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Research Article

Planning and Design of Equitable Free-Floating Bike-Sharing Systems Implementing a Road Pricing Strategy

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Promoting a more sustainable development of urban realities is one of the most important goals of the recent decades. One possible strategy to undertake in order to achieve this objective is the implementation of a road pricing: tolling private cars when passing by certain roads of the network could be a way to tone down the traffic congestion and, at the same time, encourage the shifting towards more sustainable means of transport. In this context, we suggest a method to distribute in a fair way the outcomes/revenues of this pricing strategy. In particular, we propose to design a free-floating bike-sharing system whose resources could be allocated in the territory according to spatial and social equity principles. The relation between the amount of the tolls, the number of days of application of the policy, and the pursued equity is investigated, and both a numerical application (to a test network and to a real case study) and a sensitivity analysis in support of the method are enclosed.

1. Introduction

Sustainability can be counted as one of the most decisive challenges of the 21st century; essentially, it involves urban environments to be more environmentally friendly. However, this goal must not be achieved at the cost of increased inequalities among individuals, aiming at the contrary to a substantial improvement of the quality of their life.

Every transport policy is inherently spatial: every change in the transportation system impacts the distribution of costs and benefits associated with one or more forms of mobility [1]. This is the reason why it is essential to measure the equity outcomes of any new policy strategy that aims to make the cities more sustainable [2].

Car dependence and a car-oriented development can be considered as main threats to the sustainability of urban transportation system [3]: cars contribute to considerably increasing the level of traffic, the related congestion, and the pollution [4]. It is thus essential to enhance the use of alternative modes of transportation for the sake of congestion mitigation [3]. Both public transport and vehicle-shared system need to be promoted and encouraged since they result in being more space efficient; they can satisfy the mobility needs of a quite large share of commuters; they are more environmentally friendly, thanks to the reduction in fuel consumption and emissions. Therefore, among the policy strategies oriented to the sustainability that wants to migrate part of commuters toward different transportation alternatives [5], one of the most effective is the implementation of urban road pricing [6].

The congestion pricing is based on an effective management of the transportation demand; it has been successfully adopted in some cities, such as Singapore and London [7–9], as a strategy to ease urban traffic congestion through tolling on peak hours or jammed links [10].

In this paper, we propose a methodology to invest the revenues raised by the pricing strategy in a free-floating bike-sharing system (FFBSS) [11]: this can be a valuable option to redistribute the collected money in a way that gives the potential losers a real, and not just hypothetical, compensation. The policy maker needs to be supported in his/her decision about the amount of fare to establish, the sustainable modal split to achieve in the network, and the most equitable way to allocate resources on the urban context under analysis. The novelty of our approach lies in the proposal of an equity-based optimization model to plan and design a FFBSS that could provide a sustainable modal alternative to every individual/group of people, taking into account both their spatial and their social needs. In this way, the outcome of congestion pricing is an effective policy that promotes a greater sustainability.

Summing up, not only are we suggesting an alternative way to use the money collected thanks to a congestion pricing strategy (sustainable, but also easy to put into practice on the territory), but also we are presenting a methodology to incorporate equity considerations in the design process of a FFBSS as they seem to have been too often overlooked.

The rest of the paper is organized as follows. After a literature review that clarifies the main issues addressed in this study, we move on contextualizing the problem to solve and the suggested methodology to deal with it. Both a test network and a real case study application are presented, together with a sensitivity analysis, aiming at assisting the decision maker in his/her strategical decisions, suggesting how to properly carry out a congestion price strategy on the network, fairly redistributing the derived revenues among all the users.

2. Literature Review

Traffic congestion mitigation on road networks can be considered as one of the major issues to face in urban transportation systems. One effective strategy pursued by policy makers to alleviate it consists in the application of a congestion pricing, as it is capable of solving, or at least mitigating, environmental and congestion problems in urban areas, generating also a net welfare surplus.

Among the different possible schemes, the cordon-based system has been the most widely studied charging regime in literature. This is probably due to the actual possibility to implement this system in practical contexts [12]. Incorporating this charging system into transportation models is also quite simple: a possible way to do it is considering the fare as an additional delay converted by the concept of the value of time imposed on the drivers traveling on tolled roads [13].

The main effects of congestion pricing can be classified into four groups [14]:

(1) Higher travel costs for those who travel by car on the charged links during charged hours

(2) Changed travel behavior in order to avoid the charge, for example, by switching mode and/or destination

(3) Shorter travel times for those who travel by car in the charged areas/on the charged arcs during charged hours

(4) Revenue generation, which can be spent in different ways.

This paper focuses on the fourth aspect, the revenue generation. The most common way to redistribute revenues consists in spending on specific transportation-related improvements (i.e., increasing the transit service quality and/or encouraging the modal shift): London, for example, has used most of the revenues to increase its bus services reliability [15]. Alternatively, it could be addressed to the road network, aiming at enhancing its capacity and reducing congestion [16]. Another feasible method is to redistribute revenues to individuals rather than spending on public work: think, for instance, to the credit-based congestion pricing, where all drivers receive a share of the previous month's collected revenues [17]. Viable option could be also the revenue redistribution in terms of changes in taxation linked to congestion pricing: in this context, Lewis [18] proposed a progressive and refundable mobility tax credit, under which all households would receive a tax credit based on income, location, number of wage earners, and other potential criteria.

It has to be noted that, in general, different ways of recycling will also have different equity outcomes for different population groups and areas [19]. As an example, we can mention Eliasson and Mattson [14] that studied the impacts of revenue distribution in the Stockholm congestion pricing trial. They analyzed the net benefit deriving from the implementation of such a policy looking at groups based on gender, income, household type, occupation, and neighborhood, considering four possible ways to redistribute revenues: lump sum, transit investments, reductions in driving costs, and decreases in income tax.

Therefore, we can assert that using the revenues generated from pricing policies in an effective way is a crucial step toward addressing equity concerns and restoring balance.

For the sake of clarity, we are going to briefly explain what is the meaning of the word "equity." In the transportation planning framework, it generally refers to a fair distribution of benefits and costs among different individuals/groups. It is possible to identify two main perspectives of equity: horizontal/spatial and vertical/social. According to the first one, it is important to treat people in equal circumstances equally: no individual or group has to be unjustifiably preferred over another. Applying this principle, for example, burdens and benefits deriving from a public transportation project have to be evenly distributed throughout the community.

The vertical equity, on the other side, focuses on the social existing inequalities. It considers fair a distribution that is able to provide a larger share of resources to the most disadvantaged individual or groups (in terms of income, travel flexibility, access to car, age, gender, and so on) belonging (i.e., living) to a certain study area [20]. Recalling the previous example, this happens if vulnerable categories receive a priority consideration for public transportation projects.

With this paper, we are proposing to use the revenue collected by a congestion price policy to implement a free-floating BSS. Free-floating BSS constitute a more flexible and spontaneous category of vehicle-sharing: they allow hiring and returning a bicycle very close to the demand points, without being forced to pass by a station before or after the ride [21]. The reason for this revenue redistribution choice lies in the fact that FFBSS represent a sustainable alternative of transportation that helps in the global reduction of traffic and emissions in urban realities. Furthermore, they allow savings on start-up costs, for example, avoiding the construction of stations and kiosk machines and on maintenance

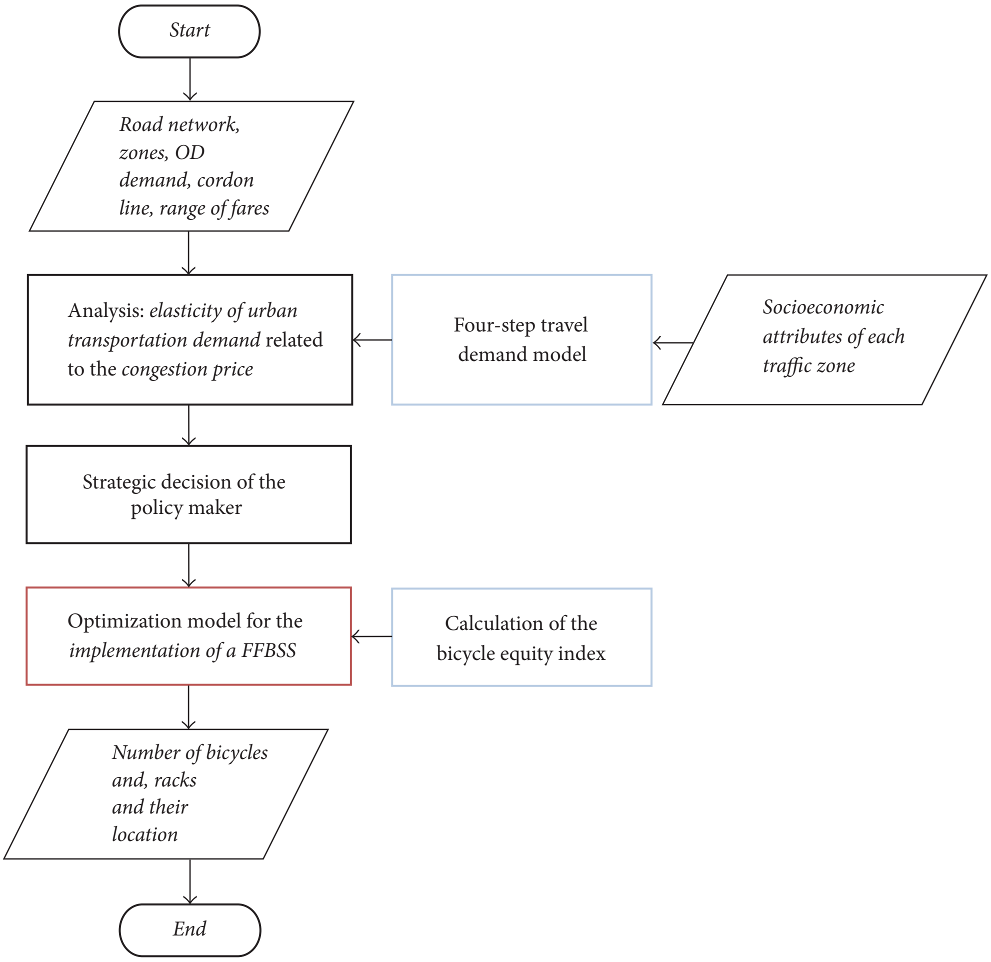

Figure 1: Flowchart of the proposed methodology.

costs, in comparison to the traditional station-based ones [11].

