Research Article

A Public Bicycle Sharing System Considering Renting and Middle Stations

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Abstract

Recently, public bicycle sharing system (PBSS) has become one of the most favorite urban transportation systems that can help governments to decrease environmental problems such as pollution and traffic. This paper studies a sharing system that includes two types of stations. The first category contains stations that users can rent or return back bicycles and each bicycle can be rented by any new user who arrives to the stations. The second group is the stations which are near shopping centers, historical and other places that users and tourists can stop and visit them. These stations are used only for parking the rented bicycles for a period of time and after that, the users must ride their bicycles and turn them back to their destination stations. After discussing the network of the model under the closed Jackson network, the Mean Value Analysis (MVA) method will be used to calculate the mean queue of each station and analyzing the proposed model.

Keywords: Transportation; Public Bicycle Sharing System (PBSS); Jackson Network; Mean Value Analysis (MVA)

1. Introduction

To lessen the environmental impacts such as pollution of the regular transportation vehicles, the use of Public Bicycle Sharing System (PBSS) is increasing in a high speed in recent years. In this system, users are allowed to rent a bike from a rental station and return it back to the same or another rental station after their journey. The history of using the public bicycle sharing system is well described and reviewed by DeMaio (2009), Shaheen et al. (2010), Laporte et al. (2015) and Patel et al. (2019). Molinillo et al. (2019) studied the socio-demographic and behavioral factors influencing the use of a public bicycle-sharing system integrated into a public transport network of local buses, metro, and commuter trains. Abolhassani et al. (2019) studied the key attributes that encourage the public to select BSS as the main urban transportation in comparison to other alternatives in a developing country. Yang et al. (2019) used the geographical information to study the urban public transport networks and discussed the performance of the transport networks considering bicycling between the short-distance bicycle station pairs and walking between the short-distance bus station pairs. Network design, locations and the capacity of the stations have been discussed by many researchers. Kaltenbrunner et al. (2010) analyzed the human mobility data in Barcelona with the goal of predicting the number of available bikes for any stations some hours ahead to improve the workability of the system. George & Xia (2011) gained the fleet size of a public sharing system considering the total profit. Correia & Antunes (2012) defined 75 possible depot locations for Lisbon by developing a mixed-integer programming model. Nair & Miller (2014) developed a bi-objective model to study the capacity of the system and maximizing the revenue of it. Fricker & Gast (2016) developed a stochastic model to gain the fleet size of the sharing system with the goal of reducing the problematic stations. Yan et al. (2017) considered deterministic and stochastic demands for their model and discussed the fleet size, routes and the location of the stations. Yan et al. (2018) optimized the allocated bicycles to stations using a set of scenarios for their stochastic models. Celebi et al. (2018) studied a bicycle sharing system considering the amount of unsatisfied demands for renting and returning bicycles as the service level to reach the proper locations and capacity of the stations. Yuan et al. (2019) developed a mixed integer linear programming model to calculate the number, location, and capacity of bicycle stations.

Balancing the inventory of the Public Bicycle Sharing System is a problem that is studied by researchers to increase users' satisfaction by decreasing fulfilled stations for parking the rented bikes and empty stations for renting bikes. Erdogan et al. (2014) considered a single vehicle for delivering bicycle between stations for their static integer programming model. Kaspi et al. (2014 & 2016)

studied a public bicycle sharing system in which users state their destination at origin station and according to their parking reservation policies a dock will be reserved for the users at destination stations. Bulhões et al. (2017) presented a static model considering multiple vehicles with identical capacities and service time limits for delivering the bicycles between the stations. Zhang et al. (2017) developed a dynamic mixed-integer programming model based on estimating the inventory levels for rebalancing the sharing system using a heuristic algorithm. Chiariotti et al. (2018) used historical data to devise an action for rebalancing the sharing system and the graph theory was used for selecting the proper path for delivering the bicycles. Vishkaei et al. (2020) defined critical levels to control requests of different routes in which a demand of a specified destination is accepted if the inventory of the original station is higher than the route's critical level.

