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Planning of parking enforcement patrol considering drivers' parking payment behavior

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ABSTRACT

This paper focuses on improving the effectiveness of parking enforcement patrol by optimizing the schedule of visit at each parking lot and the routing plan of patrol vehicles. Meanwhile, individual parking driver makes his/her parking payment decision based on knowledge of the patrol visit frequencies. Game-theoretic models are proposed to capture the interactions among the parking enforcement agency and parking drivers. We first develop a discrete formulation of the problem in the form of a mixed-integer program and propose a Lagrangian relaxation based solution approach. For large-scale instances, we also develop a continuum approximation model that can be reduced to a simpler non-linear optimization problem. A series of numerical experiments are conducted to show that, for small problem instances, both modeling approaches can yield reasonable solutions, although the continuum approximation approach is able to produce a solution within a much shorter time. For large-scale instances, the discrete model incurs prohibitive computational burdens, while the continuum approximation approach still provides a near-optimum solution effectively. We also discuss impacts of various system parameters, as well as the performance of different policy options (e.g., whether to allow multiple parking tickets to be issued to a vehicle with a long time of parking violation).

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1. Introduction

As the demand for parking continues to grow especially in urban areas, it has become a major challenge to enhance the efficiency and sustainability of parking services. Many cities have started to implement various parking management strategies (e.g., parking pricing, reservation) to improve the efficiency of their parking systems. For any of these strategies to be effective, parking enforcement has to be established to reduce or eliminate parking violations (Litman, 2006). However, this is not a trivial task. According to NYC OpenData (2016), in the fiscal year 2015 alone, 7.3 million parking violation tickets were issued in New York City, and 45% of them were due to overtime parking. As parking violations waste already limited parking resources, it is essential to strengthen parking enforcement management.

In most urban areas, parking is not free. A driver needs to pay a certain amount of money, usually at the time of arrival, to secure a parking space for a chosen length of time. However, in many systems, especially with parking meters, the drivers often do not know the exact length of needed parking duration when he or she is making the payment. In many other situations, the parking duration is actually random due to unexpected delays or distractions. A parked vehicle is considered

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to be in the violation state once the actual parking duration exceeds the paid parking time, and a ticket will be issued to such a vehicle when a patrol officer visits the parking lot. The fine associated with a parking ticket is usually much larger than the parking price. As such, a driver's parking payment decision shall be affected by the likelihood of encountering an officer, or in other words the schedule/frequency of patrol activities (Adiv and Wang, 1987; Elliot and Wright, 1982). Although the drivers may not possess accurate knowledge of the exact patrol schedule, it is not uncommon that they are aware of the approximate patrol frequency at a specific parking lot, especially for those drivers who use the parking lot on a daily basis. Accordingly, when the patrol frequency is low, a knowledgeable driver may incline to be more opportunistic and pay less money for parking; in contrast, drivers at a frequently patrolled parking lot would tend to be more conservative.

In practice, the parking enforcement agency usually divides the operating hours into multiple time periods and sends out officers to visit various parking lots in a periodic and repetitive manner. For a single period, a patrol officer departs from the base location at the beginning of the period, and visits a sequence of parking lots according to a routing plan. When the officer arrives at a parking lot, he or she checks the status of all parked vehicles to see if there is any violation. Once the officer finds a violation, he or she needs to spend some time on processing the violation, such as taking photos of the vehicle and issuing a ticket. After processing all the violations in the parking lot, the officer proceeds to the next location. Finally, the officer needs to return to the base location before the end of this period. From the perspective of the parking enforcement agency, it would be ideal if all the parking lots can be patrolled sufficiently frequently such that no parking violation exists. However, the agency may have only limited patrol resources to use. In addition, as mentioned above, there is also a time duration limit imposed on each single patrol route. As such, in order to construct an optimal or at least feasible routing plan, the agency needs to figure out the length of time that is needed for processing violations in each parking lot (which is called service time in this paper), and yet the travel time in-between parking lots. The travel time is considered to be deterministic and known, while the service time directly depends on the number of violations that is processed en route.

Parking enforcement patrol is one type of patrol activities routinely conducted by law enforcement agencies. Related resource allocation, positioning or routing problems have been explored in similar contexts. For instance, police patrol planning has been extensively studied in the urban environment (Larson, 1972; Chaiken and Dormont, 1978a; 1978b). In these models, the deployed police patrol vehicles were typically modeled as servers in a queuing system; such models capture the reactive nature of the police force (i.e., the primary mode of police operation is to respond to calls for service). Birge and Pollock (1989) extended the police patrol problem to the rural environment, and Taylor et al. (1985) proposed an integer nonlinear goal programming model which focused on maintaining a visible police presence on highways. Another example of patrol problems is the well-known art gallery and illumination problem, which deals with the positioning and deployment of guards in art galleries or museums (Urrutia, 2000).

The parking agency's problem shares some similarities with the periodic vehicle routing problem (PVRP) in which a set of given customers (each with a known visit frequency requirement) are repeatedly visited over multiple time periods, and different routes are constructed in each time period to serve the customers collectively (Christofides and Beasley, 1984). The PVRP is a variant of the classic vehicle routing problem and has been widely applied to many practical contexts, e.g., waste collection (Beltrami and Bodin, 1974), elevator maintenance and repair (Blakeley et al., 2003) and vending machine replenishment (Rusdiansyah and Tsao, 2005). The readers are referred to Campbell and Wilson (2014) for more details on PVRP. Since patrol frequency is part of the agency's decision, the closest literature might be that on PVRP with service choice (PVRP-SC), which is an extension of the PVRP that allows each customer's visit frequency/schedule to be a decision variable. Francis et al. (2006) studied the PVRP-SC in the context of interlibrary book delivery, and proposed a mixed-integer model and an exact solution method. A survey of related variants, formulations, and solution methods can be found in Francis et al. (2008).

The challenge is that, instead of knowing the exact demand in advance (as we normally assume for PVRP-SC and other patrol problems), the demand in the parking enforcement patrol problem (i.e., depending on the number of parking violations in each parking lot) is not only stochastic but also dependent on the agency's patrol decision. That is, the likelihood of a vehicle being in violation is directly related to the driver's payment decision, and this payment decision is affected by the agency's patrol frequency. Such bi-directional relationships between the number of parking violations (as well as the service time) and the agencys patrol routing plans, therefore, imposes an additional layer of complexity on the already difficult PVRP-SC type problems.

In this paper, we propose two game-theoretic mathematical models to capture the interactions between the agency's patrol decision and drivers' parking payment decision. The parking enforcement agency determines the patrol schedule at each parking lot and the routing plan of the available patrol vehicles, while taking into consideration the fact that each parking driver makes his/her optimal parking payment decision in accordance with the patrol frequencies. We model the agency's patrol planning problem as a variant of PVRP-SC and handle the driver's parking payment problem as a variant of the news-vendor problem. As the driver's parking payment problem can be solved in closed form, the parking enforcement patrol problem can be transformed into a single-level mathematical program. We first develop a discrete formulation as well as a Lagrangian relaxation based solution algorithm. To facilitate the solution process for large-scale instances, we also develop a continuum approximation (CA) formulation that can be reduced to a non-linear optimization problem. The performance of the proposed models and algorithms is tested through a series of numerical experiments. It is shown that the both the discrete and CA approach can produce reasonable solutions, though the computation time for the CA approach is much shorter. The CA approach demonstrates to be an effective alternative to avoid prohibitive computational difficulty

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