To the best of our knowledge, little attention has been paid to the network design of these systems. This concerns, for example, the distribution of racks on the territory and the associated configuration of the bicycles at the beginning of the day, usually coincident with the one that seems to satisfy the bike requests at that moment. However, especially in peak hours, for trips that are not purely recreational but necessary (e.g., to reach schools or jobs), other criteria (i.e., the demographic and economic composition of the population) often overlooked have to be taken into account. In this context, the aforementioned equity principles come into play. This is the reason why, in this paper, we focus on a fair implementation on the territory of a free-floating BSS, able to consider both the spatial and social necessities (i.e., equity aspects) of any different group of individuals.

3. Problem Description and Mathematical Notation

As stated in the introductory section of this paper, in order to mitigate the traffic congestion and promote a greater sustainability, one possible strategy may consist of applying a cordon-based road congestion pricing to the case study under analysis. We suggest using the resulting revenue to implement a free-floating BSS in the network that could satisfy the users' demand and constitute a viable transportation alternative for their everyday trips.

Symbols and notations adopted throughout the paper are presented in notations section.

4. Model Development

In this section, we are going to present and describe the proposed approach, whose main steps are summarized by the flowchart in Figure 1.

The starting point of our methodology is a multimodal network, with a cordon-based road congestion pricing to be applied during a certain daily time window Δt (e.g., peak hours only on weekdays). In this transportation systems, private cars only are subjected to the toll payment. Moreover, a public transportation system is operating on the network, and a bike-sharing system may potentially be implemented. In this framework, a preliminary analysis needs to be carried out, aiming at investigating the relation between the amount of the toll and the associated modal split and traffic assignment on the network (calculated by a four-step model, described in the next subsection), assuming the elasticity of the urban transportation demand. Elasticity is defined as the percentage change in the use of a specific transportation mode, resulting from a 1% change in an attribute, such as price, travel time, or frequency of the service [22]. In this framework, adding a congestion price scheme on the network we are changing the travel cost for car's drivers.

On the basis of the outcomes of this analysis, the decision-maker establishes the desired modal split (i.e., the percentage of demand to be satisfied by public transit and/or bicycles, looking at the promotion of sustainable transportation) and the period of time Δz (number of days) intended to collect the money deriving from the road pricing strategy. The supposed final revenue could then be calculated.

Using the available budget, new free-floating resources (namely, bicycles and racks) can be allocated in the network (using the proposed optimization model) according to horizontal and vertical equity assumptions, to better satisfy the expected bicycle demand resulting in the imposition of the toll.

4.1. Four-Step Trip-Based Travel-Demand Model System. Before getting to the heart of this subsection, an essential premise should be made: travel demand arises from the need of people to carry on with their activities in different locations, and it is strongly influenced by both the activity system and the available transportation opportunities [23]. This means that the introduction of a pricing strategy in a certain reality could entail changes in the system that it becomes necessary to analyze and estimate through mathematical demand models.

A trip-based demand model predicts the average number of trips, having certain features that are performed in a specific time-period. Usually, it is preferable to decompose the global demand function into a product of submodels. One of the most often used sequences is the following, where the elements of the product are, respectively, the trips emission or frequency model, the trips distribution model, the mode choice or modal split model, and the path choice model [23]:

$$\begin{aligned} d^i_{od}\left[s,h,m,k\right] = d^i_o \cdot \left[sh\right]\left(\mathbf{SE},\mathbf{T}\right) \cdot p^i\left[\frac{d}{osh}\right]\left(\mathbf{SE},\mathbf{T}\right) \\ \cdot p^i\left[\frac{m}{oshd}\right]\left(\mathbf{SE},\mathbf{T}\right) \\ \cdot p^i\left[\frac{k}{oshdm}\right]\left(\mathbf{SE},\mathbf{T}\right). \end{aligned} \quad (1)$$

The sequence of submodels in (1), because of its structure, is known as *four-step model*: it reflects an assumption about the order in which decisions are made and about how these decisions affected each other. A synthetic explanation of each submodel is here provided for a better understanding of the following steps of our approach. However, the reader can find a more extensive and detailed description in Cascetta [23].

(i) $d^i_o \cdot [sh](\mathbf{SE},\mathbf{T})$. This is the *trip production or frequency model*. It estimates the average number of trips undertaken by a user in class i with origin in zone o, for purpose s in time-period h; this is called *trip rate*. In this paper, we are going to use a descriptive trip production model, generally used for regularly made trips, such as home-based work or home-based school trips.

(ii) $p^i[d/osh](\mathbf{SE},\mathbf{T})$. This is the *distribution model*. It gives the fraction (percentage) of users in class i who, from their origin zone o, start a trip for purpose s in time-period h traveling to destination zone d.

Multinomial logit models are usually used for destination choice modeling; they take into account the systematic utility expressed as a function $V^u_j(\mathbf{X}^u_j)$ of attributes X^u_{kj} relative to the alternatives j and the user u (with $k \neq j$ and $k \in I^u$). The systematic utility V^u_j may be a function of any type, but it is usually assumed as a linear function, with coefficients β_k, of the attributes X^u_{kj} (see (2)), or of functional transformation $f_k(X^u_{kj})$ of them:

$$V^u_j\left(\mathbf{X}^u_j\right) = \sum_k \beta_k X^u_{kj} = \beta^T \mathbf{X}^u_j. \quad (2)$$

In the framework of our study, the systematic utility $V_{d/osh}$ has different attributes that can be grouped into two main categories: (1) attributes of the activity system in zone d, or attractiveness attributes A'_d; (2) attributes that quantify the accessibility or the travel costs between origin o and destination d, or cost attributes C'_{od}. It follows that

$$p\left[\frac{d}{osh}\right] = \frac{A'^{\beta_1}_d C'^{-\beta_2}_{od}}{\sum_{d'} A'^{\beta_1}_{d'} C'^{-\beta_2}_{od'}}, \quad (3)$$

where β_1, β_2 are the coefficients of the urban trip distribution model (note that negative coefficients are associated with disutilities for the user).

(iii) $p^i[m/oshd](\mathbf{SE},\mathbf{T})$. This is the *mode choice or mode split model*. It predicts the fraction (or probability) that users belonging to class i select mode m to travel between zones o and d for purpose s in time-period h.

With respect to functional form, multinomial logit mode choice models are often used:

$$p^i\left[\frac{m}{oshd}\right] = \frac{\exp\left(V^u_{m/oshd}\right)}{\sum_{m'} \exp\left(V^u_{m'/oshd}\right)}. \quad (4)$$

(iv) $p^i[k/oshdm](\mathbf{SE},\mathbf{T})$. This is the *path choice model*. It gives the fraction of users in class i who, traveling between zones o and d for purpose s in time-period h by mode m, use path k.

We decide to adopt an *exhaustive approach*, that is, to consider all the elementary paths on the network with *implicit path enumeration*. In particular, we propose to assign the demand to the network using a Deterministic User Equilibrium (DUE) traffic assignment model [23]. The calculation of equilibrium link flow is based on different algorithms; in our model, we adopt the Frank-Wolfe algorithm [24, 25].

4.2. Elasticity of Urban Transportation Demand Related to the Congestion Price. Once it is clarified how the four-step model works (Section 4.1), we can move on to the description of the first step of our methodology. As previously mentioned, it consists of a preliminary analysis of the relationship that exists between the demand elasticity and the amount of the toll to be applied in order to properly undertake a pricing strategy.

Assuming that the cordon (set of links), to whom the congestion price is attributed, is fixed, we propose to analyze what happens in the network if we gradually increase the value of the fare on every arc.

Since we are presenting a model for the urban commuting trips, we suppose that users have 3 potential alternative transport modes, namely, private cars, public transportation (i.e., buses), and/or bike-sharing. In Cascetta [23] it is possible to find a list of attributes for each modal choice, with their related β_k coefficients to use in the modal split model. Commonly, in literature, private bicycles (in the cycling framework) have been seen a possible mode of transportation, with their related attributes to consider; however, in our framework, we are assuming the bike-sharing system (and not the private bicycle) as possible modal alternative. Consequently, with our methodology, we are proposing to consider the travel time and the monetary cost as attributes to put in the choice model associated with the bike-sharing mode.

Based on these assumptions, at the end of the analysis, we can conclude that, for any given toll-charge pattern, it will be possible to estimate the modal split (among private cars, buses, and bike-sharing) and the traffic assignment on the network, calculated using the four-step model.

The aim is to assist the decision-maker that wants to implement the pricing strategy in a certain reality/city, achieving a targeted level of sustainable mode-share. Having a complete picture of the situation, he/she should establish the following:

(1) The desired modal split (i.e., the percentage of demand to be satisfied by public transportation and/or bicycles) and, consequently, the deriving value of the fare

(2) During which hours/days of the week the congestion pricing is applied (set the daily Δt)

(3) The time-period Δz (number of days) intended to collect money.

The daily revenue can be obtained multiplying the established amount of the toll for the flows (i.e., number of private cars) passing by each arc of the cordon during the time-interval Δt in which the pricing strategy is implemented. Then, knowing the number of days that constitute the selected Δz, the total revenue R can be calculated. Note that R coincides with the money necessary to setup the FFBSS; any other funding (i.e., additional bus tickets, money collected by the future users of the FFBSS, and toll revenue collected beyond the time-period Δz) should cover the system management costs.

