Bayesian Probabilistic Prediction Based Parking Lot Sharing Model for Residential Neighborhoods

Yihang Shen *, Yixuan Wang

School of Transportation and Logistics Engineering, Wuhan University of Technology, Wuhan Hubei 430063, China

*kobe160413@163.com

Abstract. To develop idle parking resources, enhance existing parking efficiency, and alleviate urban parking challenges, this paper focuses on residential community parking lots. It constructs a Bayesian probability matrix to predict the combination of vehicle arrival times and required parking durations. Based on this, it proposes two parking sharing modes: simultaneous opening and batch opening. It compares the differences in parking temporal and spatial coverage and turnover rate under different sharing modes, and conducts sensitivity analysis on key influencing factors to justify the rationality of the settings. The research findings indicate that under a fixed sharing scale, the average parking temporal and spatial coverage rates for the two sharing modes are 73.57% and 86.60% respectively. The second sharing mode yields higher parking temporal and spatial coverage rates compared to the former, albeit with lower turnover rates. This suggests higher utilization of parking spaces during sharing periods but lower adaptability to parking demands. Under this mode, parking lot utilization throughout the day increases by 35.88% compared to before sharing. Moreover, on the basis of the second sharing mode, sensitivity analysis is conducted on the key setting parameter of "the number of parking spaces opened per hour." It is found that under a fixed sharing scale, parking temporal and spatial coverage rates are positively correlated with the number of parking spaces opened per hour. When the sharing scale is 50 and the number of parking spaces opened per hour reaches 9 or more, the variance in parking temporal and spatial coverage rates gradually decreases and stabilizes, indicating a more economical and practical approach. Additionally, this paper provides suggestions for relatively reasonable sharing modes for shared parking lots, laying a foundation for the development and construction of urban shared parking lots.

Keywords: Shared parking; neighborhood parking; Bayesian networks; parking spatial-temporal coverage; parking turnover rate

1 Introduction

In recent years, “parking difficulty” has become a “headache” for many big cities. By the end of 2020, the shortage of parking spaces in China will be close to 80 million. The mismatch between the supply and demand of parking resources has gradually

G. Zhao et al. (eds.), *Proceedings of the 2024 7th International Symposium on Traffic Transportation and Civil Architecture (ISTTCA 2024)*, Advances in Engineering Research 241,
https://doi.org/10.2991/978-94-6463-514-0_60

become one of the key obstacles to the development of urban transportation. Traditional open parking lots, limited by urban land and space resources, have been unable to meet the parking demand brought about by the growing number of motor vehicles, while closed parking lots are only open to specific users, which will result in a waste of parking resources. The urban traffic disorder caused by insufficient parking spaces not only exacerbates congestion and automobile exhaust pollution, but also leads to vehicle competition for parking space resources [1], illegal parking and other chaotic phenomena.

The development of the sharing economy model provides a direction to solve the urban parking problem. "Sharing" can not only reduce the time of commodities in idle state [2], but also enable consumers to enjoy the services of commodities at a relatively small cost, without having to buy the ownership of commodities. The concept of "shared parking" has been proposed by scholars at home and abroad in order to cope with the severe urban parking challenges [3]. Shared parking is designed to open the free time of parking spaces to other users based on the fact that different types of parking users do not have the same parking demand for a certain parking lot or parking space in a certain area at the same time.

Domestic scholars on the issue of shared parking, the proposed measures mainly include parking allocation strategy, shared parking information platform construction, hybrid parking lot parking space sharing mechanism. Zhao Guixiang et al [4] innovated the parking lot operation and management mode for the different user parking space-time demand of hybrid parking lot; Chen Junkun et al [5] proposed the use of the Internet platform construction mechanism and coordination program to improve the shared parking service platform to realize the timely mutual sharing of parking resources; Zhang Qianmin [6] et al from the supply point of view, based on the existing parking space allocation model, constructed a redistribution strategy under the maximum parking rate of the parking space allocation model, improving the platform revenue of the parking lot as well as user satisfaction. parking allocation model under redistribution strategy, which improves the platform revenue of the parking lot as well as user satisfaction。

