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Optimal occupancy-driven parking pricing under demand uncertainties and traveler heterogeneity: A stochastic control approach

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ABSTRACT

A novel parking pricing strategy dependent on real-time sensing is proposed to manage the parking demand. Parking pricing and information provision jointly serve as a *dynamic stabilized controller* to minimize the total travel time (TTT) of the system. Parking prices are adjusted in real time according to the real-time occupancy collected by parking sensors. All the parking information along with parking prices, is then provided for travelers to make real-time parking choices. We model the optimal parking pricing in the preferred (closer) parking cluster as a *stochastic control* problem. We take into account two types of randomness, demand uncertainties and user heterogeneity in Value of Time (VOT), both of which can be learned by taking real-time measurements. The optimal parking pricing policies are solved using the dynamic programming approach. There exists a critical occupancy for each time period, and the parking prices should be set effective (by diverting travelers to the farther parking lot) when the up-to-date occupancy is above the critical occupancy. From the numerical experiments, we find that the optimal parking policies based on stochastic control models are promising. They can deal with different demand levels (high, low or unstable) and generally outperform the deterministic pricing schemes. It can approach the minimum TTT in most of the cases as if we know the traffic demand in advance of the commuting time. Providing real-time occupancy information alone without setting proper parking prices, seems useful, but marginal, in reducing the parking congestion.

1. Introduction

Parking is among the most common issues for travelers, transportation planners and operators. Statistics show that a typical vehicle parked 23 h a day (Litman, 2011), and the parking congestion (namely parking searching time) takes up to 40% of the total travel time (Axhausen et al., 1994). Efficient parking management can mitigate both traffic and parking congestion, and reduce the social costs and environmental impact. *Pricing* and *sensing* are an interactive pair to improve parking management. The objective of this paper is to investigate the intimate relations between dynamic pricing and sensing, and how they affect the total system cost. Thereafter, we propose an optimal online parking pricing strategy relying on real-time sensing.

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Though parking is responsible for significant traffic congestion and traffic modal shift, it has gained less attention than the traditional focus on roadway system in the field of urban transportation planning. The cutting-edge *sensing* technology makes it possible to obtain unprecedented parking information regarding real-time usage of parking facilities. Equipped with sensors by each parking spot, modern parking lots/blocks can provide real-time parking occupancy, space locations and parking durations. Such information, along with real-time parking prices, can be sent through smartphones or GPS receivers to travelers. Travelers then make decisions when to leave and where to park, based on all the information available, specially the parking availability and parking prices. It is then not difficult to image that based on such sensing technology, dynamic parking prices and parking availability can significantly affect travelers' parking behavior. In fact, pricing and information provision, with the help of sensing, jointly manage the traffic.

Either pricing or sensing in parking has been discussed in the literature (e.g., Litman, 2011), but previous studies usually investigate each of them separately (mostly pricing), and their relationships are not fully understood yet. On the other hand, there are quite a few descriptive and empirical studies on parking policies regarding pricing and other types of management (e.g., Axhausen et al., 1994; Thompson et al., 1998; Vianna et al., 2004), while theoretical studies on parking modeling are few, and most of them focus on the steady-state pricing (e.g., Wang et al., 2004). Bifulco (1993) considered the parking prices, parking types and access times in the static traffic assignment model to evaluate parking policies in a general urban network. Several others investigated the parking fees in simplified networks. Glazer (1992) modeled the social welfare with respect to the parking fees by assuming a constant road-usage fee and constant travel cost for all the travelers. Verhoef et al. (1995) also assumed a constant travel cost and conducted diagrammatic analysis on how parking prices and allocation affect the travel cost and modal split. Arnott and Rowse (1999) derived the expected parking time, driving time and cruising distance for searching available spaces in an ideal ring network in the steady-state context. A system optimum was thereafter derived with respect to the pricing schemes. Despite all these static models reveals the relations between network performance, traffic congestion and parking prices, they overlook the time-varying demand pattern, as well as uncertainty of the demand. Those models are particularly useful for evaluating general parking policies from the long-term planning point of view.

Dynamic parking pricing was modeled in several literatures recently. Arnott et al. (1991) are among the first to study the parking pricing by dynamic user equilibrium. They embedded the parking problem in the morning commute model (Vickrey, 1969) to show that parking fee can be efficient in increasing social welfare. This model was further extended by Zhang et al. (2008) to derive the travel pattern of the morning commute and evening commute. More recently, the parking capacity allocation, parking accessibility and parking prices were examined for a dynamic network with disparate parking areas (Lam et al., 2006; Qian et al., 2011; Qian et al., 2012; Yang et al., 2013). Zhang et al. (2011) studied the pricing of tradable parking permits in a way of achieving system optimum. The system optimum achieved by the optimal parking prices was derived, and meanwhile the traffic delay can also be reduced by setting appropriate prices. Nevertheless, these papers do not consider the effect of the parking information obtained by sensing. Dynamic pricing are set off-line rather than in real time, which may not work well for non-recurrent demand. On the other hand, sensing itself was also discussed in Teodorovic and Lucic (2006). They developed a parking space inventory control system based on occupancy information targeting the maximum revenue for parking operators. A single parking lot was studied and the parking prices for travelers are predetermined. The real-time "control" lies in the parking guidance by accepting or rejecting a new driver's parking request. The application of such a system is only for a single lot and the effect of pricing is not discussed in that paper.

Some Intelligent Transportation Systems (ITS) have been able to provide real-time parking occupancy information to travelers since almost two decades ago. The parking occupancy information is mostly regarding the number of available spaces in certain parking garages, and is usually in the form of variable message signs (VMS) or traffic radio, while a few cities (e.g. San Francisco) offer phone applications for travelers to check real-time occupancy. Although such occupancy information has the potential of improving parking efficiency and reducing cruising cost (e.g., Mei et al., 2012), several empirical studies and simulation show that the benefits of providing solely the number of vacant spaces may be limited in congested networks (e.g., Asakura and Kashiwadani, 1994). This is mainly due to two reasons. First, in most cases, parking prices remain unchanged from day to day in those systems, and thus commuters with day-to-day experience on the road are aware of the approximate occupancy of key parking lots/blocks even without the help of the system (in a formal economics language, a system day-to-day equilibrium of parking choices may exist). Their parking decisions may not largely rely on real-time parking information. Second, those ITSs only reveal the information of parking, rather than "control" the parking. The information along may not be intriguing for travelers under heavy congestion. For example, suppose a traveler is near a farther lot that is 10 min away from the closer one. He has to make a decision of either parking at the farther lot or going to a closer one. He is provided with the information that only two spots out of several hundreds available at the closer lot. If the parking demand is high, the information may not be of any value to him, because he may not risk additional driving time and cruising time (which is usually much longer than 10 min) on finding one of the available spots that could be taken in any minute. This is also the most common complain from the reviews of parking phone applications. Consequently, we can see that providing the occupancy information alone is usually not sufficient to improve the transportation system. Sensing should be connected to real-time demand "control". The real-time occupancy data could be analyzed to reflect the real-time parking demand and therefore a corresponding online pricing strategy can be set to efficiently direct travelers to different parking lots. In that sense, traffic demand can be managed in an efficient way by *sensing* and *pricing*.

The main idea of this paper is to model the optimal parking pricing as a *stochastic control* problem. Relying on real-time data from parking sensors, parking pricing and information provision jointly serve as a *dynamic stabilized controller* for the traffic demand management. The conceptual idea is shown in Fig. 1. We obtain the measurement on parking occupancy by