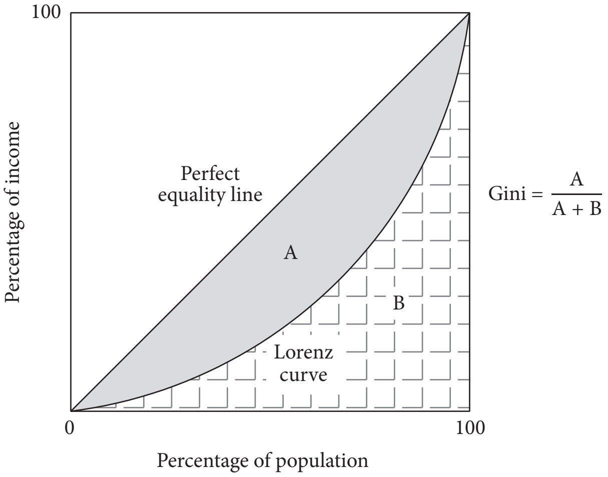

Figure 2: Lorenz curve and Gini coefficient.

4.3. Proposal of a Bicycle Equity Index. In recent decades, diverse attempts have been made to apply and incorporate equity principles to transportation systems planning [26]. However, it should be noted that, despite its relevance, few tools exist to assist planners in assessing the fairness of cost/benefit distribution over space and across population groups [1]. In this paper, we want to focus on the Gini coefficient that has been adopted to measure equity in several studies (see, e.g., [27–29]). It originally belongs to the economics, since it was used to compare the empirical distribution of income in a population (represented as a Lorenz curve; see Lorenz [30]), to a line representing the perfect equality. It is equal to the ratio of the area between the line of equality and the Lorenz curve (marked "A" in Figure 2) to the total area below the line of equality (A + B in Figure 2) [31]. Its lower and upper bounds are, respectively, 0 and 1. A perfectly even distribution would result in a Gini coefficient of 0, while a perfectly unequal distribution would result in a coefficient of 1.

However, the Gini coefficient can be applied not just to income, but also to any quantity that can be cumulated across a population. In particular, the readers could refer to Delbosc and Currie (2011) and Camporeale et al. [32]: respectively, they have suggested describing the distribution of transit supply throughout a metropolitan region using this coefficient and to plan and design public transport routes incorporating a modified version of the Gini coefficient as constraint of a Transit Network Design Problem.

Within road pricing, we can identify three main decisions that affect equity: allocating the burden of the charges, spending the revenue, and distributing the externalities [33]. More specifically, in this paper, we suppose to invest the revenue of the road pricing policy in implementing a FFBSS system, allocating bicycles and racks evenly (according to horizontal and vertical equity criteria) among the districts of the case study under analysis.

We propose a modified Gini coefficient to measure the equity impact deriving from the application of a congestion pricing scheme in the network. We call this indicator BEI, that is, bicycle equity index. It is equal to

$$\mathrm{BEI} = \frac{\mathrm{A}}{\mathrm{A} + \mathrm{B}}. \tag{5}$$

Namely, it corresponds to the ratio of the area between the line of equality and the Lorenz curve (marked "A" in Figure 2) to the total area below the line of equality (A + B in Figure 2), having still on the x-axis the percentage of population living in the study area and on the y-axis the weighted bicycle supply index, WSI, for each zone ξ, in place of the percentage of income shown in Figure 2.

$$\mathrm{WSI}_{\xi} = \mathrm{BSI}_{\xi} \cdot \left(100 - \frac{\mathrm{BNI}_{\xi} \cdot 100}{\mathrm{Pop}_{\xi}} + 1\right), \tag{6}$$

where

$$\begin{aligned} \mathrm{BSI}_{\xi} &= \sum_{n} \frac{\mathrm{Area}_{B_n}}{\mathrm{Area}_{\xi}} \cdot \overline{b}_{\xi}, \\ \mathrm{BNI}_{\xi} &= \sum_{y} w_y x_y. \end{aligned} \tag{7}$$

As a matter of fact, we are assuming that the urban reality under analysis is divided into Γ districts/zones ξ.

BSI_{ξ} is the bicycle supply index for the district (traffic zone) ξ under analysis; n is the number of walk access buffers to free-floating bicycles in each zone; B_n is the buffer n for each free-floating bicycle in each zone; Area is the square kilometer spatial area; $\overline{b}_{\xi}$ is the total number of bicycles to allocate in the zone ξ (in this context should be considered as a service level measure). This bicycle supply index BSI_{ξ} accounts for both the spatial coverage of a district by walk catchments to the bicycles and for the quality/density of the service itself.

BNI_{ξ} is the bicycle need index for the district (traffic zone) ξ under analysis. It is an indicator that can be built from sociodemographic and economic information (see [34]) like census data. In this case, y is the considered variable (i.e., students, adults without cars, low-income households, etc.); w_y is the weight assigned to each variable, representing its relative importance within the social framework of the reality under analysis; x_y is the value of y.

WSI_{ξ} is the bicycle supply index weighted according to the need index. Using this indicator on the y-axis of the graph for the calculation of BEI, we obtain that the Lorenz curve (to be compared to the perfect equality line), associated with a given network, represents the cumulative proportion of population against the cumulative proportion of the weighted bicycle supply. Indeed, our aim is to guarantee that the final configuration of free-floating bicycles and racks on the territory reaches the fairest possible compromise, according to both spatial distribution and satisfaction of social needs. Note that the expression within round brackets in (6) is equal to the complement to 100 of the disadvantage population deduced by BNI_{ξ}, plus one (component added to prevent that the resultant product equals zero). As a matter of fact, the bicycle need index is an input data of the problem, associated with the demographic composition of each zone ξ and thus unchangeable for the purposes of the global optimization. This implies that the larger the number of disadvantaged people in a demand zone is, the more the value of its correlated WSI_{ξ} tends to decrease. Consequently, in order to guarantee to that penalized zone an availability of free-floating bicycles able to compete with the one of the other districts in the network (in order to achieve a global equity), the process of optimization intervenes on those "editable" parameters related to the final configuration of the system (i.e., the number and the location of bicycles). Accordingly, the optimal solution coincides with a FFBSS capable of serving in a more widespread manner those areas that need it most.

4.4. Optimization Model to Fairly Implement a FFBSS.

In this subsection, we propose an equity-based optimization model to invest the budget collected through the pricing policy. In particular, we define a network design model to establish how to fairly allocate resources in a free-floating BSS.

Fixing the modal split in the previous policy stage, the demand origin-destination (*OD*) matrices for each modal alternative become available. Each zone/district ξ has its own centroid that constitutes both a potential origin and destination of the trips occurring in the network. Therefore, looking at the FFBSS implementation, we can set the maximum capacity of each zone c_{ξ}, that is, the maximum number of free-floating bicycles that it is possible to locate within its border. Usually, these potential capacities are quite large, as the corresponding racks can be ideally positioned in a high number of points of the network (sidewalks, squares, and parks).

Then, we can infer how many free-floating bicycles b_{ξ} (and racks r_{ξ}, knowing the ratio p between the number of racks and the number of bicycles in the system) are necessary in each zone ξ to completely satisfy the established share of bike-sharing demand $\mathbf{OD}_{\mathrm{BSS}}$ in the time-interval Δt, using the following:

$$b_{\xi} = \min\left(c_{\xi}, \sum_{f=1}^{\Gamma} od_{\xi f}\right), \tag{8}$$

$$r_{\xi} = p \cdot \max\left(b_{\xi}, \sum_{e=1}^{\Gamma} od_{e\xi}\right). \tag{9}$$

In other words, the number of bicycles needed in each zone ξ to satisfy the 100% of its bike-sharing demand corresponds to the minimum between the maximum capacity of that zone c_{ξ} and the sum of the columns $f \in [1, 2, \ldots, \Gamma]$ of the ξ row of the matrix $\mathbf{OD}_{\mathrm{BSS}}$. After that, the number of racks r_{ξ} can be calculated: it is equal to the maximum between the number of free-floating bicycles b_{ξ} in that zone, and the sum of the rows $e \in [1, 2, \ldots, \Gamma]$ of the ξ column of the matrix $\mathbf{OD}_{\mathrm{BSS}}$, and increased by p. This is required since the number of racks has to be necessarily equal or greater than the number of bicycles in each zone and should be set according to the characteristics of the system.

Knowing the unitary cost of each bicycle and rack, it is possible to deduce how much money M is necessary to implement such a system able to entirely satisfy the bike-sharing demand in the network. Three possible scenarios may occur:

(1) $M < R$, that is, the total collected revenue is greater than the money needed to buy the bicycles and racks that would allow totally satisfying the bike-sharing demand.

(2) $M > R$, that is, not enough money is available to buy the requested bicycles and racks.

(3) $M = R$, that is, the total collected revenue is sufficient to buy the exact number of bicycles and racks that would allow totally satisfying the bike-sharing demand.

In the third scenario, the problem of allocation of resources in the FFBSS is already solved, and there is no need to go on with the following optimization. Otherwise, we suggest a method to distribute fairly bicycles and racks among the zones, taking into account spatial and social equity principles. The optimization that has to be performed is expressed by the following:

$$\min \quad \mathrm{BEI} \tag{10}$$

s.t.

$$\alpha \cdot b' \leq \bar{b} \leq b' \tag{11}$$

$$\text{if } M < R: 0 \leq \bar{b}_\xi \leq c_\xi \tag{12}$$

$$\text{if } M > R: 0 \leq \bar{b}_\xi \leq b_\xi. \tag{13}$$

The objective function (10) coincides with the minimization of the bicycle equity index BEI in the network, described in the previous subsection. The inputs of the model are all the potential locations in which it could be possible to locate free-floating bicycles and racks, for each zone ξ, with their related capacity. These locations can be ranked according to the places in which it is preferable to set the racks, giving priority, for example, to those in high density urban contexts, or nearby public transportation stops. Output of the model is the optimal number of bicycles $\bar{b}_\xi$ to allocate in each zone ξ at the beginning of every time-interval Δt.

