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An Algorithm for Estimating Real Demand for Parking Spaces Based on Limited Data: Approaches, Implementation and Practical Application

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Original article

Abstract

The problem of comparability between parking zones in terms of occupancy, especially when certain zones consistently reach full capacity, remains a critical challenge in urban transport research. Once a zone reaches 100% occupancy, the latent demand – drivers who would have parked but could not due to space constraints – becomes invisible in the data, introducing systematic bias into comparative analysis. This paper proposes a methodology for restoring the true demand for parking in zones that reach full capacity, based on modeling the inflow of vehicles throughout the day using the beta distribution. The methodology reconstructs the flow of incoming cars, divides it into hourly cohorts, and applies "decay curves" to estimate the proportion of each cohort that remains parked over time. By summing these cohort-based curves, the model provides a dynamic estimate of the actual number of vehicles that would have occupied the zone under conditions of unlimited capacity. The approach is tested on 17,000 real parking sessions, demonstrating both high accuracy in demand estimation and applicability for practical parking management. Beyond parking systems, the methodology can be applied to other domains where client flows exhibit beta-distribution patterns and where data is censored due to limited capacity – including banking (branch workload forecasting), logistics (service queue management), and digital services (user activity modeling). The results show that the proposed model not only improves the validity of demand estimation in congested urban environments but also offers a transferable analytical tool for managing client flows in constrained-capacity systems.

Keywords: parking demand, beta distribution, latent demand, occupancy modeling, urban transport planning, capacity constraints

Conflict of interests: The author declares no conflict of interests.

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Цифровая трансформация транспорта

Алгоритм оценки реального спроса на парковочные места на основе ограниченных данных: подходы, реализация и практическое применение

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Оригинальная статья

Аннотация

Проблема сопоставимости парковочных зон с точки зрения их заполняемости, особенно в условиях, когда некоторые зоны достигают 100% заполняемости, является сложной задачей. Основная сложность заключается в том, что при 100% заполняемости невозможно точно определить, сколько ещё автомобилистов хотели бы припарковаться в данной зоне, но не смогли этого сделать из-за отсутствия свободных мест. Это создаёт искажение в данных и затрудняет корректное сравнение парковочных зон между собой. В статье предлагается методика восстановления такого «скрытого» спроса на основе анализа зарегистрированных сессий и статистической корректировки потока прибывающих машин с помощью бета-распределения. Поток разбивается на часовые поколения (когорты), и для каждой когорты строятся кривые «выгашивания» (тенденции удержания клиентов): какая доля автомобилей из поколения остаётся через 1, 2, 3… час(ов). Суммируя вклад всех когорт в каждый момент времени, получаются оценку числа машин на парковке. Метод проверен на реальных данных порядка 17 000 парковочных сессий: результаты демонстрируют высокую точность оценки полного спроса и хорошее соответствие между прогнозом и измерениями в непиковые и пиковые часы. Предложенный алгоритм особенно полезен в условиях ограниченности информации и может быть применён не только к парковочным зонам, но и к любым клиентским сервисам, где имеется зарегистрированный поток сессий и наблюдаются признаки цензуры. Метод обладает преимуществами интерпретируемости, невысокой вычислительной сложности и переносимости в разные города и виды услуг.

Ключевые слова: спрос на парковку, бета-распределение, скрытый спрос, моделирование загруженности, планирование городского транспорта, ограничения пропускной способности

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Introduction

From the perspective of the attractiveness of paid parking and the comparability of parking zones, occupancy data is not always suitable due to the 100% limit. Furthermore, if the analysis is based on the Service dataset, occupancy rates may be distorted by drivers not registered in the system. In any case, the limited number of spaces in a parking zone makes it impossible to estimate the number of drivers seeking parking, i.e., to determine the actual demand at the current rate. For example, if a zone has 50 spaces and all are occupied, it is impossible to estimate how many more drivers would have liked to park but were unable to. This leads to an underestimation of demand in the most popular zones and makes it impossible to accurately compare zones with lower occupancy rates. Using indirect data to estimate demand, such as analyzing the time drivers spend searching for parking or data on the number of cars passing by the parking zone, requires the implementation of monitoring systems [1-3].

It's worth noting that the owner or manager of a paid parking service only operates on registered session data and does not have access to vehicle flow data (if it even exists). Using indirect data to estimate demand, such as analyzing the time drivers spend searching for parking or the number of cars passing by a parking zone, requires the implementation of monitoring systems that record driver attempts to park, even if they are unsuccessful.

