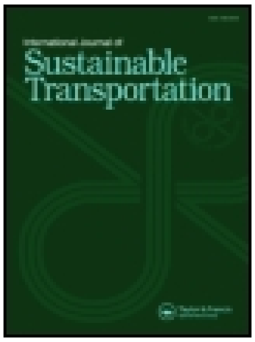

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The impact of public bike-sharing systems on mobility patterns: Generating or replacing trips?

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ABSTRACT

Bike-sharing systems allow occasional and regular users to travel by replacing other transport modes for the same trip or generating a new journey. Our research assesses the demand for Lisbon's public dock-based bike-sharing system (BSS), named GIRA. This paper aims to identify the determinant factors that influence the potential of the BSS to generate new trips or replace previous modes using a conditional logit model based on a survey of 3112 BSS users. The survey results indicate that GIRA generated approximately 20% of the BSS trips, i.e., they would not have been realized if GIRA did not exist. The remaining BSS trips replaced other motorized (55%) and non-motorized (25%) trips. The main determinants explaining a higher likelihood of replacing different modes are having a yearly GIRA pass and a bike-sharing station within a 5-min walk. In contrast, regular car users are more likely to generate new trips, suggesting they use bike-sharing for recreational purposes. The findings provide policymakers with an assessment of determinants which may influence bike-sharing users to generate or replace trips from other modes and, consequently, define policies to potentially increase bike-sharing.

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Bike-sharing; built environment; cycling; latent demand; modal shift; travel behavior

1. Introduction

The adoption of Bike-Sharing Systems (BSS) has grown widely in many cities worldwide. The main advantage of BSS is to use a bicycle without the responsibility and cost of owning one. Although the international market for bike-sharing is relatively recent, this mobility service appeared in the 1960s (Shaheen et al., 2010). BSS can operate with fixed docks at stations or dockless. Even though dockless systems allow more flexibility for users since there is no specific location for bicycle drop-off, public policymakers tend to avoid them, as bicycles are often left on sidewalks and have a higher rate of breaking (Wei et al., 2019). People typically use this system for short-distance trips, and when integrated adequately with transit, it can potentially offer a solution for the "first-and-last mile" dilemma (Fan et al., 2019; Wang & Zhou, 2017). Based on the experience of European and Japanese cities, bike-sharing policies may promote public transportation and diversify transport modal shares, reducing car dependence (Fan et al., 2019).

However, since BSS is very recent in many regions, there is a lack of research analyzing the demand patterns of trip generation or mode substitution in a system under operation. Few studies examine the expansion of existing BSS (Hsieh et al., 2021; Zhang et al., 2016), and others consider latent (or potential) demand only when planning for a new BSS (Frade & Ribeiro, 2014; Krykewycz et al., 2010). Therefore, little has been researched on the usage and behavior of current users of an operating BSS (Zhang et al., 2016). Expansion policies of operating BSS should be based on studies of potential trip replacement and latent demand satisfaction. In this context, this paper aims to identify the impact of introducing a new BSS on its users' travel patterns, using Lisbon's dock-based BSS as our case study. We are interested in determining if the BSS has generated new trips and, therefore, satisfied latent demand or replaced previous modes, particularly if it replaced car travel.

The paper begins with a literature review in Section 2, followed by a description of the research design, the travel survey, and the modeling framework in Section 3. Section 4 presents the model results, followed by the corresponding discussion in Section 5. Finally, Section 6 presents the conclusions.

2. Background

2.1. Bike-sharing systems and modal choice

Bike-sharing systems' investment can provide various social, economic, environmental, and public health benefits. Shaheen et al. (2010) enumerated the main benefits of bike-sharing systems: flexible mobility, reduced congestion and emissions, user cost savings, increased public transportation use, promoting physical activity, and providing a mobility option for the "first-and-last mile" dilemma. Nonetheless, few studies empirically validate the benefits of BSS claimed

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by Shaheen et al. (2010; Fishman et al., 2013). Furthermore, the benefits of installing a BSS cannot be taken strictly into account since promoting cycling through other measures can achieve the same benefits (Buck et al., 2013; Handy et al., 2014; Wang & Zhou, 2017). Therefore, although it seems self-evident that BSS has a positive impact on promoting cycling, it is one of several measures policymakers and city officials may pursue to encourage cycling (Buck et al., 2013).

One particular aspect of BSS is its role within an integrated transport system. BSS is arguably a public transport mode, but few studies address BSS design combined with the existing transit system (Wu et al., 2020). In practice, BSSs are implemented lacking or having minimum adjustments in the current public transportation system. Indeed, BSS investments can promote better transit access once cycling increases the pedestrian catchment areas of transit stops and stations (Hamidi et al., 2019).

Most bike-sharing programs aim not only to promote cycling but also to substitute car use. However, according to Fishman et al. (2013), studies demonstrate that people are more likely to shift from walking and transit than from automobiles. That was the case in Shanghai (Zhu et al., 2013), where BSS was associated with replacing transit, walking, and private bicycle usage, despite a slight increase in travel distances. Further evidence from several cities such as Washington, Minnesota, and Montreal in North America, Barcelona, Lyon, Dublin, Paris, and London in Europe, as well as Brisbane and Melbourne in Australia, confirm a very low modal shift from car to bike-sharing (Midgley, 2011; Fishman et al., 2013; Fishman et al., 2014). The differences in the impact of BSS on car substitution appear to be positively related to the car modal share of the city, justifying the higher replacement rates in cities such as Brisbane, Melbourne, and Minnesota in comparison to London or Paris, for instance (Fishman et al., 2014). Recent evidence has reinforced this reduced impact of BSS in replacing car trips, reinforcing the differences between cities (Teixeira et al., 2021). In general terms, and considering the entire dataset of cities analyzed by Teixeira et al., 2021, only around 10% of BSS users have replaced car trips, which contrasts with nearly 70% of BSS users replacing public transport trips. Interestingly, the same authors also found that almost 50% of the reviewed studies did not report the generation rates of new trips. The remaining studies reported average generation rates of less than 5% (ranging from 1% to 10%).

The ease of access to a bike-sharing station is a relevant factor that can impact the number of people who use the system. In a study developed in London, low-income and less educated populations tend to have lower rates of BSS usage (Ogilvie & Goodman, 2012). However, the lack of access to BSS or longer distances to a bike-sharing station of these populations may justify lower usage levels (Fishman et al., 2013; Ogilvie & Goodman, 2012). According to Ogilvie and Goodman (2012), even though people from low-income zones use less the BSS than high-income zones, they are more likely to adopt this mode due to the low levels of bicycle ownership and lack of bicycle storage facilities at home. Therefore, a better distribution of bicycle stations could provide better access to this population's latent (or suppressed) demand.