The racks $\bar{r}_\xi$ will be uniformly distributed on the territory (in the potential locations according to the established order of preference), respecting the proportion between bicycles and racks in the system (p).

The total optimal number of bicycles to buy and put in the system ($\bar{b} = \sum_{\xi=1}^{\Gamma} \bar{b}_\xi$) has to be lower than b', that is, the total number of bicycles (with associated racks, knowing p) that it is possible to buy with R (11). A greater number of resources cannot be bought since the budget R represents the total available money to realize the system. At the same time, we fixed a lower bound $\alpha \cdot b'$ corresponding to the minimum number of free-floating bicycles that has to be granted in the system. The α value (positive and lower than 1) is set by the policy maker, according to whether he/she wants or not to use the entire budget R in buying free-floating resources.

There is one further constraint to satisfy, according to the scenario that we have. If $M < R$, the upper bound of the bicycles to allocate in each zone corresponds to the maximum capacity of that zone (12). Otherwise, if we have less budget than the one needed to fully satisfy the bike-sharing demand ($M > R$), the upper bound is represented by b_ξ (13); that is, having already a limited number of bicycles (less than requested to satisfy the demand), we want to assure that the distribution among zones does not overcome their effective needs just in order to minimize BEI (and increase equity). In both scenarios, the lower bound is equal to 0.

Note that if $M > R$ the optimization model helps in an equitable distribution of the free-floating bicycles among the zones, considering the limited amount of available resources. On the other side, if $M < R$ there is enough budget to buy b_ξ and r_ξ, that is, the bicycles and racks necessary to satisfy the 100% of the bike-sharing demand. In this last case, the optimization model will be used to appropriately invest the remaining money, in order to buy more resources aiming at the minimization of the spatial and social inequalities among districts. The surplus of bicycles and racks to allocate could also compensate possible inaccuracies in the definition of the β values related to the modal split model. As a matter of fact, if the parameters related to cars and buses could be opportunely calibrated considering the actual status of the network, the bike-sharing ones cannot be identically calibrated (as the bike-sharing system does not yet exist in the network). This implies setting up β values, for example, according to what happens in similar realities, or considering the current trips by private bicycles or by applying specific stated preference methods [35, 36] or, finally, by using some traffic counts or aggregate data based methods [37].

5. A Test Network Numerical Application

This section aims to apply the suggested approach to a test network, reproducing all the steps that lead to the investment of the congestion price's revenue in an equitable FFBSS. In the following, after describing the main characteristics of the network and the setup parameters, an analysis of the elasticity of travel demand in relation to the amount of the toll is presented. Then, according to the outcomes, two possible strategies that the decision maker can choose to carry out are described, followed by a sensitivity analysis that investigates the relation between the value of the fare, days of application of the price strategy, and equity in the novel FFBSS to be realized in the network.

5.1. Sioux Falls City: Network Description and Setup. The proposed methodology has been, at first, applied on a test network. Analysis and optimizations have been performed using MATLAB software. We selected the Sioux Falls City shown in Figure 3. The links where the pricing strategy has to be implemented are the ones (highlighted in orange) that intersect the cordon line in the direction that goes toward the network center (see Figure 3).

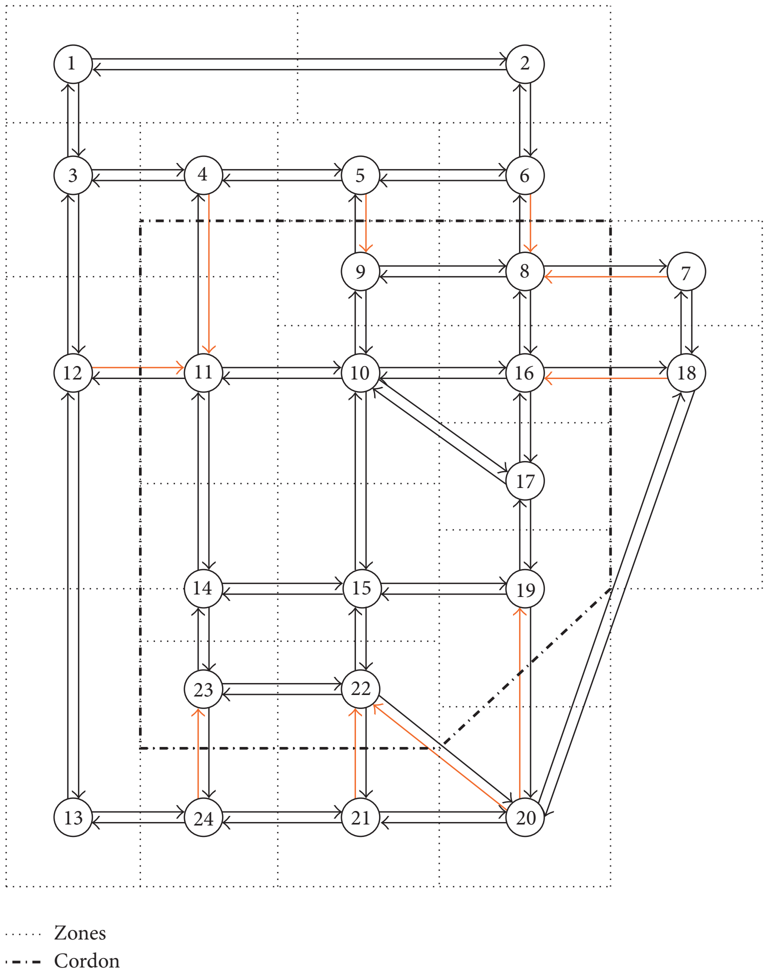

Figure 3: Sioux Falls City network, divided into traffic zones, and cordon road pricing scheme.

The Sioux Falls City network consists of 24 nodes, 76 links, and 552 origin-destination pairs; it has been divided into 24 zones ξ, each one having a node as centroid (origin and destination of every trip). Table 1 summarizes all the socioeconomic attributes of each zone, that is, residing population Pop_{ξ}, workers (individuals living in that ξ having a job), number of employees, residing disadvantaged people x_y, and setting $w_y = 1$ for each socioeconomic variable (we are considering young, unemployed, and low-income people as disadvantaged categories). Note that the employees do not need to live within the borders of the network under analysis, but only to work in one of the zones.

Then, in order to apply the four-step trip-based travel-demand model system, some parameters have to be setup. In particular,

(i) for the *trip production model*, the trip production rate is assumed equal to 40%;

(ii) for the *distribution model*, the two attributes considered for the calculation of the systematic utility are the number of employees (related to the attractiveness of the destination zone), having $\beta = 0.9$, and the distance between pairs of centroids (to quantify the travel costs between origin and destination), having $\beta = 1.89$;

(iii) for the *mode split model*, we consider three possible modal alternatives for the urban trips, namely, car ($\beta = -1.4$), bus ($\beta = -1.6$), and bike-sharing ($\beta = -3.5$). The attributes considered for these three modes of transportation are travel time (min) and monetary costs (€); supposing that 10 minutes of travel time are equivalent to 1€, they have been condensed in only one attribute, expressed in minutes (i.e., only one value of β is related to each modal alternative). Additionally, for buses we assume that only one transfer is allowed to reach the desired destination, corresponding to a penalty (to add to the travel time attribute) of 5 minutes. Only for the car mode, a dummy variable has been included in the calculation of its systematic utility: its value is 1 for the alternative "car" and 0 for the remaining two (bus and bike). This is usually denoted as alternative specific attribute (ASA) or modal preference attribute. We set its corresponding β equal to 0.3.

The average speed of the vehicles on the network has been considered equal to 20 km/h for cars, 10 km/h for buses, and 15 km/h for bicycles. Finally, for the computation of the monetary cost, it has been assumed

Table 1: Demography of each traffic zone.

Zone	Pop_ξ	Workers	Employees	x_y
1	264	121	108	80
2	906	390	78	296
3	428	240	126	55
4	483	295	357	153
5	1338	856	217	385
6	375	116	746	17
7	701	414	1299	153
8	1184	675	1081	169
9	1924	462	1223	309
10	1937	1569	104	549
11	1884	1432	394	272
12	786	534	301	134
13	374	135	1670	73
14	1074	558	481	179
15	1641	1280	453	358
16	1849	1183	737	355
17	959	480	250	67
18	455	214	113	94
19	1626	976	611	195
20	659	481	323	144
21	536	300	467	225
22	780	390	88	98
23	887	195	871	135
24	262	60	439	30

a cost of 0.60€/km when traveling by car, a cost of 1€/ticket for the bus, and the first 30 minutes free and then a fare of 0.50€/h for the users of the bike-sharing system.

Finally, we assume the public transportation system operating in the network to be partially underutilized; that is, more users could benefit from the existing bus service keeping its routes and frequency unchanged.

As inputs of the model are the hypothetical locations in which we set up the racks of the FFBSS, we decide to overlap a square grid of 200 m × 200 m to the test network. The intersections between this grid and the Sioux Falls City network are selected as potential locations in which it is possible to allocate the racks. Each location has a capacity equal to 15 and a buffer area (area of influence) with a radius of 100 m (we need these values for the BEI calculation). The ratio between the number of racks and the number of bicycles in the system p has been set equal to 1.25, according to Frade and Ribeiro [38].

5.2. Elasticity of the Demand Related to the Amount of the Toll: Preliminary Analysis. In order to provide the decision maker with the knowledge that he/she needs to undertake a proper policy strategy, a preliminary analysis on the network has to be performed. The outcomes of this analysis are summarized in Figures 4 and 5.