Zones with 100% occupancy may appear equally "congested", but the actual parking demand in them can vary significantly. For example, one zone may be full due to high traffic, while another may be full due to a lack of parking spaces. Without considering "unmet demand" (the number of drivers who were unable to park), it is impossible to objectively assess the load on a parking zone.

Understanding actual demand is essential for infrastructure planning and parking zone management. However, at 100% occupancy, demand data becomes unavailable, making forecasting and decision-making difficult. In other words, street attractiveness analysis poorly explains the situation in which two zones with hourly rates of 50 rubles and 100 rubles in similar areas have identical occupancy rates of 100%.

Traditional occupancy analysis methods (such as counting occupied spaces) do not account for unmet demand. This makes them unsuitable for comparing zones with different occupancy rates.

Literature Review

The problem of reconstructing the full demand for a parking zone under conditions of 100% occupancy spans several interrelated research areas: arrival rate modeling, analysis of parking durations and session survival, censoring observations, and reconstructing latent demand, as well as empirical studies of parking load distribution and pricing effects. The proposed method for reconstructing real demand fits into several areas of literature.

Arrival Rate Modeling. Studies [4-6] show that the daily dynamics of the flow of cars entering a parking zone are asymmetrical, with a pronounced peak in activity and a gradual decline in intensity.

The work of Arnott and Rowse (1999) demonstrated that equilibrium models of parking demand must consider not only pricing but also search time costs [7]. Gillen (1978) used a logit model of parking zone selection, which allowed him to formalize the probability of decision making under congested street conditions [8]. These studies confirm the need to approximate time flows, which in modern literature are often described by distributions close to the beta function.

To describe such profiles in transportation research, parametric distributions are used, among which the beta distribution is a convenient tool: it has flexible form and allows for adequate approximation of both morning and evening demand peaks. Using a beta curve provides a compact mathematical representation of the arrival flow and allows for its division into "generations" (cohorts) of customers by hour of day, a key step in the proposed algorithm.

Cohort and survival analysis. For each hourly group (cohort) of vehicles, the problem of estimating the parking duration arises. Survival analysis methods applied in a wide variety of fields-from medicine to marketing and banking – are useful here. In transportation research, survival models describe how the proportion of customers remaining in a system (e.g., a parking lot) changes over time. A cohort's "extinction" curve shows what proportion of cars entering at a given hour continue to occupy spaces an hour, two hours, and beyond. The combined superposition of these curves allows us to obtain the dynamics of parking lot occupancy at each point in time. This cohort approach improves the interpretability of the model and allows for the inclusion of additional factors. The literature on survival models and their application in transportation/service systems shows that retention models provide interpretability and the ability to incorporate covariates (fare type, distance from the center, weather conditions) into survival parameters [9].

Goh and Lee (2019) demonstrated that a combination of hybrid algorithms and statistical methods allows for the description of customer flow dynamics [10]. Ren et al. (2021) applied real demand models to dockless systems, demonstrating how cohort analysis helps to adjust observed data under limited information conditions [11].

Censorship and Latent Demand Recovery. A key issue is that, when the parking lot is fully occupied, the observed number of parked cars does not reflect the actual demand: some drivers leave the area without finding space. In statistics, this is described as "censored data" [12]. Modern methods for recovering latent demand, including censored Gaussian Processes, variational Tobit models, and neural network regression models, offer a solution to this problem; however, they often require significant computational resources and large amounts of data [13-15]. Gragera et al. (2021) proposed a model for estimating demand for on-street parking considering censored observations [16]. Van Ommeren et al. (2021) proposed a method for estimating parking cruising and elasticity of demand, which is directly related to the problem of recovering latent demand [17]. The proposed methodology is based on a simpler and more easily explained approach: the arrival flow is reconstructed using a beta distribution, and then, using cohort survival curves, the actual number of cars that would be in the zone if its capacity were not limited is estimated. This achieves the effect of restoring "lost" demand without resorting to overly complex tools.

Empirical Research. Recent international and Russian studies have focused on the practical aspects of occupancy forecasting, fare management, and the implementation of dynamic management algorithms [18]. Sensor infrastructure and IoT systems are often used to measure occupancy; however, such data is not always available [19]. Therefore, the proposed method, based on statistical reconstruction from transaction sessions, may be particularly useful in conditions of limited observability.