2.2. Factors impacting bike-sharing choice

Most studies demonstrate that hilliness and slopes negatively influence bicycle use on home-work trips, with less impact on experienced cyclists (Heinen et al., 2010). However, electric bicycles (E-bikes) require less physical effort and help overcome problems related to topography, increasing the number of bike riders and cycling trips (Popovich et al., 2014). As a result, E-bikes overcome common barriers for all types of cyclists (Dill & Rose, 2012). In the case of Lisbon, 66% of the public bike-sharing fleet is E-bikes. Therefore, a public BSS that offers E-bikes should have a higher utilization rate than a system that lacks this technological improvement, such as Lisbon's system.

People who lack bicycle storage at home are less likely to use bicycles (Fernández-Heredia et al., 2016). BSS can motivate this portion of the population to use bike sharing in daily commuting if docks have short distances to the origin and destination of the trip (Fishman et al., 2013). Bike-sharing users avoid problems related to bicycle thefts and access to on-demand transportation compared to regular bicycles (Fan et al., 2019). In the case of Lisbon, the housing conditions are not homogeneous, but in some districts, leaving a bicycle at home is impractical, especially in older buildings in the city's central areas (Félix, 2019). BSS is also a good option to abate bike theft concerns. In Lisbon, it is rare to find bicycles parked on sidewalks (bike racks and parking) at night due to the risk of theft (Félix, 2019), even though Lisbon is a moderately safe city. However, this might not be the case in cities with a higher bicycle mode share (Pucher & Buehler, 2008).

Some barriers faced by bike-sharing users for daily commuting are similar to those faced by private bicycle users. They are usually related to the built environment, transportation policies, socio-demographics, and travel time-related aspects (Chen et al., 2017). The built environment factors that influence bicycle use are usually related to travel distance (Cervero, 1996; Heinen et al., 2010; Pucher & Buehler, 2006); density (Heinen et al., 2010; Saelens et al., 2003; Vale et al., 2015); land-use diversity (Heinen et al., 2010; Saelens et al., 2003; Vale et al., 2015); connectivity between bike-routes (Heinen et al., 2010; Muhs & Clifton, 2016); accessibility (Vale et al., 2015); the presence of segregated bike lanes (Dill & Carr, 2003; Félix et al., 2019; Pucher et al., 2010); and the availability of a BSS (Félix et al., 2020).

Furthermore, some studies demonstrate how demographic characteristics influence people using a bicycle, such as age, gender, and physical ability (Akar & Clifton, 2009; Ma & Dill, 2015). Females, the elderly, and people with children are less likely to use a bicycle than males, young users, or childless individuals. According to Heinen et al. (2010), bicycle use may vary during hours of the day, weekdays, seasons, and weekends. Thus, the time availability of BSS is an important aspect influencing its adoption.

3. Research design

Lisbon's public BSS is our case study to evaluate how trips were generated or replaced for occasional and frequent bike-sharing users. This study assesses choice preferences and sociodemographic characteristics through a travel survey of GIRA's users (3112 valid responses). After collecting the data, it was necessary to perform some data treatment due to the lack of patterns or incomplete home addresses provided by most users. Consequently, we completed the home addresses and set them in the same format. Furthermore, we estimated each respondent's routes and corresponding distances, costs, and trip duration, for each mode. After analyzing the correlation and collinearity between variables, we used a conditional logit model to evaluate which sociodemographic, trip characteristics, and built environment variables can influence the generation or the substitution of trips with Lisbon's BSS GIRA.

3.1. Case-study

We studied the case of Lisbon, Portugal. According to the Census 2011 (Instituto Nacional de Estatística, 2011), 48% of Lisbon's population used a car to commute; 34% used public transportation; 17% commuted on foot, and only 0.2% cycled to work daily (Instituto Nacional de Estatística, 2011). In the last mobility survey (Instituto Nacional de Estatística, 2018), cycling trips represented 0.6% of all trips in Lisbon, increasing significantly. In 2018, 46% of trips were made by car, 21% by public transport, and 30% walking. The recent rise of bicycle users is partly explained by the expansion of the cycling network and other significant investments in pro-cycling policies. In 2021, segregated bicycle lanes reached an extension of 150 km (Câmara Municipal de Lisboa, 2021).

Lisbon is a valuable case study since the GIRA's BSS is not yet completed, and expansion projects are still undergoing. Lisbon's GIRA began with ten stations in June 2017 during the pilot project and had expanded to 74 stations by December 2018, with a fleet of 10 bicycles per station. A first phase expansion of at least 140 stations and 1,400 bicycles operating in the system is underway. The second expansion phase will have 3,000 bicycles and 300 stations, resulting in wider city coverage. The stations have adaptable bicycle racks that may be changed according to different demands, though not in a dynamic form (during the day, week, etc.). In addition, each station has a wi-fi connection, where a smartphone app is necessary to use the system (Pincha, 2018). In 2018, the system registered roughly one million trips (Moura & Félix, 2019). GIRA users pay 25 euros/year to use the system with no limitations and 2 euros for a daily pass.[1]

The stations are distributed in four areas: *Eixo Central*, *Parque das Nações*, *Telheiras*, and *Frente Ribeirinha*, as illustrated in Figure 1. The *Eixo Central* is the city's Central Business District with the highest employment and economic activity concentration. The average distance between stations is 200 m to 300 m depending on the zone. Nevertheless, the lack of stations between the zones served by the network may result in low adoption of bike-sharing in these unserved zones. Each station has docks for 10 to 40 bicycles (18 on average).

3.2. Survey design

An online survey was sent by e-mail to all GIRA subscribers living in Portugal. The survey was open from January 28th to February 22nd, 2019. From a universe of 25,465 users that have used GIRA for at least one trip, the survey collected 5,053 answers. We excluded respondents who reported they had never used GIRA or used it in 2017. We also eliminated observations with missing critical variables values, ending with 3,112 valid answers. Table 1 shows the descriptive statistics of the survey and compares them with the GIRA user's dataset (Moura & Félix, 2019) to validate the sample.