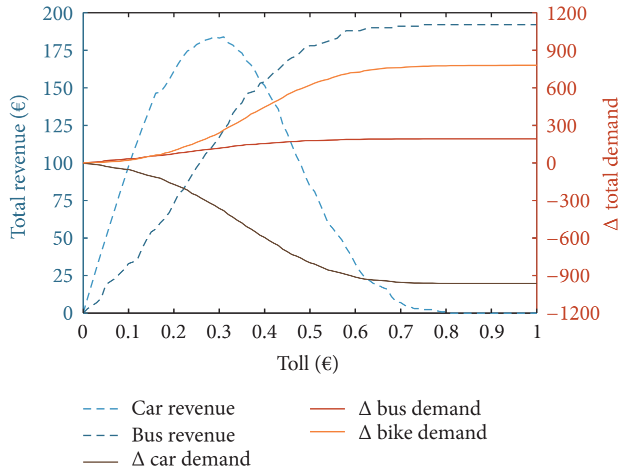

Figure 4: Revenue for one day of operation of the pricing strategy and variation of the modal split, in relation to the amount of the toll.

The graph shown by Figure 4 synthesizes the results of the analysis for one day of operation of the pricing strategy. Note that it has two y-axes and one shared x-axis, as two sets of data have been represented in different scales.

The x-axis refers to the progressive increase of the toll value, from 0€ to 1€, to be equally applied to all the links highlighted in Figure 3.

The y-axis on the left side of Figure 4 represents the total revenue (in euros) collected in one day: the light blue curve is associated with the car revenue, that is, the toll paid by the car drivers when passing through the cordon line during their trips toward the city center performed in the time-interval Δt (one peak hour). The car revenue increases until it reaches its maximum value around a 0.30€ toll value. After that, it decreases progressively, in conjunction with the car flows that pass through the cordon. Around a fare of 0.80€ it drops to zero: this means that the toll is too high for the car drivers of the context under analysis: then, none of them decides to travel on the tolled links anymore in order to reach their destinations. A greater value of the fare is not justifiable, as it does not reflect any further changes in the system. The car revenue is the actual one that will be used to implement the FFBSS in the network. However, on the graph we can also see a dark blue curve that shows the trend of the bus revenue, that is, the money deriving from the additional bus tickets that are bought in that time-interval Δt, due to a partial shift of the demand towards the transit mode. That is to demonstrate that extra money may be collected after the execution of the pricing policy.

The y-axis on the right side of Figure 4 represents the variation of the total demand on the network: the three reddish curves refer to the change in travel demand for each modal alternative. Starting values (when the toll is equal to 0€) of the demand for every travel mode are, respectively, 4911 users for cars, 338 for buses, and 54 for bicycles. Since the FFBSS does not exist yet, the bike demand has been derived from the model. We can observe that, as the toll varies, users react (demand elasticity) adapting to the new configuration of the system, and some of them decide to travel by a different

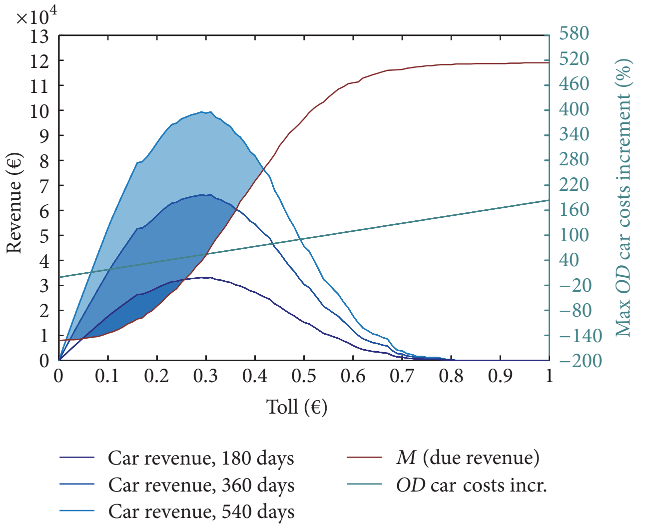

Figure 5: Number of days of operation of the pricing strategy in relation to the amount of the toll and associated *OD* car costs increment (%).

mode. That is the reason why people progressively decide to abandon the car (Δ car demand decreases) and move towards more sustainable alternatives (i.e., buses, up to the attainment of the maximum capacity of the service, and bicycles). We can note, also in this case, that after a toll value of 0.80€ the status of the system remains steady (all lines in the graphs maintain a horizontal trend).

A final remark has to be done: while the total collected revenue increases concurrently with the days of operation of the pricing strategy (Δz), the modal shift varies only according to the toll value, and it is not affected by the period of time in which the policy is implemented. This leads to the graph in Figure 5, where the amount of the toll is put in relation to Δz.

Also in this case, we are looking at a graph with two y-axes and one shared x-axis, since two sets of data have been represented in different scales.

Both the blue curves and the red one refer to the y-axis on the left side of Figure 5. Note that the car revenue (blue curves) increases with the number of days of implementation on the pricing policy. On the other hand, the dark red line displays the trend of M, that is, the total budget necessary to satisfy 100% of the free-floating bike-sharing demand on the network, according to the value of the fare (it does not depend from the number of days).

The areas colored with different shades of blue highlight the ranges of toll values (according to Δz equal to 180 days, 360 days or 540 days) for which $M < R$, that is, for such configurations of the system we collect more than enough money to satisfy the 100% of the bicycles demand. The intersections between the blue lines and the dark red one, consequently, represents the configurations where $M = R$. As an example: if the decision-maker sets a modal shift corresponding to a toll value of 0.40€ and $\Delta z = 180$ days, we obtain that $M > R$; on the other hand, with the same fare value, but setting $\Delta z = 540$ days, we have more money than required to totally satisfy the bike demand, and $M < R$.

Increasing Δz, the range of toll values that overcomes M becomes larger. It could be noted that, raising the value of Δz, we may be able to set a greater toll value, still meeting the 100% of the bicycle demand. However, it will be an unreasonable choice, as in that case the FFBSS is going to be implemented in the network at a moment too far in the future, with benefits not tangible for the users.

The y-axis on the right of Figure 5 displays the maximum cost increment for the *OD* car. This means that the more the value of the toll rises, the more the car drivers will be affected by it, bearing a greater increment in their OD travel costs. This increment has been defined following the equity performance indicator suggested by Meng and Yang [39]; it is equal to the maximal ratio of the equilibrium *OD* car travel cost after implementing the pricing strategy in the network, divided by the equilibrium *OD* travel cost before the implementation, for the set including all the *OD* pairs (see [40]). As this ratio tends to progressively increase together with the toll value, it could be preferable to avoid an excessive increment aiming at a global equity among all the users of the system. Note that, in this application, the link that experiments the greater rise of travel costs is always the 6–8 (see Figure 3) that is never congested: that is why the *OD* car costs increment shows an almost linear trend in the graph.

Looking at Figures 4 and 5, a hypothetical decision-maker has all the elements that should allow him/her to undertake a strategic decision, setting the public transport shift that he/she wants to achieve, with associated toll value, and the number of days in which the policy is implemented.

5.3. Results Associated with Two Potential Strategic Decisions.

In this subsection, two different scenarios are presented, for analogous $\Delta z = 180$ days:

(1) The decision maker sets Δ bus demand equal to about 20%; the corresponding toll value is 0.20€, and $M < R$. It corresponds to Δ car demand = −3.5%, and Δ bicycle demand = 181.5%.

(2) The decision-maker sets Δ bus demand equal to about 35%; the corresponding toll value is 0.30€, and $M > R$. It corresponds to Δ car demand = −7.4%, and Δ bicycle demand = 442.6%.

In the following, the final results are summarized in Tables 2 and 3. The minimization (see (9) to (12)) has been solved using the genetic algorithms (GA), setting a population size of 100 and a number of generations of 1000. As starting configuration for the generic algorithm, we selected the one where all the bicycles $\overline{b}$ are uniformly divided among the zones, giving priority to the zones with a greater number of disadvantaged individuals in assigning the remaining ones (as a decimal number may results from the ratio). GA has been repeated for 5 times for each configuration. The final values obtained at the end of the repetitions are comparable; however, in Tables 2 and 3, the best achieved results have been reported.

Table 2: Results for Scenario (1), $M < R$.

Zone	b_ξ	$(\bar{b}_\xi - b_\xi)$	$\bar{b}_\xi$	$\bar{r}_\xi$
1	0	2	2	4
2	8	2	10	12
3	2	1	3	5
4	7	2	9	11
5	32	2	34	37
6	2	1	3	5
7	7	2	9	11
8	2	3	5	7
9	2	6	8	10
10	16	2	18	21
11	9	6	15	18
12	17	1	18	20
13	0	1	1	3
14	0	3	3	5
15	10	2	12	15
16	6	3	9	11
17	2	2	4	6
18	6	1	7	9
19	6	5	11	13
20	12	1	13	16
21	6	3	9	11
22	0	3	3	5
23	0	2	2	4
24	0	1	1	3

Table 3: Results for Scenario (2), $M > R$.

Zone	b_ξ	$\bar{b}_\xi$	$\bar{r}_\xi$
1	1	1	3
2	17	17	20
3	9	4	6
4	22	10	13
5	67	22	25
6	4	4	6
7	18	6	8
8	2	2	4
9	2	2	4
10	16	16	19
11	9	9	11
12	38	25	28
13	0	0	0
14	0	0	0
15	10	10	13
16	6	6	8
17	2	2	4
18	12	11	14
19	6	6	8
20	35	15	18
21	17	17	20
22	0	0	0
23	0	0	0
24	0	0	0

In Scenario (1) (Table 2) we have more than the necessary revenue to satisfy the 100% of the demand (i.e., $M < R$). For each zone, the number of bicycles b_ξ that meets all the actual demand is reported, together with the number of bikes $\bar{b}_\xi$ obtained at the end of the optimization (see (9) to (12)). It can be noted that the optimization model helps in appropriately investing the remaining money ($R - M$), in order to buy more resources (bicycles and racks) that contribute at the minimization of the spatial and social inequalities among districts. As a matter of fact, the BEI coefficient corresponding to the configuration in which the 100% of the bike demand is satisfied is equal to 0.5018; the five BEI values obtained at the end of the optimizations are 0,3109, 0.3137, 0.3214, 0.2996, and 0.3270. The lowest among them is also lower than 0.5018 (Figures 6 and 7). It happens that, also for those zones (1, 13, 14, 22, 23, 24) in which the initial bike request is equal to zero, some bicycles have been allocated. This allows not only evenly distributing the available resources in the territory, according to horizontal equity principles (helping in the BEI minimization), but also compensating possible inaccuracies in the definition of the β values related to the mode split model.