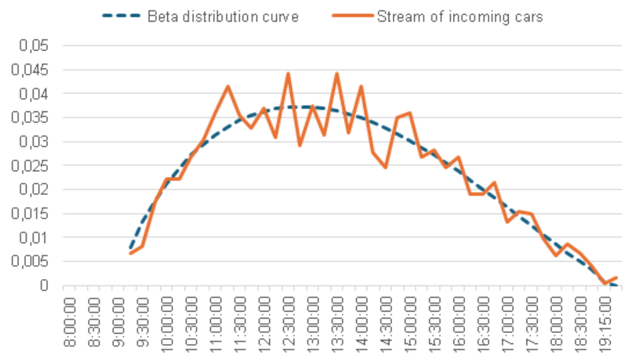
Spatial and Behavioral Factors. When analyzing demand, not only temporal characteristics but also spatial parameters play an important role – zone accessibility, the availability of alternative free parking, and proximity to attractions. In studies of transport geography and accessibility, such variables are described as covariates – additional explanatory factors included in the model to refine forecasts [20]. Covariates can be quantitative (e.g., zone capacity, fare, distance to the center) or categorical (zone type, presence of a transfer hub), and their inclusion allows for the construction of more accurate occupancy models. In the proposed approach, covariates are not considered at the stage of calculating full demand.

In the Russian literature, attention is focused on institutional and organizational aspects. For example, Naumenko (2012) demonstrated that parking infrastructure analysis should consider both actual occupancy and transport connectivity to the surrounding network, which allows for an accurate assessment of the effectiveness of parking space management [21-25].

Thus, the proposed methodology combines three ideas: parametric approximation of arrival flows using a beta distribution, cohort survival analysis of parking durations, and data correction for censored conditions at full occupancy. Unlike complex machine learning models, this approach remains interpretable, requires a moderate amount of data, and yet allows for adequate recovery of latent demand. This makes it applicable not only to transport planning but also to other service areas with similar customer flow structures, particularly in the context of data limitations and explainability requirements for municipal/budget applications.

Materials and Methods

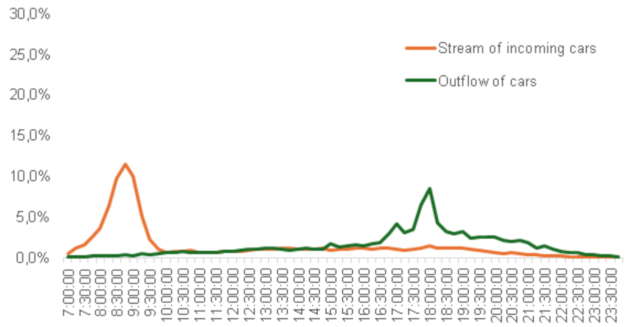
Many customer service systems allow you to record the start date and time of each session (in this case, parking). The customer flow calculated on this basis allows us to identify certain dependencies and distortions. Previous studies have shown that occupancy and the flow of incoming cars (like all similar processes: customer flow at bank branches, early repayments of consumer loans, etc.) have a beta distribution (a skewed bell curve) (see Figure 1) [6]. The flow of incoming cars is well described by the beta curve equation (R2 = 86.4%). Other authors have also pointed to a similar distribution [4].



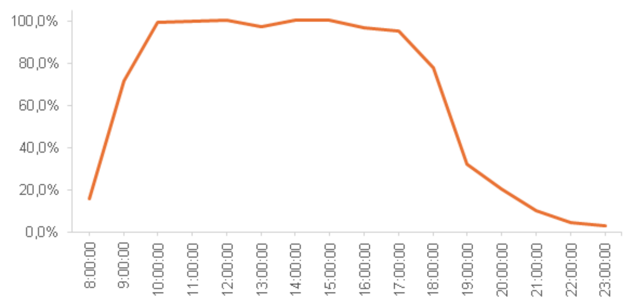
F i g. 1. Distribution of incoming users by time (quarters of an hour) during the day – Zone 40 (weekdays, 4Q 2024)

Source: Hereinafter in this article all tables and figures were made by the author.

At the same time, zones with 100% occupancy exhibit an anomaly (see Fig. 2). While occupancy peaks at 100% (see Fig. 3), the flow of incoming vehicles drops sharply to almost zero and remains at a level equal to the outflow of vehicles, as only those users for whom there is a space enter (register and pay for sessions).



F i g. 2. Distribution of incoming users by time (quarters of an hour) during the day - zone 330 (working days 4Q 2024)



F i g. 3. Daytime occupancy – zone 330 (working days, 4Q 2024)

In other words, in the example considered, the demand for parking is likely significant. To remove the 100% limit and adjust the occupancy rate, it is necessary to estimate how many cars would be parked at 1:00 PM. For this purpose, the following algorithm is proposed:

1. Obtain a beta curve describing the distribution of the flow of arriving cars without the limit.
2. Divide arriving users into "generations" (generation 7:00-8:00, generation 8:00-9:00, etc.).
3. For each "generation", determine the "burnout" curve, showing what proportion of the initial number of cars remains in the parking lot after 1 hour, 2 hours, 3 hours, etc.
4. Obtain the dynamics of the number of cars in each generation over time in units. Divide the obtained values by the number of parking spaces (the occupancy formula).

