

## Article

# Optimization Model for the Supply Volume of Bike-Sharing: Case Study in Nanjing, China

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**Abstract:** In order to solve the oversupply and repositioning problems of bike-sharing, this paper proposes an optimization model to obtain a reasonable supply volume scheme for bike-sharing and infrastructure configuration planning. The optimization model is constrained by the demand for bike-sharing, urban traffic carrying capacity (road network and parking facilities carrying capacities), and the flow conservation of shared bikes in each traffic analysis zone. The model was formulated through mixed-integer programming with the aim of minimizing the total costs for users and bike-sharing enterprises (including the travel cost of users, production and maintenance costs of shared bikes, and repositioning costs). CPLEX was used to obtain the optimal solution for the model. Then, the optimization model was applied to 183 traffic analysis zones in Nanjing, China. The results showed that not only were user demands met, but the load ratios of the road network and parking facilities with respect to bike-sharing in each traffic zone were all decreased to lower than 1.0 after the optimization, which established the rationality and effectiveness of the optimization results.

**Keywords:** bike-sharing; carrying capacity; supply volume; mixed integer programming; CPLEX



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## 1. Introduction

In the early stage of entering the market, bike-sharing has been well received by the public due to the advantages of convenient renting and returning and low charges. However, due to the large load ratio of facilities and the spatial distribution disequilibrium of bike-sharing in cities, parking, safety, and repositioning problems have occurred.

In many cities, the carrying capacity of bike-sharing parking facilities cannot meet the parking demand during peak hours, resulting in illegal parking of shared bikes. Insufficient parking capacity and unclear parking areas for bike-sharing cause many problems in terms of random parking. The environment of the city has been affected by bike-sharing. For areas with an insufficient carrying capacity in the road network, it is common for shared bikes to occupy motor lanes during peak hours, which poses a huge potential safety hazard for mixed traffic. As for repositioning problems, shared bikes have strong flexibility and mobility. The disequilibrium distribution of demand for bike-sharing during peak periods puts great pressure on the repositioning work of bike-sharing enterprises.

To solve these problems, the carrying capacities of bike-sharing parking facilities and road networks need to be improved. Adjustment of the supply volume for bike-sharing is another key way to decrease the excessive load on the environment.

Facing the imbalance between the urban traffic carrying capacity and the demand for shared bikes, both the supply volume for bike-sharing and the capacities of related facilities need to be adjusted. In this study, we developed an optimization model for adjustment of the supply volume for bike-sharing based on traffic analysis zones (TAZs). Considering the

travel costs of users, production and maintenance costs for bikes, repositioning costs, the demand for bike-sharing, the road network carrying capacity, and the carrying capacity of parking facilities, mixed-integer programming for bike-sharing supply volume optimization was performed, taking the TAZ as the unit on which to operate. CPLEX was used to obtain the optimal solution for the model. Finally, taking Nanjing city as an example, the optimization model was verified, and the supply volume and dispatching volume of shared bikes for each traffic zone were obtained. The results show that adjustment of the supply volume for bike-sharing can significantly reduce and balance the load ratio of the environment.

## 2. Literature Review

Since the appearance of bike-sharing, many scholars have studied the demand, facility configuration, and supply volume for shared/public bikes.

- **Factors Affecting Bike-Sharing Demand**

Land use and the built environment are the important factors affecting the demand for bike-sharing. The central business district (CBD) of each city is an area with a concentrated population employed in the urban area. Buck et al. (2013) found that the distance from a public bike station to the CBD was negatively correlated with the volume of bike passengers [1]. Faghih-Imani et al. (2014), Jensen et al. (2010), and Wang et al. (2016) found that the number of restaurants and retail outlets near bike-sharing stations was positively correlated with the bike passenger volume. Restaurants and retail outlets are common starting points and destinations for bike-sharing [2–5]. Ma et al. (2019) found that increases in the numbers of bus stations and rail transit sites, along with the density of public bicycle sharing sites, reduced the demand for bike-sharing during peak hours, while decreasing road network density reduced shared bike usage during peak hours on working days [6]. Bachand-Marleau et al. (2012) explored the correlation between the improvement of transportation facilities and the use frequency of public bikes through an investigation in Montreal [5]. Vogel et al. (2014) and Wang et al. (2016) found a positive correlation between the accessibility of urban rail transit and the demand for public bikes, indicating that users often use public bikes to connect with rail transit [4,7].