The survey aimed to estimate which trips GIRA has generated and which modes it has replaced. We divided GIRA users into frequent and occasional users. We consider them frequent users if they use GIRA at least once a week. Frequent users were asked about their most frequent trip origin and destination (OD pair) and which mode they replaced when using the BSS by asking: ″Having answered that you frequently use this bike-sharing system, has GIRA replaced another mode of transport in your travels?", with the options:

- Yes—this corresponds to, for example, "I used to drive to work, and now I ride GIRA" or "I use GIRA to take the subway that is further away from my home."; and
- No—this corresponds to using GIRA for trips that I would not make, for example, "to go for a ride at the end of the day" or "to go visit someone who lives beyond walking distances."

If the respondent answered "Yes," this would promp a further question, asking which transport mode was replaced by GIRA among a list of presented options.

A similar question was addressed to occasional users, differing only on the focus on their GIRA's last trip instead of travel patterns. Table 2 presents the distribution of responses per type of trip (generated or replaced and the corresponding mode) and per type of user (frequent or occasional).

The BSS generated approximately 20% of the frequent user trips, i.e., these users did not perform the journey and would not do it if they did not have access to a GIRA. Thus, the generated trips satisfy a latent demand for new and previously suppressed activities (Clifton & Moura, 2017). The remaining trips replaced other modes, i.e., shifting away from active or motorized modes. Other studies

[1]GIRA subscription plans: https://www.gira-bicicletasdelisboa.pt/passes-e-tarifarios/

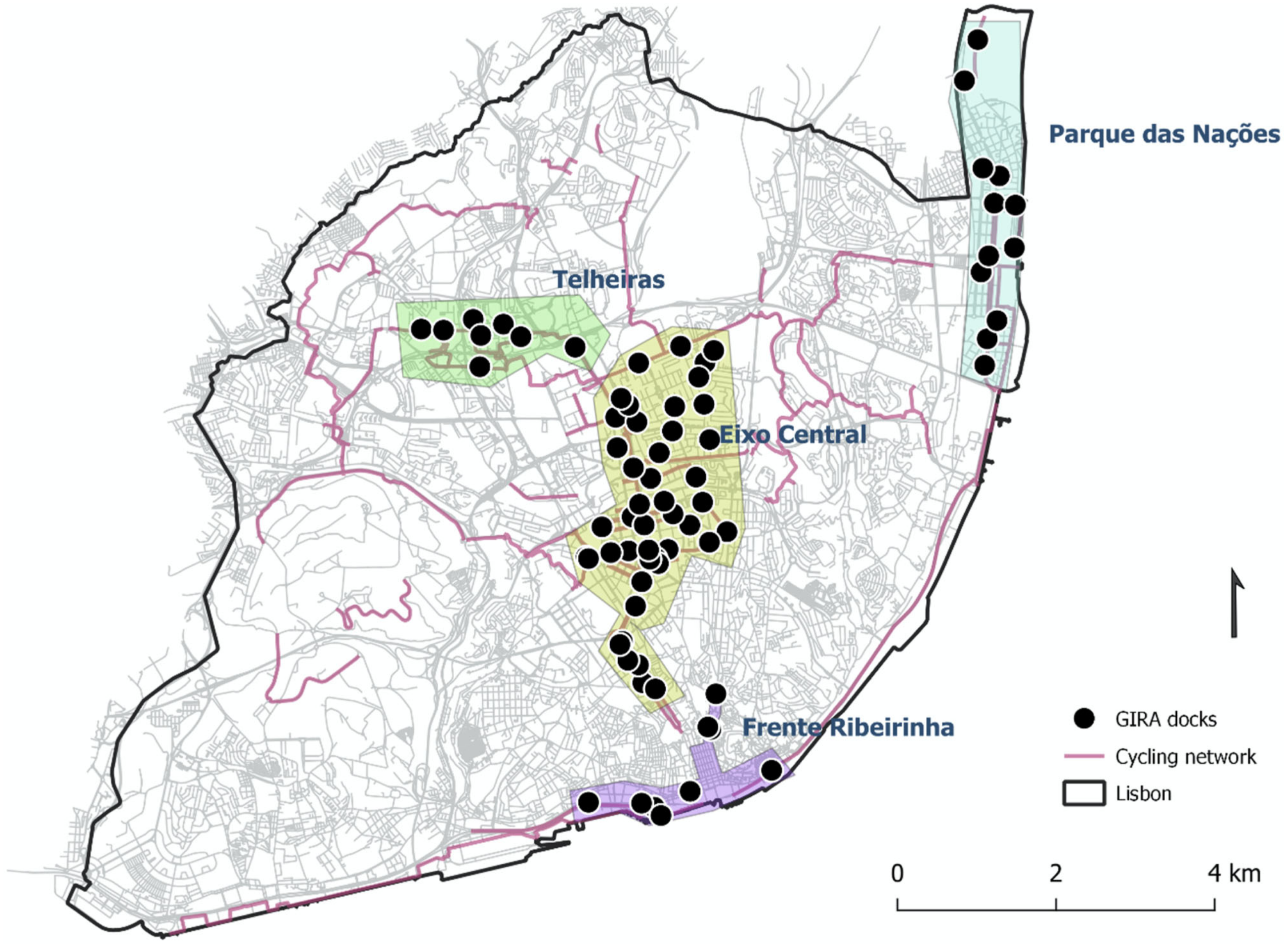

Figure 1. Distribution of GIRA stations in Lisbon's municipality at the time of the survey.

Table 1. Descriptive statistics and comparison between GIRA and survey datasets.

	GIRA dataset	Survey
Total № of users	25,465	4,970
№ residents of Lisbon	16,029 (63% of users)	3527 (70.9% of users)
№ of residents within 10 min walk to a station	12,578 (78.5% of residents)	2,734 (77.5% of residents)
№ of residents within 5 min walk to a station	9,999 (62.4% of residents)	2,196 (62.3% of residents)
Age (average)	35	36.5
Female users	37.0 %	33.0 %
Users with an annual pass	77.3 %	90.5 %
Frequent users	24.0 %	63.3 %
Home-work trip users	–	45.0%

Table 2. Answers' distribution according to types of trips and users.