Foreign scholars on the problem of excess demand for parking during working hours began to focus on developing unused private parking spaces in cities. Cheng et al [7] modified the VCG (Vickrey-Clarke-Groves) auction mechanism by utilizing a scale-control concept that can provide incentives for both the supply and demand sides to achieve shared parking in busy urban areas; Yang et al [8] combined the shared space and the the problem of matching the demand side that allows any customized parking interval, and designed an effective Lagrangian relaxation algorithm to solve the large-scale shared parking problem; Zhang et al [9] proposed a dynamic planning model with dynamic properties of the demand information, so as to solve the problem of randomness that exists in the sharing time and demand information when sharing parking platforms and validate it.

In summary, existing research on shared parking mainly focuses on the problem of parking demand adaptation, including the allocation of shared parking resources, the scheduled allocation strategy of shared parking platforms, and the revenue problem of shared parking [10]. Shared parking demand is an important consideration in the parking allocation process [11], and how to improve the prediction accuracy of parking

demand and demand adaptation is the key to realize shared parking. In this paper, starting from the development of idle parking space resources in community parking lots, we propose a demand prediction method based on Bayesian probability matrix for open sharing of residential community parking lots, designing two modes of opening and sharing all parking spaces at the same time during the time period, and opening and sharing the parking spaces in batches according to the length of time that can be shared at different points in time on average, to explore the usage efficiency of the shared parking lot after matching supply and demand in different modes and selecting a more reasonable mode to share parking spaces. We also select a more reasonable sharing mode and conduct a sensitivity analysis of the key setting parameters to explore the impact of the number of open parking spaces per hour on the utilization efficiency of the shared parking lot.

2 Model

2.1 Parking Lot Sharing Model

Considering that the national legal working hours generally start at 8:00 a.m., this paper sets the sharing period during which the district parking lot can be opened as 8:00 a.m. to 8:00 p.m., and stipulates that the maximum opening time of the shared parking space is 12 hours. Due to the differences in the idle time of each private parking space in the daytime in the small area, this paper chooses to adopt two different models for opening and sharing the parking lot in the small area. The first sharing mode is to assume that all participating neighborhood parking space owners choose the same sharing hours and open them at the same time; the second sharing mode is to assume that all participating neighborhood parking space owners will choose different sharing hours according to their own situation and open them in order of hours after the sharing period begins. According to the data of the National Bureau of Statistics, as of the beginning of 2024, the average daily working hours of employed people in China is about 8 hours, and the working hours of each household owner in the real neighborhood are generally 8 hours or longer, therefore, the second sharing mode will divide the parking spaces into 5 types of 8, 9, 10, 11 and 12 according to the criterion of the maximum length of time that the parking spaces can be opened, and open them sequentially in the whole point of the sharing period.

2.2 Parking Demand Forecast

For the shared parking lot, the parking demand that needs to be matched is mainly the arrival moment of the vehicle and the parking duration. In reality, the parking demand of vehicles has uncertainty, so this paper adopts the construction of Bayesian Network (Bayesian Network) in the prediction of parking demand. Bayesian network is a method for describing uncertainty inference problems with high flexibility and ability to handle uncertainty. Using the construction of Bayesian network, the combination of different demands in different time periods can be predicted, which can improve the accuracy of the prediction, the construction of Bayesian network includes determining the network

structure and the conditional probability of the two parts, in this paper, the topology of the Bayesian network is shown in Figure 1.

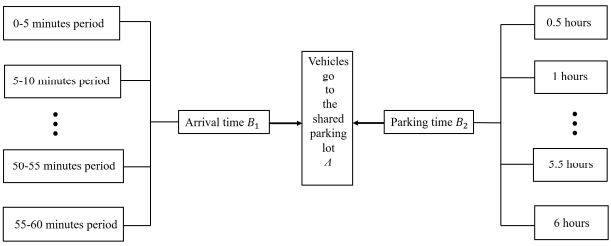


Fig. 1. Schematic diagram of Bayesian network topology for parking prediction

In reality, the probability of a vehicle going to a parking lot for parking varies during the daytime hours and has peaks influenced by time. The exponential distribution is usually used to describe the time between successive events, in which the probability of an event occurring during the time period changes gradually over time, which is close to the reality. Similarly, since in reality, the length of parking time required for each vehicle is different and does not affect each other. The Poisson distribution is usually used to describe the number of events occurring per unit of time, which can be a good description of the distribution of parking demand in the case of a large number of vehicles. Therefore, exponential and Poisson distributions are used to make assumptions about the probability values of the variables.