This paper develops a new public sharing system network considering some middle stations which the users park their rented bikes to visit a place such as a museum or a shopping center and after that, they take back their rented bikes from the parking place and drive to their destination stations. In the next sections, after developing the model under the closed Jackson network, a numerical example will be solved using the MVA method and the capacity of the stations will be discussed.

2. Model Description

In this paper, the stations of the public bicycle sharing systems are divided into two groups. The first group contains the stations that users can rent a bike from them and return the bicycles to them. These stations are known as rental stations. The priority of renting the bikes depends on the arrival time of the users and obeys FIFO rule. These stations are near bus, train and other transportation systems to connect them to shopping centers and other places that people and tourists use to visit them. Therefore, there is another type of stations that are near to these places and users can park their rented bikes for a period of time and after their shopping or visiting they take them back and ride them to their destination stations. These stations are known as middle stations. Furthermore, there are users who rent the bikes without stopping at any middle stations and go directly to their destination stations. Viewing the system from a bicycle perspective, this model can be studied under a closed Jackson network. To develop the network, five different types of nodes are needed which can be described as follows:

1) Rental nodes
2) Middle nodes
3) Route nodes which are used to show the travels between the rental stations without meeting any middle station.

4) Route nodes which are used to show the travels that start from a rental station to a middle station.
5) Route nodes which are used to show the travels from a middle station to a rental station.

Service rate at each node is defined based on the arriving rates and the traveling rates at the rental nodes and the route nodes respectively. The service rates for the middle nodes are calculated based on the average time that lasts for shopping or visiting the places that are near the middle stations. Moreover, number of servers for the rental nodes is considered one and number of servers for the other nodes is defined as an infinite number because each user can ride the rented bike between the stations without staying in a queue. In the next sections, the parameters and the indices are described and after developing the proposed network, the MVA method is used for solving a numerical example.

3. Network Analyzing

To develop a proper Jackson network for the model, various parameters are defined.

3.1. Indices and parameters

S: The set of rental stations (finite server nodes)

K: Number of rental stations

s_z: Indices for showing rental stations; $(z = 1,2,...,K)$

S': The set of middle stations (infinite server nodes)

K': Number of middle stations

s'_h: Indices for showing middle stations; $(h = 1,2,...,K')$

I: The set of route nodes for traveling from a possible rental station to a possible middle station (this set includes infinite server nodes)

i_{zh}: Indices for showing routes from a possible rental station to a possible middle station; $(z \in S, h \in S')$

I': The set of route nodes for traveling from a possible middle station to a possible rental station (this set includes infinite server nodes)

i'_{hz}: Indices for showing routes from a possible middle station to a possible rental station; $(h \in S', z \in S)$

T: The set of route nodes for traveling between the rental stations (this set includes infinite server nodes)

t_{jz}: Indices for showing the routes between the rental stations; $(j, z \in S)$

R: The set of nodes $(R = S \cup S' \cup I \cup I' \cup T)$

N: Total number of nodes $(N = K + K' + 2KK' + K^2)$

F: Fleet size

n_i: Number of available bicycles at node i; $(i \in N)$

$\pi(n_i)$: The probability of existing n_i bicycles at station i.

$\pi_i(n_i, t)$: The probability of existing n_i bicycles at station i when the fleet size equals t.

r_{zj}: The probability of renting a bike from the rental station i for going to the rental station j; $(j, z \in S)$

r'_{zh}: The probability of renting a bike from the rental station z for going to the middle station h in which $\sum_{j=1}^{K} r_{zj} + \sum_{h=1}^{K'} r'_{zh} = 1$; $(z, j \in S, h \in S')$

r''_{hz}: The probability of traveling from the middle station h to the rental station z in which $\sum_{z=1}^{K} r''_{hz} = 1$; $(z \in S, h \in S')$

