studying commuting behaviours using collaborative visual analytics. *Comput. Environ. Urban. Syst.* **2014**, *47*, 5–15. [CrossRef]
47. O'Brien, O.; Cheshire, J.; Batty, M.; O'Brien, O.; Cheshire, J.; Batty, M. Mining bicycle sharing data for generating insights into sustainable transport systems. *J. Transp. Geogr.* **2014**, *34*, 262–273. [CrossRef]
48. Oppermann, M.; Möller, T.; Sedlmair, M. Bike sharing Atlas: Visual analysis of bike-sharing networks. *Int. J. Transp.* **2018**, *6*, 1–14. [CrossRef]
49. Dai, H.; Tao, Y.; Lin, H. Visual analytics of urban transportation from a bike-sharing and taxi perspective. *J. Vis.* **2020**, *23*, 1053–1070. [CrossRef]
50. Muller, S.; Balmer, M.; Neumann, A.; Nagel, K. Mobility traces and spreading of COVID-19. *medrxiv* **2020**. [CrossRef]
51. Simić, V.; Ivanović, I.; Đorić, V.; Torkayesh, A.E. Adapting Urban Transport Planning to the COVID-19 Pandemic: An Integrated Fermatean Fuzzy Model. *Sustain. Cities Soc.* **2022**, *79*, 103669. [CrossRef]
52. Rotaris, L.; Intini, M.; Gardelli, A. Impacts of the COVID-19 Pandemic on Bike-Sharing: A Literature Review. *Sustainability* **2022**, *14*, 13741. [CrossRef]
53. Bucsky, P. Modal share changes due to COVID-19: The case of Budapest. *Transp. Res. Interdiscip. Perspect.* **2020**, *8*, 100141. [CrossRef] [PubMed]
54. Nikiforiadis, A.; Ayfantopoulou, G.; Assessing, A.S. the Impact of COVID-19 on Bike-Sharing Usage: The Case of Thessaloniki, Greece. *Sustainability* **2020**, *12*, 8215. [CrossRef]
55. Heydari, S.; Konstantinoudis, G.; Behsoodi, A.W. Effect of the COVID-19 pandemic on bike-sharing demand and hire time: Evidence from Santander Cycles in London. *PLoS ONE* **2021**, *16*, e0260969. [CrossRef] [PubMed]
56. Li, H.; Zhang, Y.; Zhu, M.; Ren, G. Impacts of COVID-19 on the usage of public bicycle share in London. *Transp. Res. Part A Policy Pract.* **2021**, *150*, 140–155. [CrossRef]
57. Kubaľák, S.; Kalašová, A.; Hájnik, A. The Bike-Sharing System in Slovakia and the Impact of COVID-19 on This Shared Mobility Service in a Selected City. *Sustainability* **2021**, *13*, 6544. [CrossRef]
58. Wang, H.; Noland, R.B. Bikeshare and subway ridership changes during the COVID-19 pandemic in New York City. *Transp. Policy* **2021**, *106*, 262–270. [CrossRef] [PubMed]
59. Bustamante, X.; Federo, R.; Fernández-i-Marin, X. Riding the wave: Predicting the use of the bike-sharing system in Barcelona before and during COVID-19. *Sustain. Cities Soc.* **2022**, *83*, 103929. [CrossRef] [PubMed]
60. Seifert, R.; Pellicer-Chenoll, M.; Antón-González, L.; Pans, M.; Devís-Devís, J.; González, L.-M. Who changed and who maintained their urban bike-sharing mobility after the COVID-19 outbreak? A within-subjects study. *Cities* **2023**, *137*, 104343. [CrossRef]
61. Barcelona.cat. Movilidad y Transportes. Available online: https://www.barcelona.cat/mobilitat/en/about-us/urban-mobility-plan (accessed on 11 July 2024).
62. Barcelona City Hall. Bicing. Available online: https://www.bicing.barcelona/dades-bicing#reference-1 (accessed on 11 July 2024).

63. Barcelona.cat. Movilidad y Transportes. Bicicleta. Available online: https://www.barcelona.cat/mobilitat/es/medios-de-transporte/bicicleta/red-ciclistaciclable (accessed on 11 July 2024).
64. Infotrànsit. Un año de Pandemia, un año de (no)Movilidad. Available online: https://infotransit.blog.gencat.cat/2021/03/10/un-ano-de-pandemia-un-ano-de-nomovilidad/ (accessed on 24 June 2024).
65. InfoBarcelona. Se Levantan la Mayoría de Restricciones de Aforo Vigentes por la COVID-19. Available online: https://www.barcelona.cat/infobarcelona/es/tema/informacion-sobre-la-gestion-del-covid-19/se-levantan-la-mayoria-de-restricciones-de-aforo-que-habia-vigentes-por-la-covid-19_1110126.html (accessed on 24 June 2024).
66. Chen, Y.; Sun, X.; Deveci, M.; Coffman, D. The impact of the COVID-19 pandemic on the behaviour of bike sharing users. *Sustain. Cities Soc.* **2022**, *84*, 104003. [CrossRef]
67. Hossain, S.; Loa, P.; Ong, F.; Habib, K.N. Exploring the spatiotemporal factors affecting bicycle-sharing demand during the COVID-19 pandemic. *Transportation* **2023**, *40*, 1–36. [CrossRef]
68. Teixeira, J.F.; Silva, C.; e Sá, F.M. Potential of Bike Sharing During Disruptive Public Health Crises: A Review of COVID-19 Impacts. *Transp. Res. Rec. J. Transp. Res. Board* **2023**, 03611981231160537. [CrossRef]
69. Gil-Alonso, F.; López-Villanueva, C.; Thiers-Quintana, J. Transition towards a Sustainable Mobility in a Suburbanising Urban Area: The Case of Barcelona. *Sustainability* **2022**, *14*, 2560. [CrossRef]
70. European Consortium For Mathematics in Industry (ECMI). Barcelona. The Future of Urban Transport: The On-Demand Bus Service in Barcelona. Available online: https://ecmiindmath.org/2024/05/14/the-future-of-urban-transport-the-on-demand-bus-service-in-barcelona/ (accessed on 11 July 2024).
71. Barcelona City Hall. Open Data BCN. Available online: https://opendata-ajuntament.barcelona.cat/en/open-data-bcn (accessed on 4 November 2022).
72. Walpole, R.E.; Myers, R.H.; Myers, S.L.; Ye, K. *Probability & Statistics for Engineers & Scientist*, 9th ed.; Pearson: London, UK, 2012.
73. Rérat, P.; Haldimann, L.; Widmer, H. Cycling in the era of COVID-19: The effects of the pandemic and pop-up cycle lanes on cycling practices. *Transp. Res. Interdiscip. Perspect.* **2022**, *15*, 100677. [CrossRef]
74. López-Pérez, M.E.; Reyes-García, M.E.; López-Sanz, M.E. Smart Mobility and Smart Climate: An Illustrative Case in Seville, Spain. *Int. J. Environ. Res. Public Health* **2023**, *20*, 1404. [CrossRef]