Type of trip	Frequent	Occasional
Generated trip	595 (20 %)	196 (13 %)
Replacing trip previously done by:		
Foot, bicycle	591 (20 %)	490 (32 %)
Motorcycle	45 (2 %)	37 (2 %)
Metro	893 (30 %)	330 (21 %)
Train	19 (1 %)	6 (1 %)
Bus	272 (9 %)	83 (5 %)
Car	518 (18 %)	402 (26 %)
Total	2,934 (66 %)	1,544 (34 %)

have evaluated that bike-sharing replaces more walking and public transit trips (Chen et al., 2022; Teixeira et al., 2021). Although our results demonstrate that bike-sharing considerably replaced previous trips by foot, we observed that the types of public transport had different results. Metro had many replaced trips, while train and bus had few, partly because the Lisbon BSS stations overlap the metro lines. Therefore, the BSS is not serving the first-and-last miles for metro service, conversely to other studies (Ashraf et al., 2021).

Furthermore, the number of trips replaced by car is also significant, especially for the occasional users (second-highest number of trips replaced). In the case of occasional users, potentially, bike-sharing can replace ride-hailing services. Nonetheless, this study will not focus on the differences between frequent and occasional users but on determining the factors influencing trip generation or substitution with public BSS. We acknowledge the importance of evaluating the differences in choices between occasional and frequent bike-sharing users, which should be further researched.

3.3. Trip-related variables estimation

The trip-related variables were estimated based on Origin—Destination coordinates. These were geocoded with GoogleMaps API based on the participant's revealed home and work seven-digit Zip Codes or closest Point-of-Interest. The trip distances and travel times were computed using Google maps API for the following transportation modes: walking, car, and public transit. Cycling distances and travel times were estimated with the Open Route Service API for each OD pair (between two BSS stations) for the *cycling-regular* profile that uses a standard bicycle as a transport vehicle. This method considers the route with the minimum travel time and not necessarily the most direct path in a road network that includes the cycling network.

Distances between home/workplace locations and public transit hubs were given by the euclidean distance, and not by using any particular mode, as the proximity and availability of BSS was our concern.

We estimated the car travel costs based on the travel distance and multiplied by constant fuel efficiency and constant fuel price for 2018. We estimated average parking costs per trip based on the data provided by Lisbon's parking manager (EMEL). The average fuel efficiency of the national car stock includes the technological distribution of private car stock (per fuel type—diesel, gasoline, LPG; and per engine size—below 1.4 liters, between 1.4 and 2 liters, above 2 liters) according to the EMEP/EEA classification (EMEP/EEA, 2019). The estimation of constant average fuel efficiency and costs relies on the data of the national car stock distribution provided by the Portuguese National Statistics Institute (INE) and the Portuguese General Directorate for Energy and Geology (DGEG). Public transit costs were calculated with the operator's average one-trip fares, distinguishing urban and suburban trips (under and above 20 km).

3.4. Dataset descriptive statistics

Tables 3 and 4 present the descriptive statistics of our final dataset. The *cycling network dependence* variable translates how the participants perceive their dependence on the existence of segregated cycling infrastructure for their trips. The *cycling network dependence* translates inversely to which degree the respondent feels confident in riding in traffic. They were asked to classify their dependence from 0 (not dependent) to 100 (totally dependent).

3.5. Conditional logit model

A conditional logit model was used to estimate the effects of sociodemographic and trip-related variables with two possible outcomes. The population surveyed had two mutually exclusive options to decide upon: generating a new trip or replacing previous modes of a trip they were planning to make, irrespective of the BSS availability. We used open-source *PandasBiogeme* software for the conditional binary logit model estimation (Bierlaire, 2018).

We consider two discrete outcomes: i) GIRA trip j generated (it would not occur if the BSS would not exist), and ii) a GIRA trip j replacing other modes. The model's framework considers the choice of a person i in performing the discrete outcome j, based on a linear function, T (Washington et al., 2011):

$$T_{ij} = \beta_j X_{ij} + \varepsilon_{ij} \tag{1}$$

where $\beta_j X_{ij}$ is the systematic component of the model; β_j is a vector of coefficients of j that is estimated through the calibration; X_{ij} is a vector of explanatory variables and ε_{ij} is the random component of the model, assumed to have a Gumbel distribution (Generalized Extreme Value distribution—Type 1).

Thereby, the probability (P_{ij}) of a trip i being generated or replacing another mode is calculated with the following equation (Washington et al., 2011):

$$P_{ij} = \frac{\exp\ [\beta_j X_{ij}]}{\sum_j \exp\ [\beta_j X_{ij}]} \tag{2}$$

where j corresponds to two alternative outcomes.

Logit models require the independence of observations and little or no multicollinearity among the independent variables and assume the linearity of independent variables (Washington et al., 2011).

For the maximum likelihood estimation, goodness-of-fit statistics were computed. The McFadden adjusted ρ^2 statistic was selected to quantify the explained variance of the fitted models (Hensher et al., 2005). Where LL^0 and LL^* are the Log-likelihood of the base and the estimated models, respectively. The ρ is related to the number of parameters used in the predicted model, ensuring that overfitting does not occur and the model is parsimonious.

4. Results

4.1. Significant variables

We analyzed a set of variables that we categorized into five dimensions: sociodemographic (SDC), mobility options and travel habits before shifting to bike-sharing (MTH), cycling habits and expertise attributes (CHE), access to cycling facilities and infrastructures (CFI), and built-environment attributes (BE). Twenty-two parameters were calibrated to identify the potential effects of each independent variable. We calibrated the model with a random selection of 80% of the sample, while 20% was used for validation.

Although researchers commonly use a 5% cutoff p-value to determine the significance level (i.e., t-test above 1,96 absolute value for a 95% confidence level), 10% (i.e., an equivalent t-test above 1,68) is widely adopted in transportation studies (Handy & Clifton, 2001; Handy et al., 2005; Ma & Cao, 2019, just to mention a few). Our final models considered statistically significant explanatory variables, with a minimum confidence level of 90%, i.e., 10% p-value, except for the variable *Cycling network dependence* (refer to Table 5). When using discrete choice

Table 3. Descriptive statistics—categorical variables.

