Data-Driven Methods for Matching Commuting Groups in Shared Parking: A Postprint

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Abstract

With the increasing ownership of motor vehicles, parking difficulty has become an increasingly prevalent urban problem. However, while parking lots at workplaces experience long queues, a substantial number of parking spaces in surrounding residential areas remain idle, leading to inefficient utilization of parking resources. Existing shared parking methods face significant implementation challenges due to their inherent randomness. To mitigate this randomness, reduce the implementation difficulty of shared parking, and minimize the waste of parking resources, this study proposes a data-driven one-to-one pairing and sharing solution based on the natural complementarity of travel times between commuter groups in adjacent office buildings and residential areas. By analyzing vehicle entry and exit records from parking facilities to address the problem, we examine the entrance and exit data to derive idle duration characteristics of residential area parking spaces and usage duration characteristics of office building vehicles, subsequently obtaining paired parking spaces and vehicles through a duration-maximization matching method. Experiments conducted on selected parking lots reveal that perfectly matched parking spaces account for 37.66%, with the average utilization rate of all matched parking spaces increasing by 15.24%, and the maximum increase reaching 57.84%. The results demonstrate the considerable feasibility of the pairing and sharing approach.

Full Text

Preamble

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Research on Data-Driven Paired Shared Parking for Commuter Groups

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Abstract: With the increasing number of motor vehicles, parking difficulty has become a common urban problem. While parking lots at workplaces face long queues, numerous parking spaces in nearby residential areas remain idle, resulting in inefficient utilization of parking resources. Existing shared parking methods suffer from high implementation difficulty due to their random nature. To reduce this randomness, lower implementation barriers, and minimize resource waste, this paper proposes a data-driven one-to-one paired sharing solution based on the natural complementarity of travel times between commuter groups in adjacent office buildings and residential areas. By analyzing vehicle entry and exit records, we extract idle duration characteristics of residential parking spaces and usage duration patterns of office building vehicles, then apply a duration-maximization matching method to pair spaces with vehicles. Experiments on selected parking facilities show that 37.66% of spaces achieved perfect matches, with average utilization rates increasing by 15.24% across all matched spaces and a maximum increase of 57.84%. These results demonstrate the substantial feasibility of paired sharing.

Keywords: urban traffic; shared parking; data analysis; parking space pairing; residential area sharing

0 Introduction

As motor vehicle ownership continues to rise, urban parking spaces have become increasingly scarce, making parking difficulties a widespread issue in many cities. Taking Chengdu as an example, statistics from the traffic management bureau show that by the end of 2017, the city' s motor vehicle population reached 4.52 million [1], while parking spaces remained severely insufficient. Particularly acute is the situation where parking at workplaces is extremely tight while nearby residential areas have numerous vacant spaces. In this context, the concept of shared parking, first introduced by the Urban Land Institute in the United States, offers a viable solution within existing parking resources.

The shared parking concept, proposed in *Shared Parking* by the Urban Land Institute, refers to the joint utilization of parking spaces among different land-use attractions within a certain area based on peak parking demand characteristics throughout the day [2]. Essentially, the same parking space serves multiple utilization purposes—for instance, a private residential space shared with external vehicles during different time periods. Building upon this foundation, numerous scholars have conducted related research on shared parking. Studies have examined commuter group shared parking problems, proposing allocation methods under various conditions, constructing economic models for solutions, and demonstrating their effectiveness through numerical experiments [3]. Research on parking demand forecasting models based on space sharing showed that peak parking demand could be reduced by 20% when sharing was implemented [4]. Investigations into parking space sharing capacity assessment models revealed that residential areas could provide approximately 55% of their parking resources to adjacent buildings [5]. Studies on optimal allocation of residential shared parking resources used ant colony algorithms to optimize space allocation, achieving an 11.82% increase in shared space utilization duration compared to first-come-first-served methods [6]. Comprehensive analyses of operator benefits and factors influencing user parking behavior proposed a 0-1 programming model maximizing system efficiency, which increased operating revenue by 13.3% and parking utilization by 8.33% compared to first-come-first-served models [7].