Results

1. Calculating the Beta Curve Equation

As previously mentioned, the flow of cars entering the parking lot follows a beta distribution (if there are enough spaces and nothing obstructs it). A "break" is observed in zone 330, but the left and right sides "follow" the shape of the beta curve. For these reasons, by minimizing the sum of squared deviations between the observed and predicted valuesusing an Excel analysis package (solving nonlinear problems using the OPG method):

$$\sum_{i=1}^{n}(y_i - \hat{y}_i)^2 \to min$$

The explanatory function is the beta distribution weight function with parameters α, β and c (the coefficient that corrects the weight value, since the resulting function describes the distribution of the potential influx of cars that is greater than the registered one), and the adjusted time values are taken as x so that x falls within the interval [0,1]:

$$\hat{y}_i = f(x;\alpha,\beta,c) = \frac{x_i^{\alpha-1}\cdot(1-x_i)^{\beta-1}}{B(\alpha,\beta)}\cdot c$$
$$= BETA.DIST(x_i;\alpha;\beta;\text{the probability density function (False)}; 6{:}45; 23{:}45)\cdot c$$

As a result, we obtained values for the share of daily demand for each quarter of an hour (see Figure 4). In total, 17,816 cars used the parking lot in Q4 2024, while the potential demand (based on the resulting equation) was 185,218.

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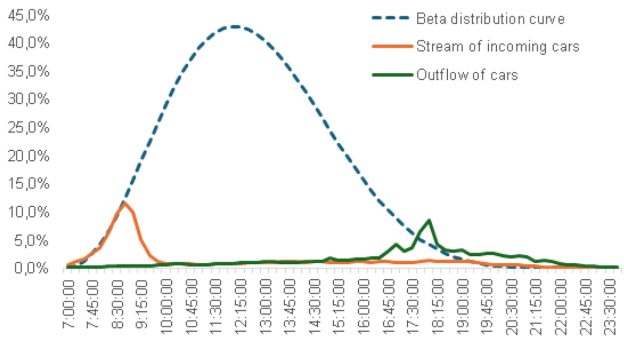
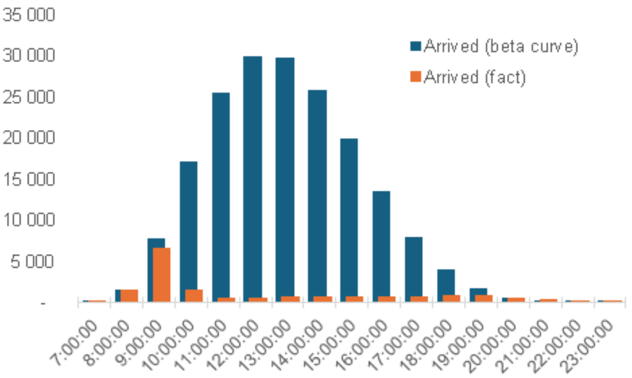


F i g. 4. Distribution of inbound users by time of day - Zone 330 (working days, 4Q 2024)

2. Forecasting daily parking demand in units

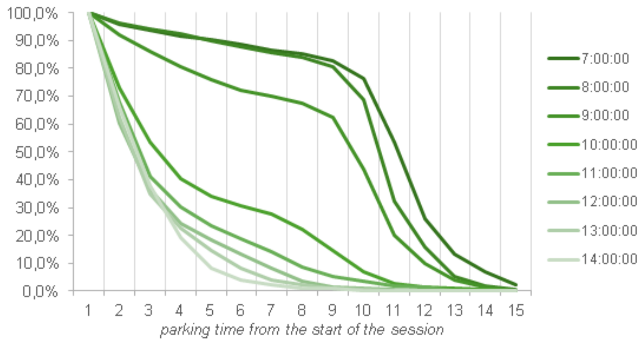
Next, it's necessary to divide arriving users into "generations" (7:00-8:00 generation, 8:00-9:00 generation, etc.) using the resulting equation. To do this, take the sum of the weights for each hour and multiply it by the total actual number of cars arriving (see Figure 5).



