Transportation Research Part B 73 (2015) 1–12

Contents lists available at ScienceDirect

Transportation Research Part B

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

Pricing of parking games with atomic players

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ARTICLE INFO

Article history:
Received 18 May 2014
Received in revised form 4 December 2014
Accepted 5 December 2014
Available online 7 January 2015

Keywords:
Atomic parking game
Equilibrium
System optimum
Pricing

ABSTRACT

This paper considers a parking competition game where a finite number of vehicles from different origins compete for the same number of parking spaces located at various places in a downtown area to minimize their own parking costs. If one vehicle reaches a desired vacant parking space before another vehicle, it will occupy the space and the other vehicle would have to search elsewhere. We first present a system of nonlinear equations to describe the equilibrium assignment of parking spaces to vehicles, and then discuss optimal pricing schemes that steer such parking competition to a system optimum assignment of parking spaces. These schemes are characterized by a union of polyhedrons. Given that the equilibrium state of parking competition is not unique, we further introduce a valid price vector to ensure that the parking competition outcome will always be system optimum. A sufficient condition is provided for the existence of such a valid price vector. Lastly, we seek for a robust price vector that yields the best worst-case outcome of the parking competition.

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1. Introduction

Parking is a growing problem in many large cities around the world. Cruising for parking is time consuming and further contributes to traffic congestion and pollution. For example, Arnott and Rowse (1999) pointed out that over 50% of the cars driving in rush hours are cruising for parking in the downtown areas of Boston and some major European cities. Assuming a three-minute search time, Shoup (2006) estimated that the cruising for a curbside parking space yields 1,825 vehicle-miles travelled each year. For a city like Chicago with over 35,000 curbside parking spaces (Ayala et al., 2012a), this translates into approximately 64 million vehicle-miles travelled, 3 million gallons of gasoline consumed and 30 thousand tons of CO_2 emitted every year (EPA, 2012).

The provision of real-time availability and prices of parking spaces will help drivers find parking spaces quickly. In many cities, this information is being distributed via, e.g., dynamic message signs or Internet. The proliferation of advanced smartphones offers new opportunities for parking information to be more widely disseminated and easily accessed in real time. The adoption of smartphones has been increasing rapidly. The number of smartphones is predicted to triple to 5.6 billion globally by 2019 (Ericsson, 2013). By communicating with, e.g., wireless sensors embedded on parking spaces, smartphone-based parking applications, such as SFpark (http://sfpark.org/), can allow drivers to easily access the information of availability and prices of parking spaces. It is envisioned that smartphone-based parking information systems will be widely

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http://dx.doi.org/10.1016/j.trb.2014.12.003
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deployed in the near future, which may intensify the competition of parking spaces and strengthen strategic interactions among drivers in the competition.