Furthermore, the impact of social and economic attributes on bike-sharing travel demand cannot be ignored. EI-Assi et al. (2017) found that public bikes in areas with high employment density are used most frequently, which indicates that a considerable number of users use public bikes for commuting. There is a positive correlation between the number of university campuses near public bike rental sites and the demand for public bikes, indicating that university students are important users of public bikes [8]. Ma et al. (2019) found that users with higher income and higher education levels are more willing to use bike-sharing to travel [6].

- **Facilities Configuration of Bike-Sharing**

Several studies have analyzed the demand distribution for public bikes or shared bikes in order to configure the facilities of the bike rental system [9,10]. Garcia-Palomares et al. (2012) used GIS-based methods to obtain the potential spatial distribution requirements of public bikes and used the location allocation model to calculate the locations and capacities of public bike sites [11]. Vogel et al. (2016) combined mathematical optimization and intelligent data analysis to assist with network optimization of public bikes. Using a time-dependent origin–destination (OD) matrix, they developed an information model to show the spatial and temporal requirements of public bikes, deploying a mathematical model to optimize the usage of a site while minimizing the cost of site relocation [12]. Frade et al. used the TAZ as the basic unit of analysis, with the aim of maximizing the proportion of public bike demand under the constraints of a maximum input budget, and constructed an optimization attribute model, using XPRESS software to obtain the optimal quantity and repositioning quantity of public bicycles [13].

The balanced design and redistribution of the bike-sharing system is crucial. Nair et al. (2016) proposed a balanced network design model to determine the optimal configuration of the public bike system in Washington D.C. and developed a meta-heuristic algorithm to obtain the solution of the model [14]. Preisler et al. constructed a user incentive scheme to encourage users to self-organize and redistribute public bikes and proposed a decentralized coordination framework to achieve it [15]. Chen et al. (2017) regarded travel inference as an inverse and ill-posed problem and constructed a weighted regularization method. The model uses the supply volume of public bike sites to infer the travel pattern of public bikes. The results of the study help to show how to reach a balanced state of public bikes in the short term and solve the site management problem [16].

- Supply Volume for Bike-Sharing

Two main factors influence the supply volume for bike-sharing: users and enterprises [17]. These two main factors can be detailed into flowing aspects: travel demand for bike-sharing, the capacity of bike-sharing facilities, travel costs for bike-sharing users, production and maintenance costs for shared bikes, and repositioning cost for shared bikes. Hua et al. (2020) predicted the real-time distribution of shared bikes by K-means and random forest algorithms, which can regulate the management of bike-sharing [18]. Yi et al. (2019) measured the reasonable supply volume for bike-sharing using a time-space consumption model, which only considered the carrying capacity of the road network [19]. Albiński et al. (2018) analyzed a hybrid bike-sharing system and found that a suitable supply and reposition scheme could increase the demand for bike-sharing [20]. Studies on the supply volume for bike-sharing are limited. Most relevant studies focus on the reposition problem of bike-sharing. However, due to the lack of regulation for the supply volume of bike-sharing, the phenomenon of oversupply frequently occurs, and the workload of repositioning increases accordingly. These lead to a severe and unreasonable distribution of bike-sharing, as well as the waste of resources and the destruction of urban environment [21].

In existing studies, supply volume regulation methods for bike-sharing do not take parking issues into account. Most studies focus on increasing the reposition efficiency for the bike-sharing system but ignore the supply management. Hence, this paper proposes an optimization model to obtain the reasonable supply volume for bike-sharing, considering the capacities of the road network and parking facilities.

### 3. Methods

#### 3.1. Model Assumptions and Parameters Setting

##### 3.1.1. Model Objective and Assumptions

The proposed model is supposed to obtain the 24-h supply volume of shared bikes in each TAZ. The main goal of this model is to minimize the travel cost of users, the bike input cost, and the repositioning workload, satisfying the complete demand for bike-sharing in each traffic zone. The following assumptions are made for the model: users' demand for bike-sharing in each TAZ is generated at the center of mass in each traffic zone; the operational capability of repositioning work is infinitely high.