While existing research provides substantial theoretical discussion and feasibility analysis of shared parking, including economic models, profitability calculations, sharing capacity models, and allocation algorithms (such as ant colony optimization), few studies address the specific allocation problem between individual spaces and vehicles in practical sharing scenarios. Although Reference [6] touched upon this issue, it employed a random sharing model. In reality, the management challenges posed by randomness create significant implementation difficulties, which explains why shared parking remains uncommon. To reduce this randomness, this paper leverages the complementary travel time patterns between office building and residential commuter groups, transforming one-to-many random sharing into one-to-one fixed sharing. We propose a data-driven, long-term fixed pairing method between adjacent office buildings and residential areas, enabling an office worker to be matched with a residential parking space owner for long-term, fixed use of their residential berth. Since external vehicles regularly use the same residential space, registering two vehicles for one space becomes feasible (using existing technology and methods). This approach not only improves space-time utilization but also reduces management difficulty, alleviates practical obstacles from property management, minimizes overtime parking conflicts, and increases the likelihood of implementing shared parking in residential areas.

1 Prerequisites for Implementing Paired Shared Parking

The essence of paired shared parking lies in establishing one-to-one relationships rather than one-to-many relationships between residential spaces and external vehicles. Based on fundamental conditions for implementing parking sharing [5] and the specific nature of paired sharing, we summarize the prerequisites as follows:

a) **Multi-vehicle registration capability**: The residential parking facility must support registering multiple vehicles for a single space, allowing system registration and access for multiple cars. Only under this condition can matched external vehicles freely enter and exit after license plate registration—this is a necessary condition for implementing paired shared parking (the residential area need not be open). Current smart parking locks and indoor mapping technologies also lay the foundation for paired sharing.

b) **License plate recognition system**: The facility must support license plate recognition for entry and exit, enabling efficient vehicle management and making shared parking feasible.

c) **Complementary travel patterns**: The vehicle travel characteristics between residential and office building facilities should form a macro-level complementarity, which is the foundational condition for paired sharing and enhances the possibility of long-term sharing. Specifically, the morning peak departure from residential areas should align with the morning peak arrival at office buildings, and the evening peak return to residential areas should align with the evening peak departure from office buildings. Only when these complementary entry and exit patterns form at the macro level can large-scale paired sharing be realized.

d) **Appropriate distance**: Adjacent residential communities and commercial office buildings should be within acceptable walking or cycling (including bike-sharing) distance. Shared parking is only feasible when travel time is reasonable; when duration exceeds tolerable limits, shared parking viability decreases significantly.

2 Matching Algorithm

2.1 Application Scenario

Commercial office building A is located within acceptable walking distance of residential area B, which can provide shared parking spaces with stable morning-departure/evening-return characteristics—matching typical commuter patterns. Simultaneously, office building A has long-term parking demand during working hours, requiring use of specific shared spaces from residential area B. The specific usage scenario is illustrated in [Figure 1: see original paper]. Space A in residential area B is available for and exclusively used by vehicle A from office building A, where the sharing period for space A is a continuous time interval during which vehicle A can freely use the space. In the diagram, diagonal shading indicates the space owner' s usage period, blank sections indicate idle periods, and mesh shading indicates external user occupancy periods.

2.2 Matching Algorithm

Our matching algorithm pairs residential spaces with office building vehicles based on characteristics derived from entry/exit records. The process is shown in [Figure 2: see original paper]. First, parking durations are calculated from the acquired data, then relevant usage characteristics are extracted from these duration data, and finally a duration-maximization matching process yields the pairing results. The algorithm is detailed below.

1) Extraction of Space Provider Idle Characteristics

We analyze residential vehicle travel patterns from entry/exit records to determine idle characteristics of parking spaces. Before calculating these characteristics, we must specify a time interval that constrains the shared parking period. Since commuters exhibit clear temporal patterns, only spaces showing distinct idle characteristics within these constraints can be shared. Let the start time be T_{start} and end time be T_{end}, which should satisfy basic conditions aligned with travel patterns between office buildings and residential areas. Define the morning peak travel interval as $[T_1, T_2]$ and the evening peak return interval as $[T_3, T_4]$, then 12[,]startTTT\in\box\box\endTTT\in\box\box.