Although the pace of parking research has increased markedly in recent years, only a dozen of attempts have been made to capture strategic interactions among drivers when competing for parking and investigate how parking competition affects travel patterns. One group of prior studies integrate parking into bottleneck models to explore how parking competition shapes travel patterns of the morning commute, and then investigate parking policies to improve social welfare (e.g., Arnott et al., 1991; Zhang et al., 2008; Qian et al., 2011; Yang et al., 2013; Liu et al., 2014a,b; Qian and Rajagopal, 2014). See Fosgerau and de Palma (2013) for a recent review of this research direction. Another group of studies examine parking competition in a spatial setting and investigate how parking search strategies affect spatial travel patterns in downtown areas (e.g., Bifulco, 1993; Arnott and Rowse, 1999; Anderson and de Palma, 2004; Arnott and Inci, 2006). Among them, the most relevant to this paper are those that consider a finite number of drivers competing for a limited number of parking spaces. For example, Guo et al. (2013) studied a static game where a group of drivers with the same destination choose between two parking lots to minimize their walking distances to the final destination. The drivers are assumed to know the capacity of both lots and the probability of finding a parking space in either lot. A Nash equilibrium would arise if drivers make decisions simultaneously and have perfect knowledge about the strategies of their fellow drivers. The percentage of drivers using either lot can thus be calculated. Kokolaki et al. (2012) examined a similar parking selection game where drivers compete for scarce low-cost public parking spaces and those who do not win the competition have to drive further for more costly private parking spaces. Considering different levels of knowledge that drivers have on the overall parking demand, the authors derived multiple equilibria and compared them with the system optimum state. Note that both studies aggregate parking spaces into two sets and thus do not capture drivers' choices of individual parking spaces within each set. Both also assume that each vehicle has the same probability of winning the parking competition, while in reality vehicles often compete on a first-arrive-first-served basis. It is thus the cursing time of each competing vehicle to a particular parking space that determines the winner. In contrast, Ayala et al. (2011, 2012a,b) considered a parking competition game where a finite number of drivers from different origins compete for a finite number of parking spaces that are located at different places. If one driver reaches a vacant parking space before another driver, he or she will occupy the space and the other driver will have to search elsewhere. The authors discussed the system optimum and Nash equilibrium states of the game, and explored the design of a parking pricing scheme to drive the system from Nash equilibrium to system optimum. Considering both vehicles and parking spaces are indivisible and the one-to-one assignments between vehicles and spaces are examined in the proposed game, we hereinafter refer to it as a parking game with atomic players or an atomic parking game.

Recognizing that it may become more practically relevant due to the growing adoption of smartphone-based parking service applications, this paper provides a systematic account of an uncooperative static atomic parking game with complete information. Compared with Ayala et al. (2011, 2012a,b), the contributions of this paper include (i) specifying the normal-form representation of the parking competition game by defining an explicit payoff function; (ii) formulating the equilibrium state of the atomic parking game as a system of nonlinear equations, which is equivalent to depicting all the equilibrium assignments of parking spaces; (iii) investigating the price of anarchy for the game of a given size; (iv) characterizing all the pricing schemes that can make the system optimum assignments of parking spaces satisfy the equilibrium conditions of the parking game; (v) establishing a sufficient condition for the existence of valid price vectors, which ensure that the parking competition outcome will always be system optimum; and (vi) formulating a robust pricing problem and developing a global optimum solution procedure for finding a pricing scheme that yields the best worst-case outcome of the game.

For the remainder, Section 2 describes equilibrium and system optimum assignments of the atomic parking game, followed by a discussion on optimal parking pricing in Section 3. Section 4 formulates robust parking pricing as a min–max problem and proposes a global optimum solution procedure. Lastly, Section 5 concludes the paper.

2. Equilibrium and system optimum

2.1. Equilibrium assignment

We consider a static non-cooperative game where there are a finite number of available parking spaces and a finite of number of drivers or vehicles (hereinafter we use "drivers" and "vehicles" interchangeably) compete for them. Considering that in reality drivers can always find a place to park if searching sufficiently far away their final destinations, the number of available parking spaces is thus no less than that of vehicles. Without loss of generality, we assume that the numbers of drivers and spaces are the same.[1] Let I and J denote, respectively, the sets of vehicles searching for parking and available parking spaces. Both sets have the same cardinality of N. Let t_{ij} represent the time it takes for vehicle $i \in I$ to travel from its current location to space $j \in J$. It is assumed that t_{ij} is given and fixed, and $t_{ij} \neq t_{kj}\ \forall j, i \neq k$. The latter implies that winners can be indisputably determined. When two vehicles compete for the same space, the one with a smaller t_{ij} will win the competition. If their cursing times are the same, the competition outcome can be random. We leave this scenario to our future study.

[1] If there are more parking spaces than drivers, the problem can be converted to the one where drivers are limited to select among those attractive parking spaces occupied in a system optimum assignment. Consequently, the numbers of drivers and spaces are the same and the results of this paper thus apply.

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