##### 3.1.2. Parameters Setting

The explanations of notations in the proposed model are shown in Table 1.  $M$  and  $K$  are the sets of TAZs and periods, respectively.  $i$  and  $j$  are both indexes of TAZs.  $t$  is the time period.  $d_{ij}$  is the distance between the centers of mass in TAZs  $i$  and  $j$ .  $O_i^t$  and  $D_i^t$  are the renting and returning demands for bike-sharing in traffic zone  $i$  at time  $t$ , respectively.  $\lambda$  is the turnover rate of bike-sharing parking spaces.  $c$  and  $p$  are the average production and reposition costs of each shared bike.  $\alpha$  and  $\mu$  are the walking distance (converted to cost) and the weight of the enterprise cost in relation to the user cost.  $O_j^{t,i}$ ,  $D_j^{t,i}$ ,  $B_i^t$ , and  $S_i^t$  are the renting, returning, supply, and reposition volume of bike-sharing in TAZ  $i$  during period

$t$ , respectively.  $B_{\max}$  is the maximum supply volume of bike-sharing in the research area. These parameters are used in the model formulation.

**Table 1.** Explanation of notations.

Notation	Explanation
Sets	
$M$	Set of TAZs $M = \{1, 2, \dots, m\}$ .
$K$	Set of periods $K = \{0, 1, \dots, k\}$ .
Constants	
$i$	The index of the TAZ, $i \in M$ .
$j$	The index of the TAZ, $j \in M$ .
$t$	The time period.
$d_{ij}$	The distance between the centers of mass in TAZs $i$ and $j$ , $d_{ij}, i \in M, j \in M, m$ .
$O_j^t$	The renting demand for bike-sharing in TAZ $j$ at time $t$ .
$D_j^t$	The returning demand for bike-sharing in TAZ $j$ at time $t$ .
$\lambda$	Turnover rate of bike-sharing parking spaces.
$c$	The average production cost of each shared bike.
$p$	The average reposition cost of each shared bike.
$\alpha$	The conversion of walking distance to cost.
$\mu$	The ratio of the enterprise cost to the user cost.
Decision variables	
$O_j^{t,i}$	The renting quantity of bike-sharing in TAZ $i$ during period $t$ .
$D_j^{t,i}$	The returning quantity of bike-sharing in TAZ $i$ during period $t$ .
$B_i^t$	The total quantity of shared bikes in TAZ $i$ at time $t$ .
$S_i^t$	The repositioning quantity of shared bikes in TAZ $i$ at time $t$ .
$B_{\max}$	The maximum supply volume of shared bikes in the research area.

### 3.2. Model Formulation

In the case that the demand for bike-sharing and the carrying capacity of traffic facilities (detailed estimating model can be found in [21]) are known, the optimization objective is to minimize the total costs for bike-sharing users and enterprises, including the walking distance of users, the input cost of bikes, and the workload of repositioning. The objective function is shown as Equation (1).

The following mixed-integer programming model can be constructed.

$$\min \left\{ \left[ \alpha \cdot \sum_{t=1}^k \sum_{j=1}^m \sum_{i=1}^m (d_{ij} \cdot O_j^{t,i} + d_{ij} \cdot D_j^{t,i}) \right] + \mu \cdot (c \cdot B_{\max} + p \cdot \sum_{t=1}^k \sum_{i=1}^m |S_i^t|) \right\} \quad (1)$$

The input cost of bikes is the maximum quantity of shared bikes in the research area. The repositioning workload is the number of shared bikes that need to be repositioned throughout the day within the research area.

The renting and returning demands for shared bikes in all traffic zones within the research area need to be satisfied; these are constrained by Equations (2) and (3).

$$\sum_{i=1}^m O_j^{t,i} = O_j^t \quad (2)$$

$$\sum_{i=1}^m D_j^{t,i} = D_j^t \quad (3)$$

Equation (4) restricts the logical relationship between the quantity of shared bikes and the reposition volume within different TAZs. The quantity of bike-sharing at time period  $t$  is determined by that at time period  $t-1$ , the renting demand and returning demand

of bikes, and the reposition volume at time period  $t$ . After a shared bike is returned and parked in a parking space, other users can use this bike again. When the bike is in use again, the parking space is accordingly available, and it can provide a service for other bikes. The turnover rate  $\lambda$  means the average parking times for each bike parking space during a certain period. The parking times for a space are consistent with the use times for a bike in a certain period. Each bike is also used  $\lambda$  times in a certain period on average. So, the demand for bike-sharing is not the actual number of shared bikes. It is  $\lambda$  multiplied by the actual number of bikes.