Variable	%
Type of trip (frequent/occasional)	68.7/31.3
Gender (female/male)	33.2/66.8
Trip replacement	
Generated	21.1
Walk	21.9
Bike	2.0
Car	23.1
Public Transit	31.8
Children in the household (< 12 years/ >= 12 years/ No)	11.8/26.9/61.3
Education level (Higher/ Other)	83.4/16.6
Employment condition (Job with the fixed place/ No job or no fixed place)	67.1/32.9
Self-assessment of income status	
Live without difficulties	39.4
Live with moderate ease	48.4
Live with difficulties	4.9
No income	7.3
Usual transportation mode	
Walk	10.5
Bike	14.0
Public Transit	25.4
Car	27.6
PT + Car	2.6
PT + Bike	13.3
Bike + Car	6.5
Transit pass monthly holder (Yes/no)	40.7/59.3
BSS pass holder (Annual/ Other)	94.6/5.4
Car in the household (Yes/ No)	82.9/17.1
Owns a bicycle (Yes/ No)	49.9/50.1
Room to park a bike at Work (Yes/ No)	55.7/44.3
Bicycle proficiency	
Experienced	33.3
Somewhat experienced	49.0
Beginner	17.1
Inexperienced	0.6
Helmet wearing when using BSS (Yes/ No)	7.9/92.1
Rides BSS when raining (Yes/ No)	50.9/49.1
GIRA dock at 5 minutes from home (Yes/ No)	55.5/44.5
Gave up GIRA to use her bicycle (Yes/ No)	2.2/97.8

Table 4. Descriptive statistics—continuous variables.

Variable	Mean	sd.	Median
Age	35.7	10.9	35
Cycling network dependence [0-100]	55.1	33	61
Frequency of BSS usage [times per month]	14.5	13.2	10
Estimated commuting trip duration [minutes]			
Walk	75.2	70.7	52.0
Bike	23.2	22.6	15.8
Public Transit	29.3	18.4	24.9
Car	13.7	6.7	12.8
Estimated commuting trip distance [km]			
Walk	5.969	5.746	4.094
Bike	6.691	6.488	4.594
Public Transit	6.969	7.107	4.747
Car	7.388	0.708	5.017
Estimated commuting trip cost [€]			
Public Transit	0.777	0.138	0.723
Car	2.400	1.200	2.000
Estimated distance from Home to … station [km]			
Metro	5.797	23.573	0.603
Train	1.697	1.149	1.420
Bus	0.176	0.162	2.152
Ferry	6.731	4.575	5.896
Estimated distance from Work to … stations [km]			
Metro	1.780	10.913	0.349
Train	1.286	0.800	1.251
Bus	0.160	0.134	0.126
Ferry	5.000	3.203	4.206

models for explanatory and exploratory purposes (within the range of observed values), higher p-values are acceptable (Washington et al., 2011).

4.2. Model and interpretation

Table 5 shows the results of the conditional logit model parameters that estimate the probability of the BSS generating new trips or replacing other modes. In the case of replacing other modes, we included all modes presented as options in a single alternative “Replacing trip” foot/bicycle, motorcycle, metro, train, bus, and car. Thereby, we model new bike-sharing trips versus replacing trips of all modes with bike-sharing. Variables with high correlation and collinearity were not included in the model. All the variables were included in the utility function of the alternative "*Generated trips*" to simplify the results’ interpretation. The alternative specific constant (ASC) was fixed for the alternative "Replacing trips," and, consequently, the "*Replacing trips*" alternative’s utility function includes only the specific constant (ASC_REP). ASC_REP is negative, suggesting that BSS are more likely to replace trips previously made by other modes than generate new trips (although the parameter is not statistically significant).

The model presents a rho square of 0.39, which is a good fit of the model to the data. Coefficients show logical signs, and all are significant with a *p-value* below 0.1, except for the variable "Cycling network," which had a *p-value* of 0.3. Although the confidence level is around 70%, we decided to keep the variable as it brings some explanation on the importance of having access to the cycle network of Lisbon.

Table 5. Conditional logit model parameters: generating vs. replacing.

Group	Variable	Value	Std err	*t*-test	*p*-value		Aggregate Direct Elasticities
	ASC_REP	−0.019	0.282	−0.07	.945		
SDC	Gender (1: female)	−0.359	0.114	−3.14	.002	**	−0.086
MTH	Regular user of PT and Bike	−0.429	0.177	−2.42	.016	**	−0.033
	Regular cyclist	−0.860	0.232	−3.70	.000	**	−0.037
	Regular car user	0.282	0.117	2.41	.016	**	0.075
	Yearly BSS pass	−0.570	0.199	−2.87	.004	**	−0.392
CHE	Experienced cyclist	−0.231	0.120	−1.92	.055	*	−0.047
	User of BSS when raining	−0.339	0.108	−3.15	.002	**	−0.105
	BSS trip frequency	−0.021	0.005	−4.25	.000	**	−0.167
CFI	Bike parking at work	0.289	0.106	2.73	.006	**	0.130
	Cycling network	0.002	0.002	1.01	.313		0.072
	5-min access to BSS (home)	−0.359	0.105	−3.41	.001	**	−0.132
	5-min access to BSS (work)	−0.277	0.112	−2.47	.014	**	−0.131
BE	Distance to Bus stop (work)	0.558	0.379	1.47	.141		0.068
	Distance to Train station (work)	−0.141	0.067	−2.10	.036	**	−0.131

Goodness-of-fit indicators.
Sample Size: 2,489.
Number of estimated parameters: 15.
Init log-likelihood: -1,945.96.
Final log-likelihood: -1,176.15.
Likelihood ratio test for the init. Model: 1,539.61.
Rho-square for the init. Model: 0.396.
Rho-square-bar for the init. Model: 0.388.
Legend: sociodemographic attributes (SDC), mobility options and travel habits prior to shifting bike-sharing (MTH), cycling habits and experience (CHE), access to cycling facilities and infrastructures (CFI), and built-environment attributes (BE); **p-value < 0.05; *p-value < 0.1.

The following table summarizes the contribution of each variable to increase the likelihood of the trips being generated after Lisbon's BSS began operating or replacing other modes.

Women have a lower probability of generating new trips with GIRA. Regular car users are more likely to generate new trips with GIRA than replacing car trips. On the other hand, regular bicycle users or regular PT users combined with bicycles are less likely to generate new BSS trips. An explanatory variable standing out in this model, in terms of magnitude, is the annual BSS subscription. GIRA subscribers are less likely to generate new trips and, thus, more likely to replace trips from other modes.

As for cycling habits, having a higher cycling experience, being a frequent cyclist, and using the BSS while raining, decreases the likelihood of generating new trips. Access to bike parking at work is more likely to generate BSS trips. Notice that GIRA is a dock-based system that does not require parking spaces at work. Nonetheless, we acknowledge that parking spaces might attract trips from private bicycle users.