In Scenario (2) (Table 3) we have less than the necessary revenue to satisfy the 100% of the demand (i.e., $M > R$). Consequently, the optimal number of bicycles derived by the optimization does not meet all the bicycle requests in the network. Anyway, the available (limited) resources have been distributed following spatial and social equity criteria, and the best BEI reaches a value of 0.4961 (the remaining four optimizations restitute BEI values equal to 0.5058, 0.5099, 0.5005, and 0.5087).

5.4. Sensitivity Analysis: Relation between Congestion Pricing and Equity of the FFBS. We want now to investigate which is the relation between the amount of the toll, the selected number of days in which to implement the pricing policy, and the level of equity in the distribution of bicycles and racks among zones (BEI). The results are summarized in Table 4. Also in this case, GA has been repeated for 5 times for each configuration, and the best results (also in this case there are slightly differences among the 5 repetitions) have been reported in the table. As mentioned above, the modal split among car, bus, and bike is not affected by the number of days, but only by the amount of the toll.

The BEI values referred to different possible configurations of the system are displayed in Table 4. The cases where $M < R$ are highlighted in bold. In the last three columns of Table 4 the values of BEI obtained by investing M have been reported (i.e., BEI(M)). These are also the cases in which the achieved BEI(R) is lower; then the equity in the distribution of bicycles and racks among the zones is greater.

On the contrary, BEI is equal to 1.00 (no equity) for all those configurations where no car flows pass through the cordon, as the toll is too high: in these situations, although there is still a modal shift toward more sustainable modes

Table 4: BEI values according to the selected amount of the toll and number of days.

		BEI opt (R)										BEI (M)		
	Toll (€)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1	0.1	0.2	0.3
Δz (number of days)	30	0.35	0.29	0.28	0.33	0.42	0.65	0.93	1.00	1.00	1.00	—	—	—
	60	0.30	0.24	0.25	0.26	0.26	0.48	0.85	1.00	1.00	1.00	—	—	—
	90	0.33	0.29	0.31	0.26	0.29	0.42	0.76	1.00	1.00	1.00	—	—	—
	120	**0.41**	0.35	0.38	0.30	0.26	0.36	0.67	1.00	1.00	1.00	**0.45**	—	—
	150	**0.26**	**0.42**	0.44	0.35	0.25	0.29	0.59	1.00	1.00	1.00	**0.45**	**0.50**	—
	180	**0.20**	**0.30**	0.50	0.41	0.27	0.30	0.58	0.93	1.00	1.00	**0.45**	**0.50**	—
	210	**0.17**	**0.24**	0.54	0.45	0.30	0.26	0.50	0.93	1.00	1.00	**0.45**	**0.50**	—
	240	**0.15**	**0.23**	**0.57**	0.48	0.34	0.25	0.49	0.93	1.00	1.00	**0.45**	**0.50**	**0.62**
	270	**0.11**	**0.22**	**0.49**	0.50	0.37	0.27	0.46	0.93	1.00	1.00	**0.45**	**0.50**	**0.62**
	300	**0.12**	**0.14**	**0.42**	0.53	0.38	0.26	0.45	0.93	1.00	1.00	**0.45**	**0.50**	**0.62**
	330	**0.12**	**0.18**	**0.34**	0.55	0.42	0.29	0.43	0.93	1.00	1.00	**0.45**	**0.50**	**0.62**
	360	**0.07**	**0.14**	**0.34**	0.57	0.44	0.23	0.42	0.87	1.00	1.00	**0.45**	**0.50**	**0.62**

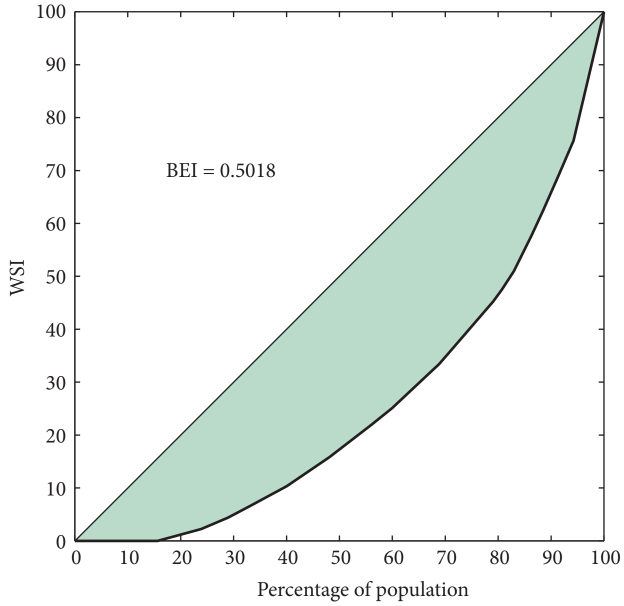

Figure 6: Scenario (1): Lorenz curve and resulting BEI calculated with M.

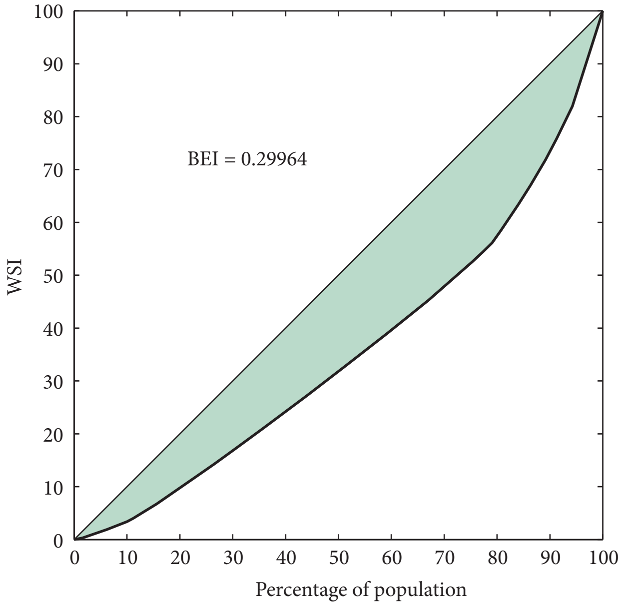

Figure 7: Scenario (1): Lorenz curve and resulting BEI calculated with R.

of transportation, no money can be collected and the FFBSS cannot be implemented.

A further remark can be done observing the trend of the values for each row (i.e., for each Δz): they tend to decrease, reach a minimum around an average amount of the toll, and then rise again. Then, it seems that the toll values that are more capable of bringing a higher level of equity in the network are those in an intermediate range (approximately, from 0.30€ to 0.60€).

The sensitivity analysis has been completed calculating the percentage of bike demand satisfaction (Table 5), according to both the amount of the toll and Δz. Also in this table, the cases where $M < R$ are highlighted in bold. The bicycle demand for each zone has been reported in the italic row.

Looking at Table 5, we can see that for toll values greater than 0.50€–0.60€ the demand satisfaction is progressively lower; then, those configurations, also if having a corresponding BEI that scores a good value, should not be preferred.

In order to further assist the decision-maker in his/her choice, we provide a conclusive proposal: the use of the Pareto front to better understand which possible configurations have to be preferred. Pareto optimality is a state of allocation of resources in which it is impossible to make any subject better off without making at least one other subject worse off. For further details, the reader could refer to Deb, 2001 [41]. In this framework, the three variables that have to be taken into account are the pursued level of equity, the unsatisfied bicycle demand, and the percentage of reduction of the *OD*

Table 5: Percentage of bike demand satisfaction according to the selected amount of the toll and number of days.

		Bike demand satisfaction (%)									
	Demand	*76*	*152*	*293*	*500*	*675*	*777*	*815*	*829*	*832*	*834*
	Toll (€)	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9	1
Δz (number of days)	30	25	21	12	6	3	1	0	0	0	0
	60	42	38	23	11	5	2	0	0	0	0
	90	64	55	31	15	8	3	0	0	0	0
	120	**108**	71	42	21	9	3	1	0	0	0
	150	**139**	**111**	53	26	11	4	1	0	0	0
	180	**166**	**138**	63	31	13	5	1	0	0	0
	210	**188**	**161**	73	36	15	5	1	0	0	0
	240	**220**	**176**	**104**	41	17	7	1	0	0	0
	270	**254**	**198**	**119**	46	19	7	2	0	0	0
	300	**268**	**220**	**135**	51	21	8	2	0	0	0
	330	**288**	**236**	**147**	56	23	9	2	0	0	0
	360	**322**	**255**	**162**	62	25	10	2	0	0	0

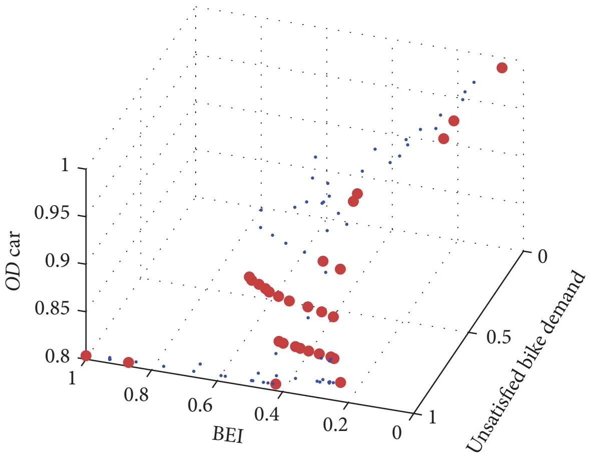

Figure 8: Graphical representation of the Pareto front.

car. Normalizing these three criteria between zero and one, we can represent the best possible solutions in a 3D graph (Figure 8). It can be seen that, in this case, the Pareto front is made up of the 29 nondominated solutions in red.

The solutions that score a lower value of unsatisfied bike demand are those related to $M < R$ (looking at the graph in Figure 8, those belonging to the Pareto front located in the top-right corner). Moreover, it seems that further best solutions (red points) can be found in correspondence to a value of BEI ranging from about 0.4 to 0.5.

6. Numerical Application to a Real Case Study: The City of Molfetta

The suggested approach is here applied to a real case study. We focus on Molfetta, a city of approximately 60000 inhabitants, located in the South of Italy (Apulia region). The goal of this application is to alleviate the congestion in the central areas, corresponding to the old historical center, migrating part of the travel demand from to private cars to more sustainable mode of transportation, that is, buses and bike-sharing.

The real transport system network is modeled by a graph (Figure 9) made by 519 directed arcs and 210 nodes. The links where the pricing strategy has to be implemented are the ones that intersect the cordon line in the direction that goes toward the network center (see Figure 9, zoomed area).

The study area has been divided into 28 traffic zones (Figure 10). Each zone was obtained by joining the elementary census sections (areas) defined by the ISTAT (Italian Institute for Statistics). The relevant socioeconomic attributes (total population, workers, number of employees, and disadvantage individuals) are available from the national census of Italy databases. In the disadvantaged category we included young, unemployed, and low-income people.

Moreover, we selected in the network those potential locations in which it could be possible to allocate the racks of the FFBSS (see Table 6 to see how many locations there are in each traffic zone). Each location has a capacity equal to 15, and the average distance between them is 200 m.

In order to apply the four-step trip-based travel-demand model system, some parameters have to be setup. Some of them are the same selected for the previous test numerical application (Section 5). In the following, we report only those that have been set according to the case study under analysis; in particular

(i) for the *trip production model*, the trip production rate is assumed equal to 60% for the selected rush hour (home-based work trips);

(ii) for the *distribution model*, the two attributes considered for the calculation of the systematic utility are the number of employees (related to the attractiveness of the destination zone), having $\beta = 0.9725$, and the distance between pairs of centroids (to quantify the travel costs between origin and destination), having $\beta = 0.7025$ (see the average values reported in [23] for the home-based work trips);

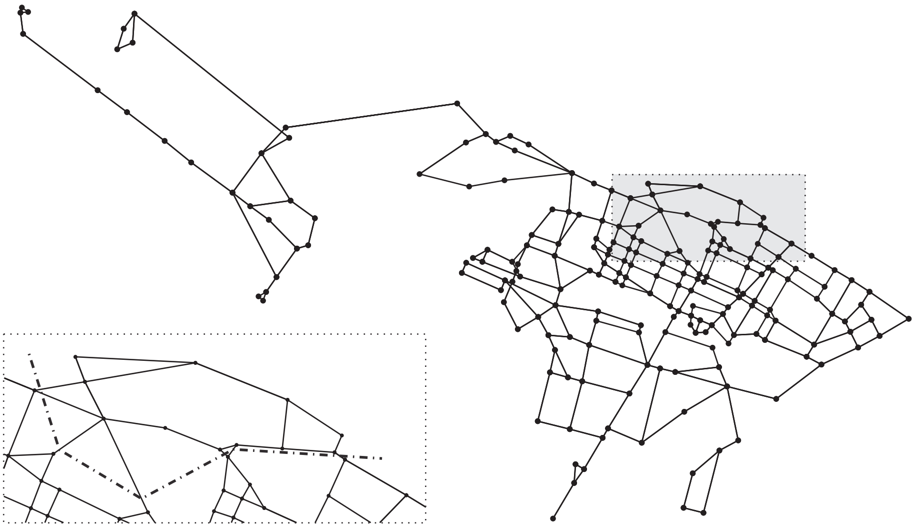

FIGURE 9: Network of the city of Molfetta, with a zoom on cordon road pricing scheme.

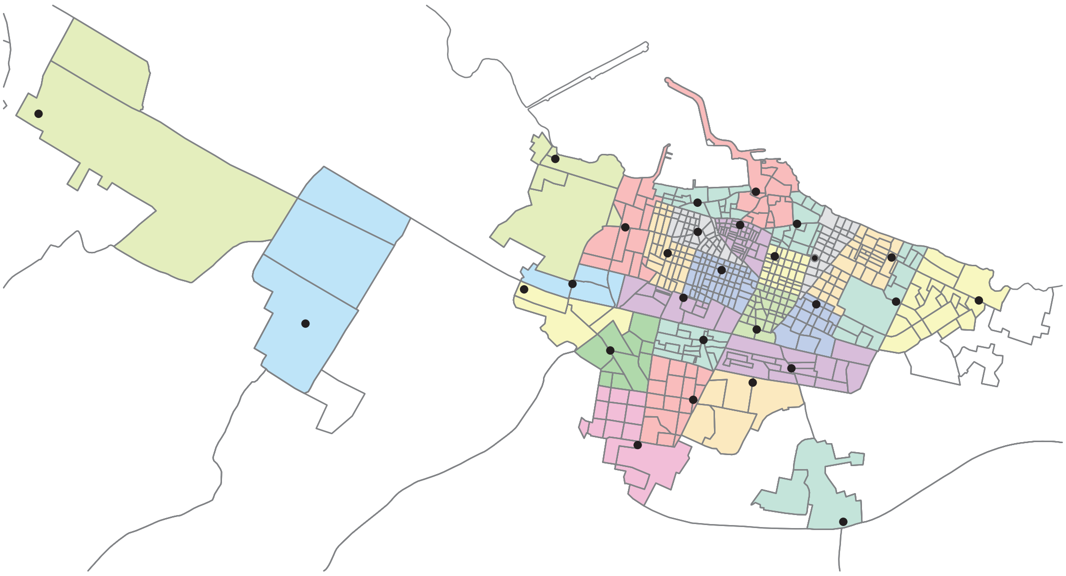

FIGURE 10: Molfetta case study: traffic zones and centroid nodes.

(iii) for the *mode split model*, we consider three possible modal alternatives for the urban trips, namely, car, bus, and bike-sharing. The attributes considered for these three modes of transportation are travel time (hours), monetary costs (€), and alternative specific attribute ASA (only for bus and bike-sharing). Their corresponding β [23] are

$$\begin{aligned}\beta_{\text{car\_time}} &= -1.6142,\\ \beta_{\text{car\_costs}} &= -0.3338,\\ \beta_{\text{bus\_time}} &= -1.6142,\\ \beta_{\text{bus\_costs}} &= -0.3338,\\ \beta_{\text{bus\_ASA}} &= -1.7827,\\ \beta_{\text{bike\_time}} &= -8.2718,\\ \beta_{\text{bike\_costs}} &= -0.3338,\\ \beta_{\text{bike\_ASA}} &= -1.5818.\end{aligned} \tag{14}$$

Setting these values, we obtain a modal split on the network able to reproduce the current one in the Apulia region, with a ratio within public transportation/private transportation equal to about 20% (see the Regional Transportation Plan). The average bicycle speed has been set equal to 10 km/h (lower than the one set in the test network application) due to the scarcity of bike lanes in the city.

TABLE 6: Potential locations in which we allocate the FFBSS racks for each traffic zone.

Zone	Number of locations
1	20
2	18
3	16
4	20
5	14
6	16
7	16
8	28
9	24
10	44
11	120
12	18
13	20
14	18
15	28
16	20
17	18
18	28
19	36
20	48
21	60
22	18
23	34
24	18
25	36
26	32
27	38
28	14

Looking at the outcomes of the preliminary analysis (Figures 11 and 12), the policy maker decides to increase to about 10% of the bus demand (Δ bus demand = 10.26%): this is a worthy objective, taking into account the global low attractivity of the public transportation in the city. It corresponds to Δ car demand = −1.8% and Δ bicycle demand = 9.6%.

Starting values (when the toll is equal to 0€) of the demand for every travel mode are, respectively, 9523 users for cars, 1247 for buses, and 455 for bicycles.

Looking at Figure 11, it can be asserted that, to significantly reduce the car use and consequently promote, in a more decisive way, the bus trips, it is necessary to set a toll on the suggested links quite high. In order to satisfy the modal shift required by the decision-maker, the toll has to be set equal to 2€. In this framework, it is sufficient to implement the strategy for a time-period of 90 days (Figure 12) to collect the money necessary to allocate the FFBSS resources in the network and satisfy entirely the bicycles pick-up demand. The choice of the decision maker appears reasonable also looking at the percentage of the maximum *OD* car costs increment, in Figure 12.

The final results have been summarized in Table 7.

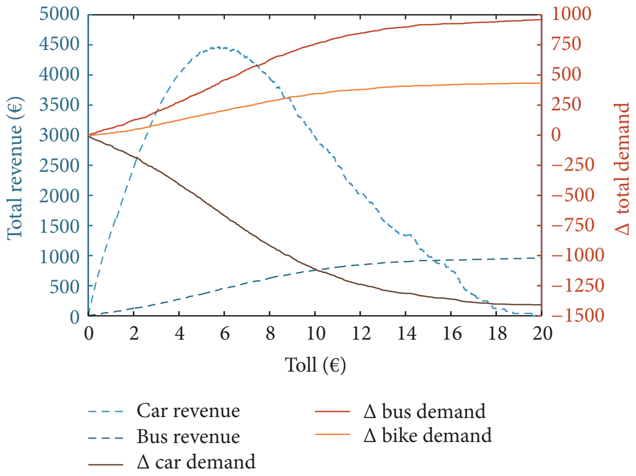

FIGURE 11: Revenue for one day of operation of the pricing strategy in the city of Molfetta and variation of the modal split, in relation to the amount of the toll.

