Transport Policy 71 (2018) 36–44

Contents lists available at ScienceDirect

Transport Policy

journal homepage: www.elsevier.com/locate/tranpol

Dynamic pricing for reservation-based parking system: A revenue management method

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ARTICLE INFO

Keywords:
Parking reservation
Revenue management
Dynamic pricing

ABSTRACT

With the improvement of urban smart level, parking reservation has become not only one of the most effective ways to solve parking problems but also an efficient tool to reduce traffic congestion in eliminating the cruising. This paper proposes a new dynamic pricing model for parking reservation, aiming to maximize the expected revenue of the parking manager. The parking requests arrive as a Poisson process, and the arrival intensity is influenced by the time-varying parking price. The optimal pricing scheme is proved to be unique for any general demand and derived in closed form for some particular types of demand functions, like exponential and linear. Numerical examples show that the dynamic pricing scheme can provide significant improvement in revenue and make full use of the parking resources during peak periods.

1. Introduction

Parking problem is growing as a major challenge in metropolitan areas, where parking resource are limited. Drivers usually have to cruise for a long time to find an available parking space (Shoup, 2006). On average, a driver in a U.S. city has to spend about 8 min each time in cruising for an available parking space (Shoup, 1997). A survey carried out in 2011 showed that 60% drivers had the experience that they were so frustrated searching for parking that eventually gave up (IBM, 2011). Quite a few theoretical studies have noticed the competition among drivers on parking resources and proposed game theoretical approaches to model the assignment of parking spaces (Zhang et al., 2008; Qian et al., 2011; Boyles et al., 2015; Geroliminis, 2015). Additionally, Leclercq et al. (2017) categorised vehicles with respect to their parking strategies and investigate the relation between mean travel distance to park and the parking occupancy.

Given the limited parking spaces, parking pricing can be a flexible and desirable tool to guide drivers' parking choices and improve the system efficiency. He et al. (2015) presented a static atomic parking game to illustrate parking competition issues and proposed an optimal pricing scheme to minimize the total travel cost in the whole system. Zou et al. (2015) proposed pricing mechanism design for parking lot assignment in the information era. Dynamic (Mackowski et al., 2015; Qian and Rajagopal, 2014a; Zheng and Geroliminis, 2016) and stochastic (Qian and Rajagopal, 2014b) issues on parking pricing have also been attempted in recent literature. Following Vickrey (1954), the primary theme of the literature on parking economics has shown that parking should be priced at its social opportunity cost, just like any other public commodity. The underpricing of downtown parking, especially curbside parking, generates inefficient cruising. Along this theme, there is a branch of literature looking into the parking pricing with interaction between cruising-for-parking and traffic congestion (e.g., Azari et al., 2013; Arnott and Rowse, 1999, 2009; Arnott and Inci, 2006; Arnott et al., 2015; Arnott and Rowse, 2009; Qian and Rajagopal, 2015; Zhang and Zhu, 2016). These studies on cruising-for-parking have provided insightful ideas for the complex interaction among cruising, traffic congestion and network performance.

With the development of smart-phone based parking applications, drivers can easily access the information of parking availability and the parking price. The parking reservation can be widely deployed to ease congestion in the near future. Drivers do not need to cruise for parking space any more, as it has been guaranteed via the reservation platform. Besides, the benefit for parking manager should also be considered, since the reservation policy will be implemented by the private owner in practice. This paper adopts a new revenue management method and presents a dynamic pricing scheme for the parking reservation system. Although revenue management has been extensively studied in hotel and airline ticket booking system (Gallego and Van Ryzin, 1994), it is relatively new in parking reservation. Actually parking reservation system is much more complicated, as a single driver usually books

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https://doi.org/10.1016/j.tranpol.2018.07.007
Received 3 October 2017; Received in revised form 13 June 2018; Accepted 20 July 2018

multiple periods for parking.

In this paper, we take into account the price sensitivity and stochasticity of the parking demands. The parking requests arrive following a Poisson process and the arrival intensity is influenced by the parking price. We establish a general parking reservation model, in which the parking price varies with the arrival demand and the number of vacant parking spaces. The proposed dynamic pricing scheme can well use the parking resources when maximizing the expected revenue of the parking manager. Numerical experiments are presented to show the effectiveness of our parking scheme in maximizing parking managers' revenue and saving drivers' cruising cost.

The rest of this paper is organized as follows. Section 2 presents the assumptions and formulation of the proposed dynamic pricing system. Section 3 addresses the optimality condition and solution of the price scheme. Section 4 illustrates the performance and potential impacts of the proposed dynamic pricing model using numerical examples. Section 5 concludes the paper.

2. Modeling assumptions and formulation

We consider a parking lot consisting of C (a nonnegative integer) parking spaces. Each parking space has a service horizon of N periods. All the periods in the same service horizon are open for booking at the same instant. Assume that the parking manager has a time period of T to sell the parking spaces. Fig. 1 illustrates the relationship between a reservation horizon and a service horizon. Drivers can send their booking requests any time during the reservation horizon through the Internet. Every driver is aware of the availability of parking spaces and the parking price when making the booking decision. Multiple-period reservations are allowed in this study. We assume that drivers can reserve at most n service periods, $1\leq n \leq N$. Group reservation is not considered. Every individual driver has a specific parking duration, and books only one parking space each time. The booking requests will be confirmed immediately if the parking lot is not fully booked during the requested service periods. Cancellation is not allowed once the booking is confirmed.