Finally, built-environment attributes (BE) had only a minor effect in the "generating versus replacing" conditional logit model. A higher distance from the workplace to the train station decreases the probability of generating trips with GIRA. Access to a GIRA station within a 5-min walk from home or work is less likely to generate new GIRA trips than to replace other modes. The availability of a cycling network was not a statistically significant variable for this model at the 90% confidence level.

5. Discussion of results

We found that bike-sharing users who subscribe to a yearly pass have a more significant influence in substituting modes than generating new trips, making sense from two perspectives. Frequent BSS users, who are more likely to use bike sharing for commuting trips, as suggested by the literature (Talavera-Garcia et al., 2021), are more likely to subscribe to a yearly pass and replace another mode for the same trip. For the occasional BSS users, who made the once-in-a-year decision to subscribe to an annual pass, it is more intuitive to consider bike sharing as a modal option with no extra costs when making an occasional trip. These trips often can be an alternative to a car, taxi, or ride-hailing. On the other hand, non-yearly pass subscribers are more susceptible to not considering bike-sharing as a mobility option for frequent or occasional trips. Promoting policy packages to increase access to yearly passes could potentially influence higher use of GIRA to replace frequent or occasional journeys, such as integrating GIRA's subscription to the public transit pass or other transportation services.

Regular car users are more likely to generate new bike-sharing trips since they are more likely to use BSS for recreational purposes than for regular trips or errands. Regular cyclists are less likely to generate new trips with BSS. Instead, they tend to replace some of their usual trips with GIRA. However, the lack of bike-sharing stations near home makes it less likely for people to shift from regular commuting mode to bike-sharing. In this case, GIRA is used mainly for recreational purposes. Our results confirm that implementing GIRA stations within 5-min walking distances to home and work locations can attract users to shift their frequent or occasional trips to bike-sharing. This finding is in the same direction as Moura and Félix (2019), stating that GIRA subscribers are located close to a bike-sharing station. As such, planners should locate BSS stations close to high-density residential and working areas.

Income and trip-related variables such as trip distance, duration, and cost were not statistically significant and thus not considered in this model, suggesting that they are irrelevant for substituting modes or generating a new trip. The

Table 6. Determinants for generating new trips vs. replacing previous modes.

Group	Variable	Generating trips	Replacing modes
SDC	Gender (1: female)	↓	↑
MTH	Regular user of PT and Bike	↓	↑
	Regular cyclist	↓	↑
	Regular car user	↑	↓
	Yearly BSS pass	↓	↑
CHE	Experienced cyclist	↓	↑
	User of BSS when raining	↓	↑
	Bike trip frequency	↓	↑
CFI	Bike parking at work	↑	↓
	Cycling network	↑	↓
	5-min access to BSS (home)	↓	↑
	5-min access to BSS (work)	↓	↑
BE	Distance to Bus stop (work)	↑	↓
	Distance to Train station (work)	↓	↑

Legend: ↓ - Decreases the likelihood; ↑ - increases the likelihood.

result is understandable, given that the respondents already chose to use bike-sharing. Therefore, we are not comparing the alternative of bike-sharing with other modes, in which travel time and distances would probably have a significant effect. Trip-related variables tend to have more of an effect on mode choice and not in differing the demand nature of the bike-sharing trip (i.e., generating or replacing trips). One reason is people choosing to use bike-sharing would already tend to have short travel times and distances.

Furthermore, Wu et al. (2019) state that high costs and increasing subscription plans can reduce frequent users using BSS for short distances. Instead, these users will prefer an alternative mode choice for short-distance trips. In the case of GIRA, as income is not significant, this may suggest that the cost of using the GIRA is inclusive for both frequent and occasional users. Also, the high percentage of yearly pass subscription users compared to unique pass users confirms this fact (refer to Table 1). Policies favoring waiving or integrating the BSS cost in public transit passes may enhance a higher bike-sharing adoption (Table 6).

6. Conclusions

This paper analyses which attributes are more relevant for Lisbon's BSS users (frequent or occasional) to generate a new trip or replace other modes of an existing trip. A survey collected answers from 5,053 GIRA users, of which 3,112 were validated. The valid sample corresponded to approximately 20% of all GIRA's users. We used a conditional logit model with two outcomes (generating or replacing trips) to determine the most relevant determinants. The results bring insights which support the definition of public policies to increase the impact of BSS on the generation of new trips (and thus satisfying an existing latent demand) or replacing other modes. We found that having a BSS station within a 5-min walking distance to home can influence frequent or occasional users to replace trips. Nonetheless, 62% of users from the sample are within a 5-min walking distance from a station (refer to Table 2), suggesting that BSS expansion projects should focus on denser residential areas in Lisbon.

Additionally, citizens who subscribe to a yearly bike-sharing pass tend to replace more trips than generate them for frequent and occasional users. While the literature indicates that frequent users use bike-sharing for commuting, occasional users are more likely to travel for recreational purposes. Thereby, replacing trips for both types of users can have short and long-term benefits in increasing cycling levels for recreational and home-work-based trips.

The results also demonstrate a challenge in making regular car users substitute their cars for bike-sharing since they tend to use bike-sharing to generate new trips. If the policy goal is to reduce regular car trips, it may be necessary to promote cycling policies and restrictions on car use. Although our initial findings suggest that bike-sharing replaces walking and the metro, it would be interesting to understand the determinants for substituting each transport mode in future studies. We acknowledge that trips' substitution from other modes should be further researched and we suggest doing a conditional multinomial or nested logit model. As a result, it would be possible to analyze if the BSS promotes less car use, which variables influence mode choice, and how municipalities and agencies can influence people to shift to BSS, shifting away from individual motorized modes.

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The authors report there are no competing interests to declare.

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References

Akar, G., & Clifton, K. J. (2009). The influence of individual perceptions and bicycle infrastructure on the decision to bike. *Transportation Research Record: Journal of the Transportation Research Board*, *2140*(1), 165–172. https://doi.org/10.3141/2140-18

Ashraf, M. T., Hossen, M. A., Dey, K., El-Dabaja, S., Aljeri, M., & Naik, B. (2021). Impacts of bike sharing program on subway ridership in New York City. *Transportation Research Record: Journal of the Transportation Research Board*, *2675*(9), 924–934. https://doi.org/10.1177/03611981211004980

Bierlaire, M. (2018). PandasBiogeme: A short introduction. *Technical Report TRANSP-OR 181219, Transport and Mobility Laboratory, ENAC, EPFL*.