γ_z: The mean requests of renting a bike from station z; $(z \in S)$

β_i: The rate of exponential distribution in which $\frac{1}{\beta_i}$ is the mean time that lasts for each bike get service from node i; $(i \in I, I', T, S')$

c_i: Number of servers at node i in which $c_i = 1$; $(i \in S)$ and $c_i = F$; $(i \in I, I', T, S')$

μ_i: The service rate at node i which equals $\begin{cases} F\beta_i & for\ i \epsilon S', i \epsilon I, i \epsilon I', i \epsilon T \\ \gamma_i & for\ i \in S \end{cases}$

$\lambda_i(t)$: The total mean flow rate into node i when the fleet size equals t; $(i \in R)$

$L_i(t)$: The expected number of bikes at node i when the fleet size equals t; $(i \in R)$

$W_i(t)$: The mean waiting time at node i when the fleet size equals t; $(i \in R)$

n_{s_z}: Number of stocks at rental station z; $(z \in S)$

$n_{s'_h}$: Number of stocks at middle station h; $(h \in S')$

3.2. Closed jackson network

The closed Jackson network is used to develop the proposed model. Nodes of the Jackson Network can be categorized into two groups: the first one includes nodes with one virtual server to describe the stations and the user arrival time is considered as the service time and the second group consists of route nodes having F virtual servers with the time of journey being defined as the service time. Note that the number of servers for route nodes must be considered infinite, but since there are at most F bikes, the number of servers is defined to be F.

Figure 1 depicts the network as an example with 3 rental stations and 2 middle stations which leads to 9 route nodes for linking the rental stations and 12 route nodes for linking the rental nodes to the middle nodes and vice versa.

4. Mean Value Analysis (MVA)

One of the most workable methods for solving the closed Jackson network is the Mean Value Analysis (MVA) method which is defined in Bruell & Balbo (1980). The steps of solving the proposed network using the MVA method can be described as the following algorithm which is based on the parameters that are introduced in section 3.

a. Solve weighted traffic equation
$v_j = \sum_{i=1}^{N} v_i p'_{if}$ $(i, f \in R)$, where $v_i = \frac{\lambda_i}{\lambda_l}$ (v_l is normalized and is equal to 1 and l is selected from the set R)

b. *For i=1:N do*
- $L_i(0) = 0$
- $\pi_i(0,0) = 1$
- $\pi_i(n_i, 0) = 0$; $n_i \neq 0$
  End do

c. *For t=1:F do*
   For i=1:K+K' do
- $W_i(t) = \frac{1}{c_i \mu_i} \left(1 + L_i(t-1) + \sum_{n_i=0}^{c_i-2} (c_i - 1 - n_i) \pi_i(n_i, t-1) \right)$
  ; $c_i = F(\forall i \in I)$ and $c_i = 1(\forall i \in S)$
- $\lambda_l(t) = \frac{t}{\sum_{i=1}^{N} \vartheta_i W_i(t)}$
- $\lambda_i(t) = \lambda_l(t)\vartheta_i$; $i \neq l$
- $L_i(t) = \lambda_i(t)W_i(t)$
  For $n_i = 1:t$ do
- $\pi_i(n_i, t) = \frac{\lambda_i(t)}{\mu_i a_i(n_i)} \pi_i(n_i - 1, t - 1)$; $a_i(n_i) = \begin{cases} n_i, & n_i \leq c_i \\ c_i, & n_i \geq c_i \end{cases}$