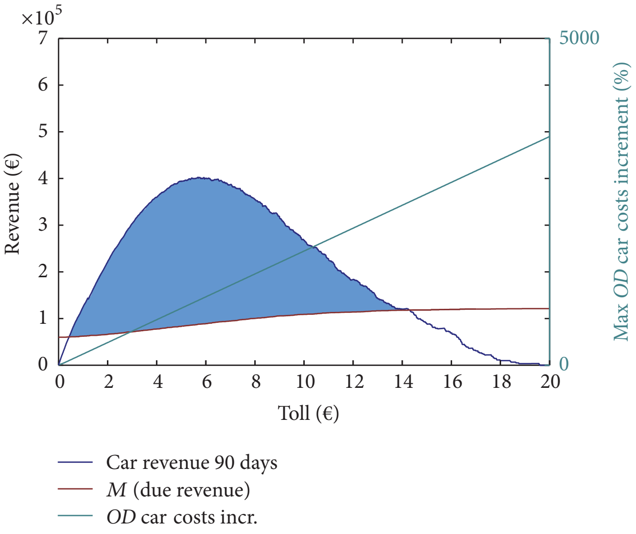

FIGURE 12: Number of days of operation of the pricing strategy in relation to the amount of the toll and associated *OD* car costs increment (%).

We can see that we have more than the necessary revenue to satisfy the 100% of the demand (i.e., $M < R$, Table 7). For each zone, the number of bicycles b_ξ that meets all the actual demand is reported, together with the number of bikes $\overline{b}_\xi$ obtained at the end of the optimization (see (9) to (12)). As a matter of fact, the BEI coefficient corresponding to the configuration in which the 100% of the bike demand is satisfied is equal to 0.2780; the BEI values obtained at the end of the 5 optimizations are similar to each other; the best (lowest) one is 0.1587.

As previously clarified, the revenue surplus allows not only evenly distributing the available resources in the territory, according to horizontal equity principles, but also compensating possible inaccuracies in the definition of the β values related to the mode split model.

Table 7: Results for Molfetta, $M < R$.

Zone	b_ξ	$(\bar{b}_\xi - b_\xi)$	$\bar{b}_\xi$	$\bar{r}_\xi$
1	16	15	31	41
2	10	11	21	31
3	5	13	18	28
4	29	3	32	42
5	22	7	29	39
6	15	23	38	48
7	33	16	49	59
8	44	7	51	61
9	48	58	106	117
10	12	44	56	66
11	2	9	11	21
12	1	17	18	28
13	18	21	39	49
14	22	17	39	49
15	32	12	44	54
16	43	56	99	110
17	9	32	41	51
18	8	20	28	38
19	23	63	86	97
20	29	21	50	60
21	8	23	31	41
22	4	16	20	30
23	33	40	73	84
24	18	26	44	54
25	15	27	42	52
26	0	13	13	23
27	0	11	11	21
28	0	17	17	27

7. Conclusions and Further Researches

In response to the challenge towards sustainability that is characterizing the last decades, one of the responsibilities of the decision makers is to propose strategies/solutions that could help in mitigating the congestion and the car-oriented urban transport system development, aiming at a society centered on alternative ways of transportation.

This paper focuses on the implementation of a cordon-based charging scheme, able to partially migrate the car travel demand to both the transit and bike-sharing systems, collecting at the same time some money thanks to the application of the toll. We propose to evenly redistribute the outcomes of this pricing strategy among the network users, planning and designing a FFBSS whose resources (i.e., bicycles and racks) are allocated following horizontal and vertical equity principles. In particular, a bicycle equity index has been proposed to assess the fairness of this distribution among the zones of the city. Through the given numerical applications (on both a test and a real network), we analyzed the relationship between the modal shift to achieve the amount of the toll and the number of days in which the pricing strategy is applied. The analysis also showed that the proposed methodology could assist the decision-maker in determining the best choice for the community.

Furthermore, a sensitivity analysis about the pursued level of equity of the FFBSS is enclosed. We demonstrate how it could be possible for all the users (also the ones belonging to disadvantaged categories) to benefit from the effects of a pricing strategy, promoting at the same time more sustainable travel alternatives.

Notations

i: The user's class (category of socioeconomic characteristics)
o, d: Origin and destination of each trip
s: The trip purpose
h: The time-period in which trips are undertaken
m: The mode, or sequence of modes, used during the trip
k: The trip path, that is, the sequence of links connecting o and d over the network and representing the transportation service provided by mode(s) m
SE: Socioeconomic attributes
T: Performance attributes
V_j^u: Systematic utility relative to the alternatives j and the user u
I^u: Choice set of alternatives for the user u
X: Attribute set
$\mathbf{X}_j^u$: Attribute vector belonging to the set X relative to the alternatives j and the user u
X_{kj}^u: Generic attribute of the systematic utility relative to the alternatives j and the user u, with $k \neq j$ and $k \in I^u$
β_k: Utility function coefficient
A_d: Attractiveness variable of zone d
A'_d: Natural logarithm of A_d (i.e., $\ln(A_d)$)
C_{od}: Variable related to the generalized transportation cost for traveling from o to d
C'_{od}: Natural logarithm of C_{od} (i.e., $\ln(C_{od})$)
β_1, β_2: Coefficients of the urban trip distribution model
Δt: Daily time-interval in which apply the congestion pricing
Δz: Time-period in which collecting the toll (number of days)
R: Total revenue collected through the congestion price strategy
Γ: Total number of zones/centroids
ξ: Generic travel-demand zone/centroid, $\xi \in [1, 2, \ldots, \Gamma]$
BEI: Bicycle equity index
BSI_ξ: Bicycle supply index for each zone ξ
BNI_ξ: Bicycle need index for each zone ξ
WSI_ξ: Bicycle supply index for each zone ξ weighted according to the BNI_ξ

n: Number of walk access buffers to each free-floating bicycle location in each zone ξ
B_n: Buffer n for each free-floating bicycle in each zone ξ
Area: Spatial area [km^2]
y: Socioeconomic variables
w_y: Weight of the variable y
x_y: Value of the variable y
Pop_ξ: Total population in the zone ξ
M: Budget necessary to satisfy 100% of the bike-sharing demand in the network
R: Total revenue collected after implementing the pricing strategy
c_ξ: Capacity (maximum number of free-floating bicycles) of the zone ξ
$\mathbf{OD}_{\text{BSS}}$: Bike-sharing origin-destination demand matrix for Δt
od_{ef}: Generic element of the bike-sharing matrix $\mathbf{OD}_{\text{BSS}}$ (row e, column f) with $e \in [1, 2, \ldots, \Gamma]$ and $f \in [1, 2, \ldots, \Gamma]$
b_ξ: Total number of free-floating bicycles to allocate in zone ξ to satisfy 100% of its bike-sharing demand
r_ξ: Total number of racks to allocate in zone ξ to satisfy 100% of its bike-sharing demand
p: Ratio between the number of racks and the number of bicycles in the system
b': Total number of bicycles (with associated racks) that it is possible to buy with R
$\overline{b}_\xi$: Optimal number of bicycles to allocate in zone ξ
$\overline{r}_\xi$: Optimal number of racks to allocate in zone ξ
$\overline{b}$: Total optimal number of bicycles to allocate in the system, $\overline{b} = \sum_{\xi=1}^{\Gamma} \overline{b}_\xi$.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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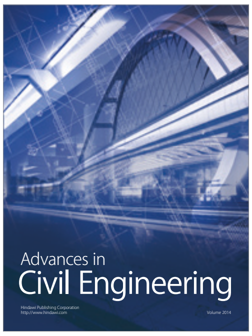
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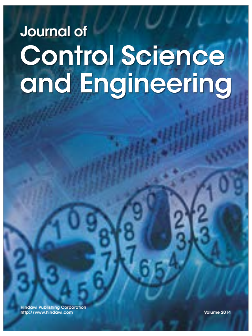
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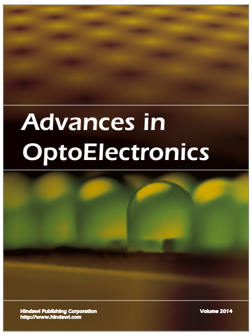
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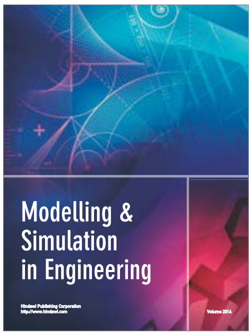
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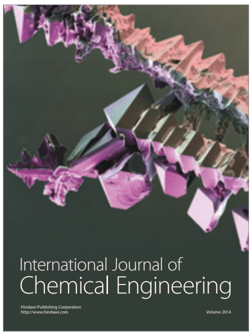
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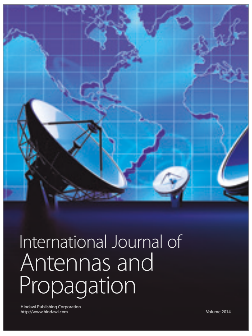
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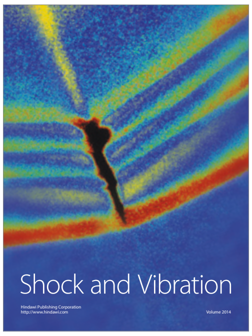
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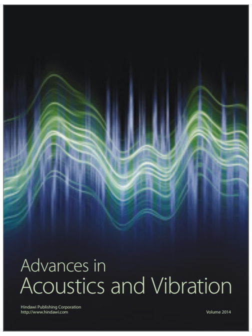
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