$$B_i^t = B_i^{t-1} - \frac{\sum_{j=1}^m O_j^{t-1,i}}{\lambda} + \frac{\sum_{j=1}^m D_j^{t-1,i}}{\lambda} - S_i^{t-1} (t > 1) \quad (4)$$

The quantity of shared bikes needs to meet the renting demand for bikes within the same period in the TAZ, as shown as Equation (5).

$$\lambda(B_i^t - S_i^t) \geq \sum_{j=1}^m O_j^{t,i} (t > 0) \quad (5)$$

Equations (6) and (7) restrict the travel demand and parking demand of shared bikes in each TAZ so that they do not exceed the capacity of the road network and parking facilities.  $C_{R_{i,t}}$  and  $C_{P_{i,t}}$  are the carrying capacities of the road network and parking facilities, respectively.

$$\max \left( \sum_{j=1}^m O_j^{t,i}, \sum_{j=1}^m D_j^{t,i} \right) \leq C_{R_{i,t}} \quad (6)$$

$$\sum_{j=1}^m D_j^{t,i} \leq C_{P_{i,t}} - \lambda(B_i^t - S_i^t) \quad (7)$$

The  $B_{\max}$  in Equation (8) is the maximum quantity of shared bikes in the whole research area across all research periods.

$$B_{\max} = \max \left[ \sum_{i=1}^m (B_i^t - S_i^t) \right] \quad (8)$$

Equation (9) restricts the lower and higher bounds of the reposition volume. When the shared bike enters a TAZ, the supply volume of shared bikes is limited by the capacity of parking facilities. When the shared bike exits a TAZ, the quantity of exiting bikes cannot exceed the number of shared bikes at the initial time in the TAZ.

$$S_i^t = \begin{cases} < 0, & \text{entering traffic zone } i, |S_i^t| \leq \frac{C_{P_{i,t}}}{\lambda} - B_i^t \\ \geq 0, & \text{exporting traffic zone } i, |S_i^t| \leq B_i^t \end{cases} \quad (9)$$

Equations (10) and (11) show that all values for the demand for shared bikes are natural numbers. Equation (12) means that all quantities of shared bikes in each TAZ and period are natural numbers and the repositioning quantities are integers.

$$O_j^{t,i} \in N, D_j^{t,i} \in N, \forall i, j \in M, \forall t \in K \quad (10)$$

$$O_i^t \in N, D_i^t \in N, \forall i \in M, \forall t \in K \quad (11)$$

$$B_i^t \in N, S_i^t \in Z, \forall i \in M, \forall t \in K \quad (12)$$

Then, the following mixed-integer programming model can be constructed.

$$\min \left\{ \left[ \alpha \cdot \sum_{t=1}^k \sum_{j=1}^m \sum_{i=1}^m (d_{ij} \cdot O_j^{t,i} + d_{ij} \cdot D_j^{t,i}) \right] + \mu \cdot (c \cdot B_{\max} + p \cdot \sum_{t=1}^k \sum_{i=1}^m |S_i^t|) \right\} \quad (13)$$

subject to Equations (2)–(12).

This model is formulated as a mixed-integer programming problem. CPLEX can be used for this problem.

#### 4. Case Study

Taking 183 TAZs of Nanjing city, China, as an example, combined with the demand data for bike-sharing on September 26 2018 and the carrying capacity of facilities, the supply volume of shared bikes was calculated. There were 124,316 pieces of operational data for bike-sharing. The laptop we used was equipped with an Intel(R) Core(TM) i7-8550 CPU and 16.0 GB RAM. The solving time of this problem was around 3 h. The supply volume of bike-sharing uses a kind of static data which do not require real-time regulation, so the solving time is acceptable in this case.

We used ArcGIS to obtain the value of  $d_{ij}$  (distance matrix of the center of mass in different TAZs). The detailed processes are shown below.

Step 1: the “element transition point” function in ArcGIS software was used to extract the elements of the traffic partition surface into point elements. The field attributes and contents were retained;

Step 2: the layer of the generated traffic partition centroid point element file was exported and duplicated;

Step 3: the “point distance” function in ArcGIS software was used to calculate the distance between the centroid of the traffic division and form the distance matrix of the centroid of the traffic division.