In this paper, Bayesian network construction will be carried out for vehicle arrival moment and parking duration. It is assumed that the arrival time and parking duration of vehicles are variables B_1 and B_2 respectively, and the vehicles going to the shared parking lot in each hourly period are variable A. The basis for the division of each variable and state is as follows:

(1) Variable A indicates that vehicles go to the shared parking lot to park in different time periods within the shared time period T. In this paper, the time period is divided into 12 hourly time periods (1 stands for 8:00 - 9:00), and so on;

(2) Variable B_1 represents the probability of vehicles arriving at the shared parking lot at different moments of each time period. B_1 is divided into 12 states, (1 represents 0:00 to 5:00 moments of each hour, and so on), and the probability values of each state are generated using a probability distribution;

(3) The variable B_2 represents the probability of a vehicle choosing on different parking hours. Considering that the shared parking lot is mainly used to meet the short-term parking demand of vehicles, this paper sets twelve different time durations (0.5h, 1h, 1.5h...6h), and the variable B_2 is divided into a total of twelve states, and the values of the variables are generated using a probability distribution;

Each of the above three variables A, B_1, and B_2 is categorized into 12 different states, counted as $B_{ij} = (i = 1,2;\ \mathrm{j} = 1,2,3,\ldots 12);\ ;\ A_j(j = 1,2,3,\ldots 12)$. According to Bayes' theorem:

$$P(B_{ij}\left|A_j\right.)=\frac{P(A_j\left|B_{ij}\right.)P(B_{ij})}{\sum_{j=1}^{12}P(A_j\left|B_{ij}\right.)P(B_{ij})} \tag{1}$$

The Bayesian probability matrix for predicting the combination of vehicle arrival moments and parking duration demand can be obtained by performing calculations in the above equation.

2.3 Comparative Analysis of Sharing Models

Once the shared parking lot is open, mark the arriving cars during the shared time period. The vehicles arriving to park in the shared parking lot are noted as $a_1, a_2, a_3 \ldots a_k$, while the corresponding parking duration of each vehicle is noted as t_1, t_2, $t_3 \ldots t_k$. Calculate the hourly parking coverage of shared parking spaces based on the total number of shared parking spaces identified and the number of hours of open sharing periods Eq:

$$P=\frac{\sum_{\mathrm{i}=1}^{\mathrm{k}}a_{\mathrm{i}}\times t_{\mathrm{i}}}{N'T} \tag{2}$$

N' is the total number of identified shared parking spaces;
T is the length of the shared time period;
t_i is the parking duration corresponding to each vehicle.
and the parking turnover rate Q of the shared parking lot during the shared time period: Eq:

$$Q=\frac{\mathrm{k}}{N'} \tag{3}$$

k is the total cumulative number of vehicles visiting the parking lot for parking during the shared time period;
N' is the determined capacity of the shared parking lot berths.

According to the above two different community parking lot sharing modes, the parking space-time coverage rate and parking turnover rate of the shared parking lot during the sharing period can be calculated respectively, which in turn reflects the utilization of the parking space in the shared parking lot in a day. Comparing the parking space-time coverage rate and turnover rate under two different modes, a more efficient and reasonable sharing mode can be obtained under a certain sharing scale.

2.4 Scene

It is assumed that there exists an urban residential neighborhood, which has a parking

lot that serves it individually, and the total number of parking spaces open for use in the parking lot is N, and there are no vacant unused parking spaces. Since the neighborhood generates a large amount of parking demand during the day, and the private parking spaces in the neighborhood are unused, it is possible to open up some of the parking spaces for a kind of "shared" use model.