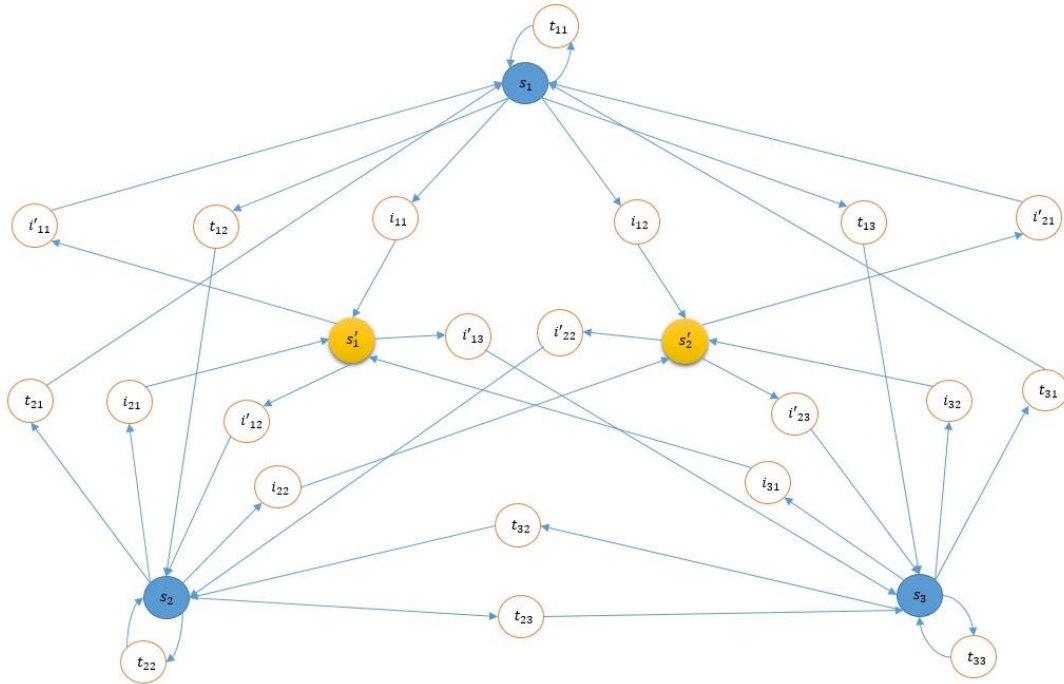 *End do*

     End do

     End do

Fig. 1. Closed Jackson network considering 3 rental stations and 2 middle stations.

5. Numerical Example

Consider a public bicycle sharing system with five stations in which three of them are for renting and returning back bicycles and the two other stations are considered as middle stations for parking the bicycles for a period of time to visit a museum or a shopping center. The fleet size equals 200, and the other parameters are shown in table 1.

The Mean Value Analysis (MVA) method is used to find out the mean number of bicycles that are available for renting at the rental stations ($L_z; z \in S$) and the mean number of bikes that are being parked in the middle stations ($L_h; h \in S'$). The rental stations are considered as the finite server nodes and the middle stations and the routes are defined as the infinite server nodes. Number of servers for the rental stations equals 1 and when a bicycle

enters, it should wait in a queue to be rented and the waiting time is considered as the service time. As the total number of bicycles that are being delivered between the nodes equals F, number of servers for the infinite server nodes is considered 200. Service time at the middles stations and the route nodes is the time which last for a customer to visit the museum or the shopping time and the time that is needed to travel between the nodes respectively. Table 2 depicts the probability matrix which defines the probability of delivering the bikes between different nodes. Obviously, each route node only has one output based on the users' destination.

The result of solving the numerical example using the MVA method is shown in table 3. This table indicates the mean number of parked bicycles at each rental station and each middle station.

Table 1
The parameters of the example.

No des	s_1	s_{12}	s_{13}	i_{11}	i_{12}	s_2	s_{21}	s_{23}	i_{21}	i_{22}	s_3	s_{31}	s_{32}	i_{31}	i_{32}	s'_1	i'_{11}	i'_{12}	i'_{13}	s'_2	i'_{21}	i'_{22}	i'_{23}
c_i	1	200	200	200	200	1	200	200	200	200	1	200	200	200	200	200	200	200	200	200	200	200	200
γ_i	44	-	-	-	-	58	-	-	-	-	52	-	-	-	-	-	-	-	-	-	-	-	-
β_i	-	5	3	4	2	-	5	4	3	3	-	7	3	2	2	4	2	4	3	5	3	5	4
μ_i	44	1000	600	800	400	58	1000	800	600	600	52	1400	600	400	400	800	400	800	600	1000	600	1000	800