The values of the parameters used in the model were assigned as shown in Table 2.

**Table 2.** Model parameter assignment.

Parameter	Value	Parameter	Value
$m$	183	$c$	1000
$k$	24	$p$	0.5
$\lambda$	2	$\alpha$	1

#### Results and Discussion

In order to meet the travel demand, the increase in capacity must be reduced as much as possible due to the limit of the capacity expansion space. The total carrying capacities of the road network and parking facilities were increased to 1.5, 1.6, 1.7, and 1.8 times the current capacities. When the carrying capacity was smaller than 1.8 times of the current capacity, the model was not feasible, indicating that the carrying capacity still could not meet the demand of bike-sharing users. When the capacities of the road network and parking facilities were increased to 1.8 times the current capacity, the optimal solution was obtained.

The initial quantity of shared bikes  $B_i^1$  must meet the demand in each TAZ, and the initial repositioning quantity of shared bikes  $S_i^1$  was set to 0. Using the output results for  $B_i^t$  and  $S_i^t$  in the model, the supply volume of shared bikes in each period and TAZ could be obtained. The calculation formula for the supply volume in each period is as follow:

$$V_i^t = B_i^t - S_i^t \quad (14)$$

where  $V_i^t$  is the supply volume of shared bikes in traffic zone  $i$  at the beginning of time  $t$ .

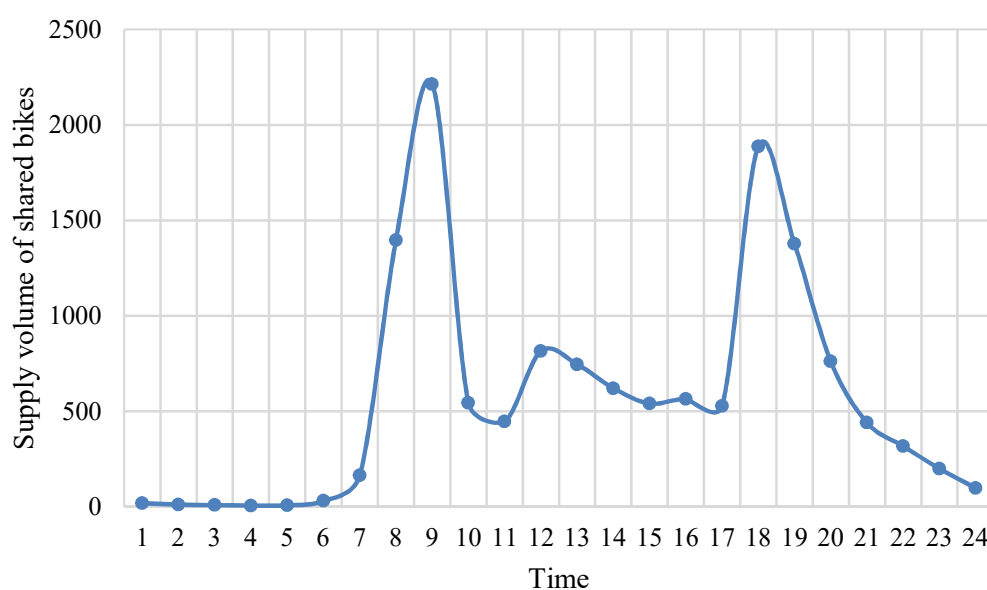
Finally, the optimal supply volume of shared bikes in the whole research area was obtained as 72,749.

The initial volume of shared bikes, the reposition volume for the bikes, and the supply volume in each period for a whole day in the study area were calculated, as shown in Table 3. The accumulated reposition volume of bike-sharing required for the full day was 310,645 bikes, and the accumulative supply volume was 629,167 vehicles.

