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A mechanism design based approach to solving parking slot assignment in the information era

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ABSTRACT

This paper proposes a mechanism design based approach for public parking slot assignment in an environment empowered by recent advances in parking sensing, infrastructure-to-vehicle, and vehicle-to-infrastructure communications. An important part of the parking slot assignment deals with eliciting truthful private information from drivers while maximizing social welfare. We consider both static and dynamic mechanisms and provide theoretic proofs that, by using coupled slot allocation and payment rules, drivers will be incentivized to participate in the assignment process and truthfully report their private information. The parking manager will benefit by generating non-negative revenue from each assigned driver. Our numerical analysis provides further insights into the implementation of the dynamic mechanisms.

1. Introduction

Parking presents a major challenge in metropolitan areas, where the supply of physical parking infrastructure is often constrained by available land vis-à-vis the extent of business, commercial, and other activities. As a result, arriving drivers spend many minutes searching for available parking space, which constitutes an important yet often ignored source of congestion. Previous research concludes that the average search time for parking in large cities is 8.1 min per vehicle; in addition, 30% of city road traffic is cruising for parking (Shoup, 2006). Putting this in aggregate, parking space search in the city of Chicago resulted in 63 million vehicle-miles-traveled, 3.1 million gallons of gasoline consumption, and 48,000 tons of CO_2 emissions per year (Ayala et al., 2011). Given that the possibility of increasing parking supply is limited, solving the urban parking problem often requires a demand management perspective.

Allocation of parking resources using existing infrastructure is being made increasingly efficient thanks to recent technological advances in sensing to collect real-time information on parking availability (Park et al., 2008; Panja et al., 2011) and infrastructure-to-vehicle communications to disseminate parking availability information to drivers. Examples of the latter are: data access via a peer-to-peer (P2P) environment (Wolfson and Xu, 2004; Kokolaki et al., 2011); coupled open space detection with information sharing (Mathur et al., 2010); and wireless ad-hoc networking for data sharing (Verroios et al., 2011). These new technologies enable real-time allocation of parking slots to demanding drivers.

New vehicle-to-infrastructure communication technologies further allow *private information* from drivers to be sent to the parking manager. For a driver, her parking-related information can include how much she values parking, when she arrives, how late she could stay and wait to be assigned, and the time of departure from the parking. Smartphone

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applications today have made information submission from drivers to the parking manager in real time and at almost no cost. Exchange of information on parking availability and demanding drivers between the parking manager and drivers promotes the development of disaggregate, agent-based parking slot assignment. A public parking manager, for example, can assign parking slots based on the information he has to achieve desired system-wide outcomes, such as maximizing social welfare.

A number of recent studies have looked into parking management in the context of a centralized authority and with information technologies. The relationship between parking price and real-time parking occupancy is investigated in Qian and Rajagopal (2014) under user equilibrium. Qian and Rajagopal (2013) consider information provision and pricing jointly as an efficient way of managing parking traffic. Caicedo (2010) develops a demand assignment model to evaluate the benefits of manipulating information to reduce time and distance involved in search of parking space. Ayala et al. (2011) present a slot assignment model that maximizes social welfare and investigate the price of anarchy. In Ayala et al. (2012), a parking pricing authority uses information about parking availability and drivers' natural cost to set charges in order to entice drivers and minimize total vehicle driving distance. An auction-based and a vehicle-specific pricing algorithms are further proposed to move Nash equilibrium to system optimum.

In the above studies, the objective of a parking manager/pricing authority, if there exists, is to minimize system-wide parking-related costs. The costs are calculated based on drivers' distance to the parking garage, parking price, and in some cases cruising time for parking. However, the heterogeneity of parking benefits across drivers has rarely been considered. Different drivers also have non-identical value-of-travel-time and thus the cost of driving/cruising for the same amount of time will be different. From the economic efficiency perspective, the best assignment should give available parking slots to drivers who value the slots most.

One fundamental assumption underlying centralized parking slot assignment problems is that *truthful* information of drivers is readily available to the parking manager. However, having the truthful private information relies on the goodwill of drivers who fully cooperate with the parking manager. The reality is often different, since drivers are inherently selfish. With knowledge about how slots are assigned and information on parking slot availability, a driver can misreport private information in order to maximize her own utility. Given untruthful driver private information, suboptimal system-wide allocation will result. To prevent this, appropriate mechanisms must be in place that incentivize drivers to report truthful private information. Such mechanisms need to align the selfish behavior of drivers with the system objective, so that optimal allocation of parking resources can be achieved under an intervened driver equilibrium.

This paper contributes to the parking literature by introducing mechanism design principles to parking management in an environment empowered by parking sensing, infrastructure-to-vehicle, and vehicle-to-infrastructure communications. Both drivers and the parking manager will be informed of parking slot availability in real time. The parking facility in our study is publicly owned, with the objective of the parking manager being maximizing social welfare, which is characterized by the sum of drivers' net utilities gained from using the parking facility. We consider both static and dynamic parking slot assignments, and show that truth telling is unlikely to hold absent intervention due to the intrinsic selfishness of drivers. We develop mechanisms that blend slot allocation with pricing rules such that drivers' utility-maximizing decisions are incentive compatible, i.e., revealing their true information is the best action to take for each driver.[1] The mechanisms developed in this study fall into the category of "direct mechanisms", in which drivers are asked to reveal their preference parameters (i.e., valuation). In contrast to this are indirect mechanisms (Nisan et al., 2007), which this paper does not deal with. The pricing scheme in our mechanisms aligns drivers' selfish behavior with the objective of the public parking manager, so that optimal allocation of parking resources is achieved. We show that implementing the proposed mechanisms can increase parking efficiency in the real world.

We begin with an overview of mechanism design in Section 2, followed by discussion on a static parking slot assignment mechanism in Section 3. The case of dynamic parking is presented in Section 4, where we describe the base mechanism, provide the formal proof that the mechanism is incentive compatible, and explore other properties of the mechanism and its variant. To further examine the dynamic parking slot assignment, numerical experiments are performed in Section 5. Section 6 offers conclusions and directions for future research.

2. An overview of mechanism design with a simple example

According to Hartline (2013), mechanism design gives a theory for the design of protocols, services, laws, or other "rules of interaction" in which *selfish behavior leads to good outcomes*. "Selfish behavior" means that each agent in the mechanism individually tries to maximize her own utility. Such behavior is defined as rational. "Leads" means in equilibrium. A set of agent strategies is in equilibrium if no agent wants to change her strategy unilaterally. "Good"-ness of an outcome is assessed with respect to the criteria or goals of the designer. A natural economic criterion is social welfare, the sum of utilities of all agents. An alternative criterion can be profit, which is the total payment made by agents to the mechanism less any cost of providing the mechanism. Therefore, mechanism design intends to align agents' best strategies under the rational behavior assumption with the achievement of good outcomes, as desired by the mechanism designer. Mechanism design is

[1] In this paper we interchangeably use the terms "truth telling" and "incentive compatible".