F i g. 5. Distribution of inbound users by hour during the day - Zone 330 (weekdays, 4Q 2024)

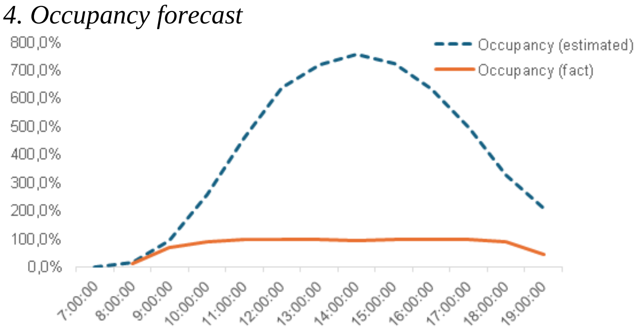
3. User generation survival curves

Next, for each "generation", using actual data for Q4 2024, we determined "amortization curves" (a term used in banking to reflect the dynamics of principal debt over the life of the loan). These curves show the proportion of the initial number of cars remaining in the parking lot for 1 hour, 2 hours, 3 hours, etc. Based on actual data for Q4 2024, a clear difference is observed between the behavior of the three generations of morning users and that of daytime users: morning users park practically all day and then begin to abruptly leave the parking lot towards the end of the workday (see Figure 6).



F i g. 6. User cohort survival curves

4. Occupancy forecast



F i g. 7. Dynamics of occupancy during the day in zone 330 (estimated and actual)

Т a b l e 1. **Calculation of the dynamics of the number of cars by cohorts**

Arrived (beta curve)	**Cogorts**	**Occupancy rate, cars**										
		7:00	**8:00**	**9:00**	**10:00**	**11:00**	**12:00**	**13:00**	**14:00**	**15:00**	**16:00**	**17:00**
11	7:00:00	11	10	10	10	10	10	9	9	9	8	6
1 499	8:00:00		1 499	1 445	1 409	1 383	1 347	1 314	1 286	1 257	1 208	1 031
7 817	9:00:00			7 817	7 189	6 735	6 315	5 929	5 654	5 486	5 261	4 878
17 143	10:00:00				17 143	12 496	9 164	6 889	5 832	5 223	4 742	3 781
25 444	11:00:00					25 444	17 260	10 440	7 659	5 981	4 774	3 567
29 909	12:00:00						29 909	17 984	10 924	7 298	5 438	4 007
29 759	13:00:00							29 759	18 580	10 400	6 778	4 324
25 844	14:00:00								25 844	17 125	9 825	4 982
19 834	15:00:00									19 834	12 143	6 322
13 461	16:00:00										13 461	8 520
8 002	17:00:00											8 002
4 079	18:00:00											
1 717	19:00:00											
559	20:00:00											
125	21:00:00											
15	22:00:00											
1	23:00:00											
0	0:00:00											
Total		**11**	**1 509**	**9 272**	**25 750**	**46 068**	**64 005**	**72 324**	**75 787**	**72 613**	**63 637**	**49 419**
Occupancy (estimated)		**0,1%**	**15,0%**	**92,3%**	**256,3%**	**458,5%**	**637,0%**	**719,8%**	**754,3%**	**722,7%**	**633,3%**	**491,8 %**

Discussion and Conclusion

This article proposes a method for reconstructing the full demand for parking zones with occupancy rates reaching 100%. The main difficulty with this analysis is that under full occupancy conditions, it is impossible to directly observe the amount of unmet demand, which leads to data distortion and complicated comparisons between zones. The developed approach is based on approximating the flow of incoming cars using a beta distribution, which allows for the adequate accounting of the nonlinear dynamics of customer flow throughout the day.

Further division of the flow into cohort groups and the construction of their "extinction" curves allowed us to estimate the actual number of cars remaining in the zone at any given time. This, in turn, enables the accurate reconstruction of actual occupancy and comparison of zones, including those experiencing congestion.

Calculations performed on a real-world data set (over 17,000 parking sessions) confirmed that the proposed method not only reveals the amount of latent demand but also generates a more accurate estimate of customer flow. This improves the quality of paid parking revenue forecasts and forms the basis for decision-making on rate adjustments and the planning of new parking zones.

The proposed methodology is universal and can be applied not only to transport planning but also to other areas where system capacity is limited and customer flows with a beta distribution exist. Such areas include banking, logistics, and digital services.

However, the methodology has a limitation: reconstructing the flow using a beta distribution does not consider user behavioral characteristics, in particular the tendency to arrive early to secure a parking space. This leads to a possible overestimation of the flow rate at the beginning of the day. Future studies may consider this circumstance by introducing additional behavioral adjustments or using combined distributions, allowing for a more flexible description of the customer flow pattern.

Thus, the obtained results are of interest both to researchers in the field of transport analytics and to practitioners working with customer flow management systems, and the identified limitations form the basis for further development of the model.

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