Table 2
The probability matrix of the numerical example.

	s_1	s_{12}	s_{13}	i_{11}	i_{12}	s_2	s_{21}	s_{23}	i_{21}	i_{22}	s_3	s_{31}	s_{32}	i_{31}	i_{32}	s_1'	i_{11}'	i_{12}'	i_{13}'	s_2'	i_{21}'	i_{22}'	i_{23}'
s_1	0	0.1	0.2	0.4	0.3	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s_{12}	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s_{13}	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
i_{11}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
i_{12}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
s_2	0	0	0	0	0	0	0.1	0.1	0.3	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0
s_{21}	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s_{23}	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
i_{21}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
i_{22}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
s_3	0	0	0	0	0	0	0	0	0	0	0	0.1	0.15	0.4	0.35	0	0	0	0	0	0	0	0
s_{31}	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
s_{32}	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
i_{31}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
i_{32}	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	1	0	0	0
s_1'	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.25	0.4	0.35	0	0	0	0
i_{11}'	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
i_{12}'	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
i_{13}'	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0
s_2'	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.35	0.35
i_{21}'	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
i_{22}'	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
i_{23}'	0	0	0	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0

Table 3
The mean queue of bicycle at each station in the numerical example.

	Rental Stations			Middle Stations	
Stations:	s_1	s_2	s_3	s_1'	s_2'
Mean number of parked bikes:	12.7285	10.5643	67.3017	13.1180	11.2718
Capacity of station:	22	18	117	23	20

In the proposed example, there are 200 bikes in the system. If the capacity of each station be considered based on the mean available bikes, the capacity of station 1 equals 22

$(n_{s_1} = \frac{12.7285}{(12.7285+10.5643+67.3017+13.1180+11.2718)} \times 200)$. The capacity of each station based on the mean number of parked bicycles is shown in table 3. The probability of facing fulfilled stations for parking the bicycles for each station equals the probability of existing bicycles more than the capacity of each station ($\pi(n_z \geq n_{s_z}); z \in S$) and $\pi(n_h \geq n_{s'_h}); h \in S'$). These probabilities are calculated using the MVA method and are brought into table 4.

Table 4
The probability of facing fulfilled stations for parking the rented bikes.

	Rental Stations			Middle Stations	
Stations:	s_1	s_2	s_3	s_1'	s_2'
Probability of facing fulfilled station:	0.2077	0.2169	0.00036	0.0171	0.0241

Lack of free capacity for parking the rented bikes is more critical for the middle stations because the users need to park their bicycles for a while to go shopping or visiting some places. On the other hand, lack of inventory is another factor that leads to dissatisfied users. As it is depicted in table 4, the probability of facing a fulfilled parking place in the middle stations is less than %2, and

the most probability is related to the rental stations 2 and 1 respectively.

In other words, it rarely happens for the customers to wait at station 3 for returning their bikes to the system and there is at least a free dock for parking most of the times. About 20 out of 100 customers may face lack of parking place at stations 1 and 2. Finally, about two customers out of 100 customers may face full middle stations.

6. Conclusion

In this paper, a public bicycle sharing system (PBSS) is studied in which each user can rent a bicycle from a rental station and return it to the same station or to another rental station. Besides that, the users are allowed to park their rented bicycles in one of the middle stations which are considered as parking places near shopping centers or historical places before returning their bicycles to their destinations. The proposed model is studied under a closed Jackson network and the Mean Value Analysis is used to solve it. For more explanations, a numerical example is developed and the capacity of the stations is discussed based on the mean available numbers of bicycles at each station. The probabilities of facing fulfilled stations for parking the bicycles in the middle stations or the rental stations are calculated and the owner of the system can revise the capacity of stations to reduce the amount of the probabilities. As further studies, the model can be extended considering decision variables such as the fleet size and the capacity of the stations with the goal of maximizing users' satisfaction. Moreover, the model can be developed by defining multi-stop criteria for the users to have permission to stop in more than one middle station before reaching to their destinations.

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