Buck, D., Buehler, R., Happ, P., Rawls, B., Chung, P., & Borecki, N. (2013). Are bikeshare users different from regular cyclists? A first look at short-term users, annual members, and area cyclists in the

Washington, D.C., Region. *Transportation Research Record: Journal of the Transportation Research Board*, *2387*(1), 112–119. https://doi.org/10.3141/2387-13

Municipal de Lisboa, C. (2021). *Como Pedala Lisboa? Rumo a uma cidade mais sustentável, inclusiva e segura*. https://www.lisboa.pt/fileadmin/cidade_temas/mobilidade/documentos/Como_Pedala_Lisboa.pdf

Cervero, R. (1996). Mixed land-uses and commuting: Evidence from the American Housing Survey. *Transportation Research Part A: Policy and Practice*, *30*(5), 361–377. https://doi.org/10.1016/0965-8564(95)00033-X

Chen, P., Zhou, J., & Sun, F. (2017). Built environment determinants of bicycle volume: A longitudinal analysis. *Journal of Transport and Land Use*, *10*(1), 655–674. https://doi.org/10.5198/jtlu.2017.892

Chen, Z., van Lierop, D., & Ettema, D. (2022). Dockless bike-sharing's impact on mode substitution and influential factors: Evidence from Beijing. *Journal of Transport and Land Use*, *15*(1), 71–93. https://doi.org/10.5198/jtlu.2022.1983

Clifton, K. J., & Moura, F. (2017). Conceptual framework for understanding latent demand: Accounting for unrealized activities and travel. *Transportation Research Record: Journal of the Transportation Research Board*, *2668*(1), 78–83. https://doi.org/10.3141/2668-08

Dill, J., & Carr, T. (2003). Bicycle commuting and facilities in major U.S. cities: If you build them, commuters will use them—Another look, 1–9.

Dill, J., & Rose, G. (2012). E-bikes and transportation policy: Insights from early adopters. *Transportation Research Record: Journal of the Transportation Research Board*, *2314*(1), 1–6. https://doi.org/10.3141/2314-01

EMEP/EEA. (2019). Air pollutant emission inventory guidebook 2019. EEA Technical report N°. 13/2019. Updated 2019, European Environment Agency, Luxembourg, ISBN 978-92-9480-098-5

Fan, A., Chen, X., & Wan, T. (2019). How have travelers changed mode choices for first/last mile trips after the introduction of bicycle-sharing systems: An empirical study in Beijing, China. *Journal of Advanced Transportation*, *2019*, 1–16. https://doi.org/10.1155/2019/5426080

Félix, R. (2019). [*Barriers and motivators to bicycle in low cycling maturity cities: Lisbon case study*]. [Doctoral dissertation, University of Lisbon]. Instituto Superior Técnico, Universidade de Lisboa Repository. https://sotis.tecnico.ulisboa.pt/record/c384735d-1f3c-4dd8-a216-c4a5295d0006

Félix, R., Cambra, P., & Moura, F. (2020). Build it and give 'em bikes, and they will come: The effects of cycling infrastructure and bike-sharing system in Lisbon. *Case Studies on Transport Policy*, *8*(2), 672–682. https://doi.org/10.1016/j.cstp.2020.03.002

Félix, R., Moura, F., & Clifton, K. J. (2019). Maturing urban cycling: Comparing barriers and motivators to bicycle of cyclists and non-cyclists in Lisbon, Portugal. *Journal of Transport & Health*, *15*, 100628. https://doi.org/10.1016/j.jth.2019.100628

Fernández-Heredia, Á., Jara-Díaz, S., & Monzón, A. (2016). Modelling bicycle use intention: The role of perceptions. *Transportation*, *43*(1), 1–23. https://doi.org/10.1007/s11116-014-9559-9

Fishman, E., Washington, S., & Haworth, N. (2013). Bike share: A synthesis of the literature. *Transport Reviews*, *33*(2), 148–165. https://doi.org/10.1080/01441647.2013.775612

Fishman, E., Washington, S., & Haworth, N. (2014). Bike share's impact on car use: Evidence from the United States, Great Britain, and Australia. *Transportation Research Part D: Transport and Environment*, *31*, 13–20. https://doi.org/10.1016/j.trd.2014.05.013

Frade, I., & Ribeiro, A. (2014). Bicycle sharing systems demand. *Procedia—Social and Behavioral Sciences*, *111*, 518–527. https://doi.org/10.1016/j.sbspro.2014.01.085

Hamidi, Z., Camporeale, R., & Caggiani, L. (2019). Inequalities in access to bike-and-ride opportunities: Findings for the city of Malmö. *Transportation Research Part A: Policy and Practice*, *130*, 673–688. https://doi.org/10.1016/j.tra.2019.09.062

Handy, S. L., Cao, X., & Mokhtarian, P. (2005). Correlation or causality between the built environment and travel behavior? Evidence from Northern California. *Transportation Research Part D: Transport and Environment*, *10*(6), 427–444. https://doi.org/10.1016/j.trd.2005.05.002

Handy, S. L., & Clifton, K. J. (2001). Local shopping as a strategy for reducing automobile travel. *Transportation*, *28*(4), 317–346. https://doi.org/10.1023/A:1011850618753

Handy, S. L., Wee, B. V., & Kroesen, M. (2014). Promoting cycling for transport: Research needs and challenges. *Transport Reviews*, *34*(1), 4–24. https://doi.org/10.1080/01441647.2013.860204

Heinen, E., van Wee, B., & Maat, K. (2010). Commuting by bicycle: An overview of the literature. *Transport Reviews*, *30*(1), 59–96. https://doi.org/10.1080/01441640903187001

Hensher, D., Rose, J., & Greene, W. (2005). *Applied choice analysis: A primer* (2nd ed.). Cambridge University Press.