**Table 3.** Reposition and supply volumes of shared bikes.

Period	Initial Volume	Reposition Volume	Supply Volume
1	2149	0	2149
2	2510	1275	1543
3	1909	1046	1069
4	1294	602	866
5	994	625	1327
6	1401	3579	4912
7	4483	15,463	19,672
8	16,568	41,172	57,276
9	49,612	27,393	72,749
10	74,326	45,446	34,632
11	34,117	11,822	27,337
12	26,922	10,950	34,362
13	32,902	9606	34,530
14	36,007	8890	31,017
15	31,427	8200	30,161
16	30,011	7432	33,607
17	30,519	10,635	38,052
18	37,093	23,864	59,167
19	53,457	17,507	50,130
20	50,752	21,654	31,236
21	35,843	14,841	23,608
22	26,294	10,424	18,654
23	21,283	10,347	12,902
24	15,315	7872	8209

At the same time, the supply volume can be obtained for a 24-h period in each traffic zone. Taking TAZ 48 as an example, Figure 1 shows the 24-h supply volume for this TAZ.



**Figure 1.** Supply volume for 24 h in TAZ 48.

Due to the high travel demand during peak hours, the load of the bike-sharing traffic facilities reached the highest level within one day, and the supply volume during peak



hours was the key value during the whole day. In this paper, the calculation results are supposed to effectively optimize the load of bike-sharing traffic facilities. Therefore, taking the scheme during the peak period (8:00–9:00) as an example, the loads of the traffic facilities before and after optimization were compared.

According to the calculation results, the load ratios of the bike-sharing road network and parking facilities in the traffic zone were recalculated. The parking demand is given by  $N_{P_i,t} = \lambda(B_i^t - S_i^t) + \sum_{j=1}^m D_j^{t,i}$ .  $(B_i^t - S_i^t)$  is the supply volume  $V_i^t$  of the  $i$ th TAZ in the period  $t$ . The load ratios of the road network and parking facilities before and after optimization are shown in Table 4. The load ratio is equal to the ratio of the demand to the carrying capacity of bike-sharing, and it was generated for each traffic analysis zone. The “maximum”, “minimum”, and “average” of the load ratio mean the maximum, minimum, and average values among these 183 traffic analysis zones. Before optimization, the maximum and average load ratios of the road network and parking facilities in 183 traffic zones were all greater than 1.0. After optimizing the quantity of shared bikes, the load ratios of the road network and parking facilities in 183 traffic zones were all lower than 1.0. An optimized supply volume of shared bikes can significantly reduce and balance the load ratio of traffic facilities.

**Table 4.** Load ratios of traffic facilities before and after optimization.

Load Ratio	Before Optimization		After Optimization	
	Road Network	Parking Facilities	Road Network	Parking Facilities
Maximum	10.701	62.398	1.000	1.000
Minimum	0.001	0.012	0.007	0.029
Average	1.785	4.468	0.629	0.896

When this model is applied to other cities, the demand for bike-sharing and the traffic carrying capacity of bike-sharing in the target cities need to be calculated first. The detailed calculation method can be found in [21]. The demand and carrying capacity are necessary input parameters of the proposed model. With these, a reasonable supply volume scheme can be obtained directly using the proposed optimization model.

## 5. Conclusions

This paper proposed an optimization model to obtain a reasonable supply volume scheme for bike-sharing. By analyzing the factors that influence the supply volume of shared bikes, the constraints in the process of adjusting the supply volume of shared bikes were obtained, including users’ demand and the capacities of the road network and parking facilities. Users’ travel costs and the input and reposition costs of bike-sharing were considered in the objective function. Then, a mixed-integer programming model based on traffic analysis zones was constructed to optimize the supply volume of bike-sharing. The model proposed in this paper differs from previous studies in the optimized object, model formulation, and influence factors considered. Taking Nanjing city as an example, the programming model was solved using CPLEX and the supply volume of shared bikes and the reposition volume for the whole day, based on TAZs, were obtained. In the study area, the total reposition volume for bike-sharing for the whole day was 310,645 and the total supply volume of vehicles was 629,167. The load ratios of the traffic facilities before optimization revealed that the load ratio of the parking facilities was extremely large, which indicated that the constraints of parking facilities, as well as those of the road network, had to be taken into account. Constrained by the carrying capacities of the road network and parking facilities, the optimization model can significantly reduce the load ratio of bike-sharing facilities.

However, there are still some limitations to this research. The work load of repositioning was regarded as having no upper bound, and the distribution of bike-sharing within



each TAZ was not considered. For further work, the two hypotheses need to be relaxed and the differences in demand between weekdays and weekends, and sunny days and rainy days, need to be taken into account for the optimization of the supply volume of bike-sharing.

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