Let p_i^t denote the parking price for horizon i if booked t time in advance, then the average price from period u to period v, can be calculated as $\overline{p}_{[u,v]}^t = \sum_{i=u}^{v} p_i^t/(v-u+1)$. Denote the drivers who request the parking periods from u to v as the u-v class drivers. It is reasonable to claim that the number of booking requests (demand) fluctuates with the price. We express the demand as a rate that depends only on the current price through a demand function. The parking manager can estimate the demand function from the historical data and manage the parking requests by adjusting the parking price. It is assumed that the demand only depends on the current average price of his/her target periods, i.e., demand $d_{[u,v]}^t$ only depends on $\overline{p}_{[u,v]}^t$, and is independent of the price of other parking periods. In other words, the cross-price effect is ignored in this study. Although drivers may weigh alternative durations or even change their travel schedule according to different parking prices of different periods in reality, this paper stands on the viewpoint of the parking manager and will not emphasize how drivers make their scheduling decisions on their travel plans or parking durations in our model, since such particulars are not observable to the parking manager. Similar assumptions can be found in studies on parking facilities (Lam et al., 2006) and location (Chaniotakis and Pel, 2015) choices. Let $d_{[u,v]}^t = d_{[u,v]}^t\left(\overline{p}_{[u,v]}^t\right)$ denote the demand function for period $u-v$ on time t. To some extent, the price-demand interaction in our study reflects the impact of parking price on travellers' mode choice. The lower price would attract more people to drive (or park), while the higher price would force more people to use public transport. It is assumed that the realized parking requests arrive as a Poisson process, which is usually used in the literature (e.g., Clark and Watling, 2005; Kamath et al., 1998) to model the traffic arrivals.

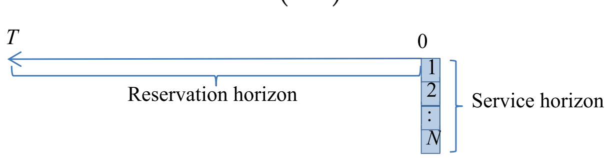

Fig. 1. The booking horizon and the service horizon.

The above current-price assumption is somewhat restrictive. But it is reasonable when parking spaces are scarce resources, that booking policy is proposed to avoid the congestion caused by the competition for parking spaces among drivers. Drivers would care more about the availability of the parking spaces rather than how to act strategically in response to the parking manager's pricing strategy. Similar assumption can be found in Gallego and Van Ryzin (1994).

The market is with imperfect competition. For example, the parking lot has market power, namely either several parking lots within the area are run by the same manager and share the same pricing platform, or the parking lots are differential from each other to customers. Due to the capacity of parking spaces, not all the demand can be satisfied. The booking request for u-v class drivers can only be confirmed when there is at least one parking space available for each period during $[u, v]$. Let $\mathbf{x}^t = (x_1^t, x_2^t, \ldots, x_N^t)^T$ be the state of parking spaces at reserving time t, where x_i^t is the number of vacant parking spaces of service period i. The state space for $\mathbf{x}^t$ is denoted as $\chi = \{\mathbf{x}^t | 0 \leq x_i^t \leq C, i = 1, \ldots, N\}$. The price $\mathbf{p}^t = (p_1^t, p_2^t, \ldots, p_N^t)^T$ is determined by the parking state $\mathbf{x}^t$ and the time t. Let $A_{[u,v]}^t(\mathbf{x}^t)$ be the indicator, which is 1 if there is at least one vacant parking space in all periods during $[u, v]$, and 0 otherwise. The realized reservation is stochastic and can be modeled as a Poisson process with an intensity of

$$\lambda_{[u,v]}^t(\mathbf{x}^t, \mathbf{p}^t) = A_{[u,v]}^t(\mathbf{x}^t) \cdot d_{[u,v]}\left(\sum_{i=u}^{v} p_i^t/v - u + 1\right).$$

The total parking reservation rate at time t is $\Lambda^t(\mathbf{x}^t, \mathbf{p}^t) = \sum_{u=1}^{N} \sum_{v=u}^{\min\{N,u+n\}} \lambda_{[u,v]}^t(\mathbf{x}^t, \mathbf{p}^t)$.

As a normal good, the demand for parking is downward sloping and thus there is a one-to-one mapping between the price and the demand (reservation) rates. Let $\overline{p}_{[u,v]}^t(d_{[u,v]}^t)$ denote the inverse function of demand. On such an invertible base, we can consider this problem from an alternative way that the parking manager can determine the target sales (demand) intensity and the market will determine the price accordingly. We assume that the revenue rate is continuous and bounded.

Apparently the above parking reservation benefit the drivers, as it saves the drivers cruising time. Drivers with reservation are guaranteed to have parking spaces and the booking platform will guide the driver to the exact position of the parking space directly. Drivers who fail the reservation will give up cruising for parking and switch to other inconvenient parking lot since they are told the parking spaces have been fully booked.

This study aims to design a dynamic pricing scheme that can benefit both drivers and the parking manager. For the drivers, the scheme wants to sell out all the parking spaces over the full service horizon, then the parking resources are well utilized. For the parking manager, the scheme can provide him as much revenue as possible. Since booking requests arise randomly, the parking manager has to determine the booking prices for each period in the service horizon such that the expected revenue gained during the whole reservation horizon is maximized in long run.

Let δ be a sufficiently small time interval such that there is at most one request arriving. We define P_0^t as the probability of having 0 reservation in such an interval, and P_1^t as the probability of having 1 reservation. Thus, we could have $P_1^t = \Lambda^t(\mathbf{x}^t, \mathbf{p}^t)\delta = 1 - P_0^t$. The maximum expected revenue generated over $[0, t]$ can be formulated as the following stochastic dynamic program: