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Dynamic pricing and reservation for intelligent urban parking management

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ABSTRACT

Despite rapid advances of information technologies for intelligent parking systems, it remains a challenge to optimally manage limited parking resources in busy urban neighborhoods. In this paper, we use dynamic location-dependent parking pricing and reservation to improve system-wide performance of an intelligent parking system. With this system, the parking agency is able to decide the spatial and temporal distribution of parking prices to achieve a variety of objectives, while drivers with different origins and destinations compete for limited parking spaces via online reservation. We develop a multi-period non-cooperative bi-level model to capture the complex interactions among the parking agency and multiple drivers, as well as a non-myopic approximate dynamic programming (ADP) approach to solve the model. It is shown with numerical examples that the ADP-based pricing policy consistently outperforms alternative policies in achieving greater performance of the parking system, and shows reliability in handling the spatial and temporal variations in parking demand.

1. Introduction

In recent years, rapid advances of information technologies bring in fast development of intelligent parking systems (IPS) all over the world. Inside IPS, dynamic parking pricing is an important component that makes the system "intelligent" in terms of utilizing limited parking resources. For example, in 2008, San Francisco Municipal Transportation Agency (SFMTA) launched an *SFpark* project, through which it successfully implemented a demand-responsive parking pricing scheme for on-street metered spaces and SFMTA managed garages in several selected areas in San Francisco (San Francisco Municipal Transportation Agency, 2014). The fundamental idea of the program is, by properly manipulating parking rates, to maintain an ideal level of occupancy in every city block, such that any newly arriving driver can always find a suitable open space without circling around for parking. Similar practices of smart parking include the so-called *LA ExpressPark*™ program in Downtown Los Angeles, and *SeaPark* in Seattle. These existing programs nevertheless share a common feature: the parking prices are updated once per several weeks or even several months, which is not sensitive enough to deal with the highly dynamic parking demand in realistic daily operations. The lack of quick response would inevitably limit the effectiveness of dynamic pricing strategies.

The rapid advances of information and communication technologies have presented tremendous opportunities for smart parking; e.g., on-site detectors can track occupancy status at a parking space (Panja et al., 2011; Park et al., 2008) and instantaneously communicate that information to drivers via smartphone. The drivers can also make parking searches

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and reservations online in real time. The emergence of numerous parking applications on smartphone, e.g., SpotHero, ParkWhiz, ParkMe, Parking Panda, has made it possible for drivers to check the availability of parking spaces and make reservations in advance of their trips (Chen et al., 2015). Besides the fact that drivers' experiences can be greatly improved by introducing reservation service, the size of the parking market would also be potentially expanded. For instance, some first-time travelers who are unfamiliar with parking neighborhoods can now conveniently find suitable parking space through the reservation system. In addition, parking reservation service may as well have a positive effect in reducing urban congestion. Yang et al. (2013) pointed out that allowing reservation service for a portion of parking spaces is helpful to reduce congestion because it helps spread the departures of those morning commuters.

As such, the prospect of implementing dynamic parking pricing and reservation strategies has become technically feasible and socioeconomically appealing. Our study, therefore, is devoted to developing sophisticated mathematical models to maximize the performance of dynamic parking pricing strategies so as to make the best use of limited parking resources in urban areas. We attempt to implement the system through an online reservation system which allows drivers to make reservations to secure a parking spot for a certain period of time. One of the challenges associated with the parking system is that stakeholders, usually including the agency and individual drivers, exhibit certain gaming behaviors in their decision-making processes. For example, the agency uses differential pricing strategy to influence drivers parking location choice, increase parking revenue, or balance spatial distribution of parking reservations. Meanwhile, individual drivers compete for limited parking spaces at popular locations based on the parking price and their travel convenience. Hence, it is essential to come up with an overarching modeling framework to jointly consider the objectives of different stakeholders in conducting parking system management.

This paper develops a mathematical programming model for the demand-driven dynamic parking pricing and reservation problem, where drivers are allowed to make parking reservations prior to the trips and secure parking spaces for a length of future time. The problem is formulated in the form of a multi-period mathematical program with equilibrium constraints (MPEC), which is extremely difficult to solve. We further develop an effective non-myopic algorithm based on approximate dynamic programming (ADP) to solve the model, such that future parking supply and demand information is incorporated into a dynamic pricing decision-making process. An embedded subroutine is also proposed to transform the bi-level MPEC model (for each period) into a solvable single-level mixed-integer quadratic program (MIQP). The performance of the proposed model and algorithm is tested through a series of numerical experiments, and managerial insights are drawn. It is shown that, through ADP-based pricing policy, the parking system can achieve much more superior performance as compared with those under alternative policies.

The remainder of the paper is organized as follows. Section 2 first presents a literature review over parking pricing, parking management, as well as a few state-of-the-art modeling and solution methodologies. Section 3 explains the notation and formulation of the proposed parking pricing problem. Section 4 describes the solution algorithm based on ADP and MIQP transformation. Section 5 illustrates the numerical experiments. Finally, Section 6 concludes the paper and discusses possible directions of future research.

2. Literature review

The parking management problem has attracted considerable attention in the past decade. Shoup (2005) illustrated the significant role of parking pricing in changing the landscape of modern traffic system. Some of the ideas in this monograph have inspired the *SFpark* project mentioned above.

Most of the existing research on parking pricing is devoted to investigating ways to use parking pricing strategies to influence drivers' competitions for parking resources. The hope is to eventually enhance the performance of the transportation system, especially for urban morning commute (Arnott et al., 1991; Lam et al., 1999; Zhang et al., 2008; Qian et al., 2011, 2012). Qian and Rajagopal (2014a) proposed a dynamic parking pricing model to achieve optimal flow pattern in a network. The day-to-day recurrent behavior of morning commuters is formulated under driver equilibrium conditions, while the drivers are assumed to always know parking price and occupancy information. The authors also studied a similar parking pricing problem under stochastic demand (Qian and Rajagopal, 2014b), and further extended the scope to investigate both departure time choices and parking location choices (Qian and Rajagopal, 2015). Some reservation strategies have also been proposed to mitigate parking-related delay and traffic congestion. For example, Zhang et al. (2011) and later Liu et al. (2014b) introduced a tradable parking permit scheme for the morning commuters parking management problem. Yang et al. (2013) studied a morning commute problem under the circumstance that some commuters have reserved parking spots. Later, Liu et al. (2014a) considered a parking reservation scheme with expiration, where a commuter is required to arrive at its parking space before a predetermined expiration time. Chen et al. (2015) proposed a parking reservation system to manage the allocation of downtown curbside parking spaces; a simple reservation scheme was proposed to minimize the total social cost associated with parking. Chen et al. (2016) later showed that reservation service can improve the performance of a stylized parking system where a destination of parking demand is located on a long one-way street and on-street parking spaces are scattered around the destination. However, in these studies, parking pricing as a strategy to balance spatial demand is not integrated into the reservation mechanism.

Only a small amount of literature is devoted to considering pricing as a management strategy to improve the performance of the parking system. For example, Guo et al. (2012) proposed a game theoretic based parking choice model and pointed out