After consulting with each parking space owner, the unused parking spaces are opened for sharing, and the total number of parking spaces available for sharing is N'. When the shared parking lot is open. Temporary users will be allowed to make reservations (for arrival time and parking duration), and some scenarios of the parking lot will be simplified and designed during the experiment as follows:

(1) Ignores the time the vehicle spends cruising through the parking lot, the vehicle enters a parking space and begins to park as soon as it reaches it, and does not leave until it has completed the full amount of parking time required;

(2) The vehicle does not change parking spaces midway through the parking process;

(3) If any vehicle chooses a parking duration end time that exceeds the end time of the shared time slot, it will not be considered in this paper;

(4) If all the parking spaces in the parking lot are already used when the vehicle arrives, the vehicle will not wait but just leave.

After roughly determining the operation rules of the parking lot, due to the provisions of this paper, the vehicle arrival time interval is specified as 5 minutes, the average short-term parking demand of vehicles in reality is about 3 hours, this paper uses the exponential distribution with a scale parameter of 0.2 and the Poisson distribution with a mean of 3 to generate 12 groups of values, and assigns values to the probabilities of the groups of variables B_1 and B_2 after normalization, and the values of the variables and node variables i The values of each variable and node variable i are shown in Table 1 :

Table 1. Value of each variable node in Bayesian network

	1	2	3	4	5	6	7	8	9	10	11	12
B_1	0.013	0.205	0.072	0.075	0.069	0.039	0.010	0.020	0.072	0.317	0.036	0.072
B_2	0.097	0.032	0.129	0.032	0.065	0.129	0.064	0.129	0.032	0.097	0.129	0.065

Since the parameters of the calculation process have been determined, the Bayesian probability matrix calculation can be completed and the expected value of the shared parking lot parking space-time coverage and parking turnover can be calculated.

3 Results and Analysis

Assuming the existence of a community parking lot that allows the opening of 50 parking spaces, simulation experiments are carried out according to the two sharing modes specified above. In order to avoid the chance that Bayesian as a means of prediction has in the calculation, this paper carries out several experiments on the two sharing modes, analyzes the general rule of the opening and use of the shared parking lot under different modes, and explores the reasonable number of open parking spaces in the

shared parking lot and the way of the sharing mode setup.

3.1 Parking Spatial-Temporal Coverage and Turnover

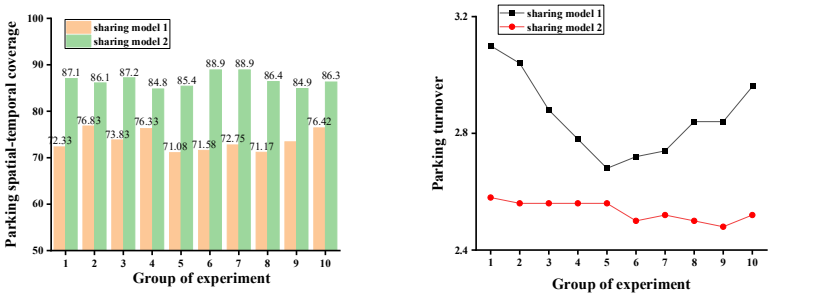
The results of parking spatial-temporal coverage (%) and parking turnover for the two sharing models obtained from the simulation experiments are shown in Table 2 and Table 3:

Table 2. Simulation results of parking spatial-temporal coverage in shared parking lots

	1	2	3	4	5	6	7	8	9	10	E
Model1	72.33	76.83	73.83	76.33	71.08	71.58	72.75	71.17	73.42	76.42	72.00
Model2	87.10	86.10	87.20	84.80	85.40	88.90	88.90	86.40	84.90	86.30	86.40

Table 3. Simulation results of parking turnover rate in shared parking lots

	1	2	3	4	5	6	7	8	9	10	E
Model1	3.10	3.04	2.88	2.78	2.68	2.72	2.74	2.84	2.84	2.96	2.88
Model2	2.58	2.56	2.56	2.56	2.56	2.50	2.52	2.50	2.48	2.52	



(a) The parking space coverage rate results **(b) The parking turnover rate results**

Fig. 2. Comparison of simulation results of different sharing modes in shared parking lots

Figure 2 shows the experimental results of parking space-time coverage and parking turnover under the two sharing modes. In terms of parking space-time coverage, the average space-time coverage of the parking lot during the shared time period is 73.57% in the first sharing mode and 86.60% in the second sharing mode, which is close to the expected values of 72.00% and 86.40%. The parking space-time coverage rate can reflect the efficiency of the parking spaces in the parking lot during the specified time period, compared with the second sharing mode, the use of the parking spaces during the sharing time period is more efficient, and the parking spaces are idle for a shorter period of time.

Regarding the parking turnover rate, the average parking turnover rate of the parking lot during the shared time period is 2.86 for the first sharing model and 2.53 for the second sharing model, with the former being closer to the expected value of 2.88. The parking turnover rate can show the use of parking spaces in the parking lot during a fixed period of time, and it can be seen from the figure that the parking turnover rate fluctuates in a wider range in the first sharing mode, while the latter changes less. Since the first sharing mode opens all parking spaces at the beginning of the sharing period, it can match the long-time and short-time parking demand of vehicles better, and the parking turnover rate decreases if there are more vehicles in the long-time parking demand, on the contrary, the parking turnover rate is higher if there are more vehicles in the short-time parking demand, so the average total number of parking entering the parking lot during the sharing period is more; the second sharing mode puts 50 parking spaces in the parking lot at each time of the day from 8:00 to 12:00, and the parking turnover rate of the second sharing mode is more than the average number of parking entering the parking lot. The second sharing mode will open 10 parking spaces at each whole point from 8:00-12:00, which will reject the parking demand of some vehicles when some parking lots are just opened, and at the same time, due to the differences in the permitted opening hours of different parking spaces, the matching degree of personalized parking demand is lower in this mode, so the average parking turnover is lower, but the trend of change is more stable.

The first sharing model has a higher parking turnover rate, but opening all parking spaces at 8:00 a.m. at the same time is too idealistic and does not take into account the individual differences in the working hours of each owner in the residential area, and the economic costs paid to the owner of the parking space are also higher, leaving the parking space idle for a longer period of time. The second sharing model opens the parking spaces in batches, which is more relevant to the reality, and the spatial and temporal coverage of the parking lot is relatively high, which not only ensures the admission of a certain number of incoming cars, but also reduces the cost of sharing parking spaces and brings stable economic benefits. Overall, the second sharing mode is closer to the reality and is a more reasonable way to share parking lots, taking into account the interests of both supply and demand.

3.2 Sensitivity Analysis

The number of parking spaces open per hour in the shared parking lot model is a key parameter and an important part of the shared parking lot that affects the hourly parking coverage and parking turnover rate. Therefore, it is necessary to conduct a sensitivity analysis of the number of open parking spaces per hour set in the model to discuss the extent to which changes in the parameters affect the results within a certain degree. Since the parking space-time coverage rate mainly reflects the use of parking spaces, and the parking turnover rate mainly reflects the number of parking spaces in a specified period of time, the parking space-time coverage rate can be regarded as the main index describing the utilization rate of the shared parking lot, and in the case of guaranteeing that the shared scale remains unchanged, this paper perturbs the number of open parking spaces per hour with a specific step±1 on the basis of an initial value of 10, and obtains

the results of the parking space-time coverage rate and parking turnover rate results are shown in Fig. 3.

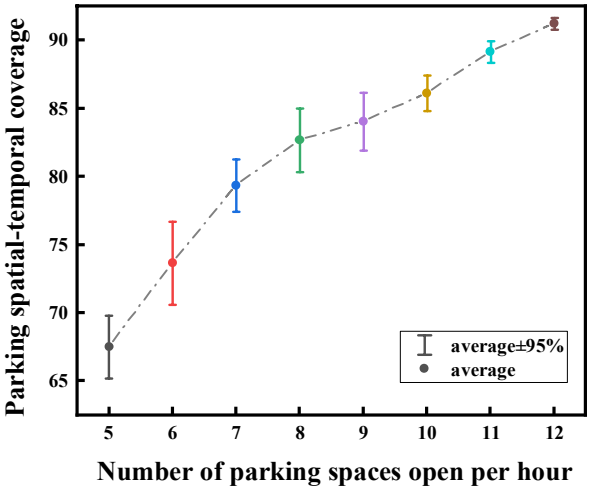


Fig. 3. Parking spatial-temporal coverage - trend in the number of open parking spaces per hour

From Figure 3, we can see the change of parking space-time coverage ratio after the change of the number of open parking spaces per hour. When the sharing size is kept constant, the parking space-time coverage rate is positively correlated with the number of openings per hour, and the variance of the parking space-time coverage rate gradually decreases with the increase of the number of open parking spaces per hour.

From the results of multi-group simulation experiments, the average parking space-time coverage rate increases from 67.53% to 91.21%, when the number of open parking spaces per hour is less than or equal to 9, it can be seen that the changes in the parking space-time coverage rate of each group of experiments are more obvious, which may be due to the fact that the number of open parking spaces per hour is too small, and the number of initially open open parking spaces is too much, and in this case the parking lot can satisfy the parking demand of many different time durations, which makes the experimental variance of each group larger, and on the other hand, it can also lead to the inefficient use of parking spaces in the parking lot due to the oversupply of parking spaces. As the number of open spaces per hour rises, the time window of the parking lot opening decreases, the phenomenon of excess parking slows down the matching degree for different parking demands decreases, and the change of the parking time coverage rate is stabilized within a certain range.

From the simulation results, although the higher the number of open parking spaces per hour, the higher the parking space-time coverage, but in practice the number of open spaces per hour should not be set too much, due to the start of the opening around 8:00 a.m. may have been part of the parking demand, so the parking lot should ensure that a certain number of parking spaces can be provided to match the beginning of the sharing time, to avoid the peak parking time period If the number of parking spaces to

meet the maximum opening hours is small, it is not possible to match the long-time parking demand, and cannot meet the personalized parking demand. Taking the simulation results of this paper as an example, when the sharing scale is 50, when 10 parking spaces are opened every hour, the utilization rate of the whole day is increased by 35.88% compared with that before the parking lot is opened for sharing, which is a more feasible mode of sharing parking lot opening.

4 Conclusions

Based on the Bayesian conditional probability matrix, this paper makes a combination prediction of parking demand around residential neighborhoods, obtains the probability of parking under different combinations of demand conditions, improves the scope and accuracy of the prediction, and lays a good foundation for the prediction of parking demand and the opening of shared parking lots under the background of big data.

(1) This paper proposes a feasible parking lot sharing model based on the assumption that the parking lot sharing scale is 50, and the calculated parking lot improves the efficiency of all-day space-time utilization by 35.88% compared with that before the opening and sharing, reflecting that the sharing and opening of the parking lot can bring stable economic and social benefits to the region where it is located, and is a feasible sharing economic model for the future;

(2) Simulation experiment results indicate that, under a fixed sharing scale, categorizing parking spaces based on sharing duration can indeed enhance the efficiency of parking space utilization. However, it may reduce the degree of matching between parking lots and individualized parking demands;

(3) For the second sharing mode, this paper conducts a sensitivity analysis on the key parameter of "the number of parking spaces open per hour." Under a constant sharing scale, the temporal and spatial coverage of parking is positively correlated with the number of parking spaces opened per hour. When the number of parking spaces opened per hour reaches 9 or more, the variance of temporal and spatial coverage gradually decreases and eventually stabilizes.

Generally speaking, this article provides some reference for the setting mode of parking lots in various regions in the future when they are open for sharing. In reality, Bayesian prediction matrices require surveys of users and vehicles within the area and statistical analysis of various probabilities before inputting, while shared modes should consider specific parking lot conditions such as the maximum sharable parking capacity, nearby parking demand, willingness to share among different owners, and incentives for parking space sharing. Moreover, not only residential parking lots but also parking lots in office areas, commercial areas, and even schools can be opened for sharing during their idle periods. From the perspective of urban management, the parking lot sharing and private parking space sharing measures adopted by cities at home and abroad to address parking difficulties have achieved good results. This article provides a certain foundation for sharing residential parking lots, and urban residents and city managers should carry out secondary planning and development of existing resources to jointly address urban parking problems.

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