Hsieh, H., Lin, F., Jiang, J., Kuo, T., & Chang, Y. (2021). Inferring long-term demand of newly established stations for expansion areas in bike sharing system. *Applied Sciences*, *11*(15), 6748. https://doi.org/10.3390/app11156748

Instituto Nacional de Estatística. (2011). *Censos 2011: Resultados Definitivos—Portugal*. https://censos.ine.pt/xportal/xmain?xpid=CENSOS&xpgid=censos2011_apresentacao

Instituto Nacional de Estatística. (2018). *Mobilidade e funcionalidade do território das Áreas Metropolitanas do Porto e de Lisboa 2017*. https://www.ine.pt/ngt_server/attachfileu.jsp?look_parentBoui=350975555&att_display=n&att_download=y

Krykewycz, G. R., Puchalsky, C. M., Rocks, J., Bonnette, B., & Jaskiewicz, F. (2010). Defining a primary market and estimating demand for major bicycle-sharing program in Philadelphia, Pennsylvania. *Transportation Research Record: Journal of the Transportation Research Board*, *2143*(1), 117–124. https://doi.org/10.3141/2143-15

Ma, L., & Cao, J. (2019). How perceptions mediate the effects of the built environment on travel behavior? *Transportation*, *46*(1), 175–197. ISO 690 https://doi.org/10.1007/s11116-017-9800-4

Ma, L., & Dill, J. (2015). Associations between the objective and perceived built environment and bicycling for transportation. *Journal of Transport & Health*, *2*(2), 248–255. https://doi.org/10.1016/j.jth.2015.03.002

Midgley, P. (2011). *Bicycle-sharing schemes: Enhancing sustainable mobility in urban areas*. New York: United Nations. http://www.un.org/esa/dsd/resources/res_pdfs/csd-19/Background-Paper8-P.Midgley-Bicycle.pdf

Moura, F., & Félix, R. (2019). *Externalidades socioeconómicas do sistema de bicicletas públicas partilhadas (GIRA) na cidade de Lisboa—Parte II*. Report submitted to EMEL, Lisbon, Portugal.

Muhs, C. D., & Clifton, K. J. (2016). Do characteristics of walkable environments support bicycling? *Toward a Definition of Bicycle-Supported Development*, *2*, 1–42.

Ogilvie, F., & Goodman, A. (2012). Inequalities in usage of a public bicycle sharing scheme:Sociodemographic predictors of uptake and usage of the London (UK) cycle hire scheme. *Preventive Medicine*, *55*(1), 40–45. https://doi.org/10.1016/j.ypmed.2012.05.002

Pincha, J. (2018, October 18). Escassez de bicicletas é pedra no caminho das Gira para fora de Lisboa. *Público*. https://www.publico.pt/2018/10/18/local/noticia/escassez-de-bicicletas-e-pedra-no-caminho-das-gira-para-fora-de-lisboa-1847967

Popovich, N., Gordon, E., Shao, Z., Xing, Y., Wang, Y., & Handy, S. (2014). Experiences of electric bicycle users in the Sacramento, California area. *Travel Behaviour and Society*, *1*(2), 37–44. https://doi.org/10.1016/j.tbs.2013.10.006

Pucher, J., & Buehler, R. (2006). Why Canadians cycle more than Americans: A comparative analysis of bicycling trends and policies. *Transport Policy*, *13*(3), 265–279. https://doi.org/10.1016/j.tranpol.2005.11.001

Pucher, J., & Buehler, R. (2008). Making cycling irresistible: Lessons from The Netherlands, Denmark and Germany. *Transport Reviews*, *28*(4), 495–528. https://doi.org/10.1080/01441640701806612

Pucher, J., Dill, J., & Handy, S. (2010). Infrastructure, programs, and policies to increase bicycling: An international review. *Preventive Medicine*, *50* (Suppl 1), S106–S25. https://doi.org/10.1016/j.ypmed.2009.07.028

Saelens, B. E., Sallis, J. F., & Frank, L. D. (2003). Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. *Annals of Behavioral Medicine*, *25*(2), 80–91. https://doi.org/10.1207/S15324796ABM2502_03

Shaheen, S., Guzman, S., & Zhang, H. (2010). Bikesharing in Europe, the Americas, and Asia. *Transportation Research Record: Journal of the Transportation Research Board*, *2143*(1), 159–167. https://doi.org/10.3141/2143-20

Talavera-Garcia, R., Romanillos, G., & Arias-Molinares, D. (2021). Examining spatio-temporal mobility patterns of bike-sharing systems: The case of BiciMAD (Madrid). *Journal of Maps*, *17*(1), 7–13. https://doi.org/10.1080/17445647.2020.1866697

Teixeira, J. F., Silva, C., & Moura e Sá, F. (2021). Empirical evidence on the impacts of bikesharing: A literature review. *Transport Reviews*, *41*(3), 329–351. https://doi.org/10.1080/01441647.2020.1841328

Vale, D. S., Saraiva, M., & Pereira, M. (2015). Active accessibility: A review of operational measures of walking and cycling accessibility. *Journal of Transport and Land Use*, *9*(1), 209-235. https://doi.org/10.5198/jtlu.2015.593

Wang, M., & Zhou, X. (2017). Bike-sharing systems and congestion: Evidence from US cities. *Journal of Transport Geography*, *65*(May), 147–154. https://doi.org/10.1016/j.jtrangeo.2017.10.022

Washington, S., Karlaftis, M., & Mannering, F. (2011). *Statistical and econometric methods for transportation data analysis* (2nd ed.). Chapman and Hall/CRC.

Wei, X., Luo, S., & Nie, Y. (. (2019). Diffusion behavior in a docked bike-sharing system. *Transportation Research Part C: Emerging Technologies*, *107*(August), 510–524. https://doi.org/10.1016/j.trc.2019.08.018

Wu, L., Gu, W., Fan, W., & Cassidy, M. J. (2020). Optimal design of transit networks fed by shared bikes. *Transportation Research Part B: Methodological*, *131*, 63–83. https://doi.org/10.1016/j.trb.2019.11.003

Wu, Y. H., Kang, L., Hsu, Y. T., & Wang, P. C. (2019). Exploring trip characteristics of bike-sharing system uses: Effects of land-use patterns and pricing scheme change. *International Journal of Transportation Science and Technology*, *8*(3), 318–331. https://doi.org/10.1016/j.ijtst.2019.05.003

Zhang, Y., Thomas, T., Brussel, M. J. G., & Van Maarseveen, M. F. A. M. (2016). Expanding bicycle-sharing systems: Lessons learnt from an analysis of usage. *Plos One*, *11*(12), e0168604. https://doi.org/10.1371/journal.pone.0168604

Zhu, W., Pang, Y., Wang, D., & Timmermans, H. (2013). Travel behavior change after the introduction of public bicycle systems: Case study in Minhang District, Shanghai. Paper presented at the Transportation Research Board, 92nd Annual Meeting, DC.