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Parking space management via dynamic performance-based pricing

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ABSTRACT

In congested urban areas, it remains a pressing challenge to reduce unnecessary vehicle circling for parking while at the same time maximize parking space utilization. In observance of new information technologies that have become readily accessible to drivers and parking agencies, we develop a dynamic non-cooperative bi-level model (i.e. Stackelberg leader–follower game) to set parking prices in real-time for effective parking access and space utilization. The model is expected to fit into an integrated parking pricing and management system, where parking reservations and transactions are facilitated by sensing and informatics infrastructures, that ensures the availability of convenient spaces at equilibrium market prices. It is shown with numerical examples that the proposed dynamic parking pricing model has the potential to virtually eliminate vehicle circling for parking, which results in significant reduction in adverse socioeconomic externalities such as traffic congestion and emissions.

1. Introduction

In practically all major cities, the time and frustration associated with finding a parking space during peak hours not only upsets drivers, but also significantly decreases the city's economic, environmental, and social sustainability. The economic impact, measured in terms of wasted resources (time or fuel) and lost economic potential, is the most visible. On average, 8.1 min are wasted each time a driver circles around a U.S. city in search of a parking space (Shoup, 2005). This extra circling can account for up to 30% of urban traffic congestion, and generate an extra 4927 vehicle-miles-travelled (VMT) per parking space per year (Shoup, 2006). A large portion of this circling occurs in densely developed downtown areas. Additionally, according to a survey in Year 2011, 60% of the responded drivers reported that at least once they were so frustrated searching for parking that they eventually gave up, leaving behind only congestion and lost economic opportunity (IBM, 2011). The environmental impacts are also significant. In a large city such as Chicago (with over 35,000 parking spaces), the excess vehicle distance caused by circling burns 8.37 million gallons of gasoline into an extra 129,000 tons of CO_2 each year (Ayala et al., 2012).

Due to these economic and environmental issues, management of urban parking, via pricing schemes for example, is often necessary. Such efforts can impose significant social impacts, including direct influences on travel demand and equity issues. For example, outdated parking policies such as free or tax-exempt parking in essence provide a subsidy to those owning and operating a vehicle, which may be worth hundreds of dollars per motorist per year (Litman, 2005). This subsidy, often also seen as one approach to demand management, tends to favor wealthier car-owning households and may divert investments

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from alternative transportation modes (such as pedestrian, bicycling, or transit). However, regardless of the city's mode split, it is important to efficiently utilize the parking resources allocated to car owners, as they are also important customers of the local economy. While easy to implement, spatially and/or temporally invariant parking management strategies, common in many cities' parking meter programs, may not be able to optimally regulate parking demand, which results in congestion and lost economic potential.

The rapid advances of information technology in recent years hold the promise to bring in a new paradigm of parking management systems that can reduce the negative externalities associated with urban parking. However, this new paradigm, commonly referred to as "smart parking," faces three types of barriers: political, technological, and operational. The political and technological barriers were lowered significantly over the past decade with the empirical implementation of several full-scale systems that include real-time occupancy sensing, public information dissemination, electronic payments, and so forth. The pilot SF*park* variable pricing program in San Francisco, for example, has shown the possibility of overcoming the political barrier to time-varying parking policies. Hence, the biggest remaining barrier is operational, which focuses on effectively managing urban parking while considering infrastructures, policies, enforcement, and general operations. In particular, demand management, often accomplished through parking pricing, is critical to efficient parking operations. To the authors' best knowledge, no demand management strategies yet exist (beyond experimental) that are able to utilize dynamic and real-time information to improve efficiency, equity, and the user experience, and in turn mitigate congestion and other social and environmental issues. The working mechanism of such a management system should also be easily understood by drivers and other stakeholders.

Even with real-time information, the implementation of new parking systems that will affect thousands of people every day is complex. Most existing models predict travel and parking demand based on historical data, but unfortunately fail to address complex interactions among various parking supply/demand factors and the interrelationships among pricing/travel/parking decisions. In reality, the decision-making process of the stakeholders (e.g. parking agency, individual drivers) often involves complicated gaming behaviors. On one hand, the agency's parking management strategies (e.g. pricing) directly affect drivers' travel and parking decisions, which in turn influence the parking demand. On the other hand, drivers with different origins, destinations, and socioeconomic characteristics compete against one another for limited parking resources at popular locations, and this competition eventually shapes the parking market and pricing at equilibrium. Integrating multiple layers of such decisions into one overarching modeling framework is challenging, as it involves different stakeholders who have independent and sometimes conflicting objectives.

This paper presents a new parking pricing and management system that incorporates ideas from variable pricing (e.g. SF*park*), on- and off-street parking reservation systems (e.g. Xerox, ParkWhiz), game theory, and downtown parking economics (see Arnott et al., 2013). The primary goal of this paper is to develop a dynamic, demand based real-time pricing model to optimally allocate parking spaces in busy urban centers, thus reducing congestion and other negative economic and environmental costs. This pricing model is online in nature and is able to react to real-time demand variations. It allows a parking agency to set system optimal pricing policies (e.g. to minimize congestion, maximize economic surplus, maximize revenue) while considering user competition and market equilibrium. Additionally, analysis of this pricing model provides insights into practical solution techniques for complex bi-level programming problems, i.e. mathematical programs with equilibrium constraints (MPECs), in dynamic settings.

The remainder of this paper is organized as follows. Section 2 reviews the literature related to smart parking, the existing variable pricing systems, and state-of-the-art modeling methods. Section 3 presents the assumptions, notation, and formulation of the proposed non-cooperative Stackelberg leader–follower game model for dynamic parking pricing. A solution approach is developed by transforming the bi-level MPEC into a solvable single-level mixed-integer quadratic program (MIQP) that is implemented in a rolling-horizon scheme. Section 4 illustrates the performance and potential impacts of the proposed dynamic pricing model using a numerical example based on an urban neighborhood in SF*park*'s current system. Section 5 concludes the paper and discusses possible future research.

2. Literature review

Problems associated with urban parking have gained considerable attention over the past decade. Shoup (2005) provides a meticulous summary of the status quo of parking management and a number of innovative ideas. Using ideas from the book, the pilot SF*park* program successfully applied demand responsive performance-based pricing to seven neighborhoods in San Francisco (SFMTA, 2014). The underlying theory is that if there is always one open space on each block, drivers can immediately find an open space that suits their preferences, which would virtually eliminate circling for parking. The program uses recorded occupancy data to raise or lower meter and garage prices every six weeks with the goal of achieving a target average occupancy level (e.g. 85%) on every street block during every time period (e.g. morning, afternoon, evening). Another pricing model by Xerox® utilizes historical data to predict future parking demand and set parking prices accordingly. This model, currently implemented in Los Angeles's LA ExpressPark™ program, can take special events into account, but also updates pricing tables rather infrequently (i.e. only once every several weeks). Unfortunately, for both programs, such long intervals between price updates limit the models' ability to handle anything other than an average parking demand.

It is now possible to collect accurate information dynamically and use it to predict real-time demand (Caicedo et al., 2012). Information technology and its subset of "smart parking" applications have evolved rapidly over the past decade.