Based on statistical analysis of residential travel times, we select specific time nodes. Let T_{jc} be the time node with the highest departure proportion from the residential area, and T_{jh} be the time node with the highest return proportion. Then $T_{start} = T_{jc}$ and $T_{end} = T_{jh}$.

For the selected interval $[T_{start}, T_{end}]$, we analyze the idle characteristics of all monthly rental spaces (temporary spaces lack sharing conditions) in the residential area. First, we calculate idle durations for monthly rental vehicles. Let t_{arr} denote vehicle arrival time and t_{lea} denote departure time, with I representing the set of residential monthly rental spaces. For each space $i \in I$, let x_i be the number of idle periods for space i, yielding the idle period matrix N for all monthly rental spaces with bound vehicles:

$$\begin{bmatrix} \{t_{lea}^{arr}, t_{lea}^{arr}, \dots, t_{lea}^{arr}\}_1 \\ \{t_{lea}^{arr}, t_{lea}^{arr}, \dots, t_{lea}^{arr}\}_2 \\ \dots \\ \{t_{lea}^{arr}, t_{lea}^{arr}, \dots, t_{lea}^{arr}\}_{x_i} \end{bmatrix}$$

To calculate idle characteristics within the specified time interval, if $(t_{lea}, t_{arr}) \cap (T_{start}, T_{end}) = (T_{start}, T_{end})$, meaning the idle period fully contains the specified interval, we define this as an effective sharing period where sharing is possible; otherwise, it is non-shareable. Let H represent the set of workdays (holidays lack sharing significance). For $i \in I, j \in H$, the idle characteristic $f_T(\Delta)_{ij}$ for monthly rental space i on workday j is:

$$f_T(\Delta)_{ij} = \begin{cases} 1 & \text{if } T_{start} \le t_{lea} \text{ and } t_{arr} \le T_{end} \\ 0 & \text{otherwise} \end{cases}$$

Here, $f_T(\Delta)_{ij} = 1$ indicates shareability, while 0 indicates non-compliance. This yields the space idle characteristic matrix F. Since commuter parking follows periodic patterns (weekly cycles), we categorize workday j by Monday through Friday into different cycles, with O representing the cycle set. For $i \in I, n \in O$, converting by workday date yields $f_T(\Delta)_{in}$. If $\forall \Delta f_T(\Delta)_{in} \neq 0$, then space i is shareable in cycle n, denoted $P_{in} = 1$, meaning vehicles meeting conditions can park in space i during cycle n. Conversely, if $\exists \Delta f_T(\Delta)_{in} = 0$, space i has idle durations that don' t meet requirements and cannot be shared long-term, denoted $P_{in} = 0$:

$$P_{in} = \begin{cases} 1 & \text{if } \forall \Delta f_T(\Delta)_{in} \neq 0 \\ 0 & \text{if } \exists \Delta f_T(\Delta)_{in} = 0 \end{cases}$$

This produces the cycle-based idle characteristic matrix F':

$$F' = \begin{bmatrix} p_{11} & p_{12} & \cdots & p_{15} \\ p_{21} & p_{22} & \cdots & p_{25} \\ \cdots & \cdots & \cdots & \cdots \\ p_{i1} & p_{i2} & \cdots & p_{i5} \end{bmatrix}$$

2) Extraction of Potential Space User Characteristics

Similar to the method above but with a key difference: we define effective parking duration as being constrained within the specified interval $(T_{start} - \alpha, T_{end} + \alpha)$, where α is a time node float value. For T_{start}, we allow forward floating, and for T_{end}, backward floating, because long-term sharing partners have some negotiation flexibility regarding entry/exit times. We consider parking duration valid only when $(t_{arr}, t_{lea}) \subseteq (T_{start} - \alpha, T_{end} + \alpha)$.

Let L be the set of monthly rental vehicles in the office building. For vehicle $k \in L$ on workday j, the x_i-th parking duration within the interval is:

$$u_{ikj} = \begin{cases} t_{lea} - t_{arr} & \text{if } T_{start} - \alpha \leq t_{arr} \text{ and } t_{lea} \leq T_{end} + \alpha \\ 0 & \text{otherwise} \end{cases}$$

These parking durations are organized into a parking duration matrix for monthly rental vehicles. Converting by workday date yields v_{kn}, the effective parking duration for vehicle k in cycle n. Taking the mean of durations within the same cycle as the average duration, denoted m_{kn}, we construct matrix V':

$$V' = \begin{bmatrix} m_{11} & m_{12} & \cdots & m_{15} \\ m_{21} & m_{22} & \cdots & m_{25} \\ \cdots & \cdots & \cdots & \cdots \\ m_{k1} & m_{k2} & \cdots & m_{k5} \end{bmatrix}$$

3) Space Provider-Potential User Pairing

The most common method for parking space allocation is first-come-first-served, which often fails to maximize space utilization because it lacks duration constraints. When a short-duration vehicle arrives before a long-duration vehicle, it may occupy a space with long idle time, wasting potential usage. Since this approach suits random short-term sharing but not our long-term fixed sharing, we propose a duration-maximization matching method.

We match matrices F' and V' by calculating a matching degree S as the product of each space' s idle characteristic vector and each vehicle' s parking duration vector. Larger products indicate better matching and longer potential shared duration. For $i \in I, k \in L, n \in O$, S_{ik} represents the sharable duration between space i and vehicle k:

$$S_{ik} = \sum_{n=1}^{5} p_{in} * m_{kn}$$

To obtain optimal matching results that maximize S_{ik}, we solve:

$$\max \sum_{i,k,n} p_{in} * m_{kn}$$

To improve algorithm efficiency, we divide the duration-maximization matching into two parts: full-characteristic matching and partial-characteristic matching. Full characteristic means the space' s idle features are all 1 across all cycles; otherwise, it' s partial characteristic. This is illustrated in [Figure 3: see original paper].

a) Full-characteristic matching:
Assume we have a full-characteristic spaces from F'. We match these a spaces with the top a vehicles from V' sorted by total parking duration sum. Full-characteristic spaces are sorted by average departure-arrival time interval, with longer intervals prioritized to increase sharing success probability. For these a spaces, the matching degree S reaches its maximum, as shown in the upper part of [Figure 3: see original paper] (spaces 1-4 matched with vehicles 1-4).

b) Partial-characteristic matching:
After removing successfully matched spaces and vehicles from F' and V', let e represent a space' s shareability degree (count of idle feature 1s). Sort partial-characteristic spaces by e in descending order; if e is equal, use the same sorting method as full-characteristic matching. Remaining vehicles are sorted by parking duration, represented by the lower part of [Figure 3: see original paper].

c) For space $i \in I$, compile the cycles n where idle feature equals 1 into set W. For matrix V', filter rows where $m_{kn} > 0$ for cycles corresponding to set W, identifying vehicles that park during shareable cycles.

d) Among filtered vehicles, calculate S values using the formula. The vehicle k maximizing S_{ik} is the best match for space i, as shown in Figure 3: see original paper where vehicle 4 is the optimal match for space 4.

e) Remove successfully matched spaces and vehicles from the respective matrices and repeat steps (b)-(d) until all elements in either matrix are matched.

This process yields a matched vehicle for each parking space.

3 Case Analysis

To verify the feasibility of the paired parking sharing method, we conducted a case analysis using R 3.3.2.

3.1 Data Acquisition and Processing

Our data source consists of vehicle entry/exit records from parking lot gates. We obtained entry/exit records from seven parking lots in Chengdu, all using license plate recognition for detection. Sample record fields are shown in , where "type" indicates parking type (monthly rental or temporary—only monthly rentals have long-term parking patterns).

The raw data required cleaning of redundant records, errors, and long-term 滞留 data, including duplicate recognition records, unrecognized license plates, and vehicles 滞留 in the garage for extended periods. Additionally, for spaces registered with multiple license plates, entry/exit records needed merging.

3.2 Screening Feasible Parking Lots

Among seven parking lots in the same district, we selected four: office building lots (Shangding International Underground Parking and Waltz Parking, combined as "Commercial Parking") and residential lots (Jinguan New City East and West District Parking, combined as "Residential Parking"). All support multi-vehicle registration per space and use license plate recognition. Field investigation revealed cycling time between office and residential lots never exceeded 10 minutes.

Analyzing vehicle entry/exit characteristics using 150,000 monthly rental vehicle records from January to April 2017, we found residential areas exhibit clear morning-departure/evening-return patterns with idle periods during work hours, while office lots show complementary morning-arrival/evening-departure patterns—ideal conditions for paired sharing. These meet all prerequisites, so we selected these lots for experimentation.

[Figure 4: see original paper] and [Figure 5: see original paper] show weekday travel characteristics. The morning peak for office building entry and residential exit concentrates in 7:00-10:00, while 17:00-19:00 represents the peak for office exit and residential entry. Within this interval, we calculated travel and return proportions in half-hour units as shown in . Residential departure peaks at 8:00-8:30 (26.48% of vehicles), with over 50% departing between 7:00-8:30, so we set $T_{start} = 8:30$. Similarly, we set $T_{end} = 17:30$.

Using the interval [8:30, 17:30], we calculated shareable and potential parking quantities (matchable numbers) as shown in . Shareable spaces accounted for 27.53% of total spaces. With float time $\alpha = 0.25$ hours, we constructed matrices

F' and V' for all monthly rental vehicles. Initial matching yielded 231 successful pairs, with 17 spaces unmatched. Analysis revealed these could match with remaining vehicles but fell outside our set time interval. After adjusting the interval and reapplying the algorithm, we obtained final results shown in (with desensitized license plates). For example, residential space bound to [川 A****2] matched with office vehicle [藏 H****5]. Total successful matches: 248 pairs.

3.3 Data Analysis

To validate effectiveness, we used April 2017 data as test data and January-March 2017 data as experimental data. Monthly rental vehicle counts are shown in : 566 in office lots and 919 in residential lots.

Taking two paired monthly rental vehicles as examples, Figure 6: see original paper shows their parking periods merged by time nodes, where gray indicates non-idle periods and white indicates idle periods. Residential vehicle [川 A****6] and office vehicle [川 A****8] are combined. If time conflicts exist, the office vehicle' s parking period is excluded from the merged period. The "conflict non-mergeable" box in the figure shows such a conflict period.

Well-matched cases like Figure 6: see original paper show residential parking in gray and office parking in diagonal shading. We calculated post-merge duration utilization (total duration utilization = total parking duration / total duration) and loss rate (loss rate = office vehicle utilization + residential space utilization - matched space utilization). Loss rate serves as a perfect-match indicator—smaller values indicate better matching, with 0 representing seamless sharing. Results for [川 A****6] and [川 A****8] appear in : utilization increased from 40.92% to 53.41% (12.49% improvement) with 5.09% loss rate, indicating good matching.

Applying this method to all paired vehicles, we calculated weekly matching effectiveness statistics shown in . Average utilization improvement was 15.24%, with maximum improvement of 57.84% and mean loss rate of 10.01%. Perfect matches (zero loss rate) totaled 87 pairs, with 102 pairs achieving good matching (loss rate 5%).

Perfectly matched residential spaces and office vehicles can park without any time conflicts, fully achieving the paired sharing effect. These spaces account for 37.66% of total pairs, with average utilization improvement of 15.24% and maximum improvement of 57.84%, demonstrating substantial feasibility and providing a new approach for implementing shared parking.

4 Conclusion

Based on the complementary travel time characteristics between commuters in adjacent residential and office areas—where residential commuters vacate spaces during work hours while office commuters need parking—this paper proposes a one-to-one shared parking model and solution based on duration maximization, offering a new perspective for addressing urban parking challenges. By analyzing vehicle travel records, we extract idle characteristics of residential spaces and usage patterns of office spaces, then apply a duration-maximization matching method to pair residential spaces with office vehicles. Validation using test data shows 37.66% perfect matches with 15.24% average utilization improvement, confirming the approach' s significant feasibility.

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Note: Figure translations are in progress. See original paper for figures.