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Parking search equilibrium on a network

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ABSTRACT

This paper describes an equilibrium formulation for incorporating parking search into traffic network assignment models. The proposed model allows general network topologies and reflects uncertainty related to parking availability, including the possibility of cycling behavior as drivers search for parking. The equilibrium framework represents the mutual dependence between the probabilities of finding parking at different locations and the search processes employed by drivers to minimize total expected journey time (or cost). In this framework, network loading is represented by a system of nonlinear flow conservation networks, and feasibility and uniqueness issues are discussed. The equilibrium problem is formulated as a variational inequality and a convex combinations heuristic is proposed. Numerical results show that neglecting parking search can substantially underestimate network flows, and quantitatively demonstrate the relationship between parking duration effects and the cost of time spent walking relative to driving, and the expected driving and walking times.

1. Introduction

Travel forecasting models are used to predict traffic patterns and overall system-level congestion for evaluating transportation system improvement measures. One of the key steps in travel forecasting models is traffic assignment, which predicts the route choices of travelers and the resulting flows on the networks (Patriksson, 1994). Parking is an underappreciated aspect of transportation network modeling. While some studies conclude that over a third of traffic volume can be attributed to drivers searching for parking (Shoup, 2006), most traffic assignment models used in practice neglect additional time at the destination due to parking search. Integrating the parking search process into network traffic assignment models will result in better prediction of traffic flows, leading to more accurate evaluation or rankings of transportation improvement projects, such as where to add capacity, pricing, and so forth (Meng et al., 2001; Boyce et al., 2004; Gardner et al., 2011). Many cities are exploring policies related to parking in order to reduce congestion in urban areas, such as dynamic pricing based on parking availability (Rye, 2006; Polycarpou et al., 2013; Glasnapp et al., 2014). Recent advances in sensor technologies and parking-related smartphone apps also suggest the value of a quantitative framework for calculating the potential impacts of these technologies as drivers adapt their parking behavior in response.

As with route choice in general, parking search can be viewed from the perspective of equilibrium. Assuming that drivers aim to minimize the time spent traveling (including both driving and walking from the parking space to the destination),

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drivers' route and parking search behaviors depend on the probabilities of finding parking at particular locations in the network; however, these probabilities depend on the route and search strategies employed by drivers in the network. A natural model for this mutual dependency is an equilibrium framework in which no driver can improve his or her expected travel time by adjusting their strategy.

As discussed in the literature review, the model presented in this paper builds on existing network parking models in the following ways. First, it is explicitly stochastic and reflects the dependence of parking probability on searching rates. Second, it applies to general networks of any topology, and directly allows planners to identify which specific links and regions are particularly affected by increases in volume due to parking search. Third, the concepts of route choice and parking search are unified in a natural way which does not require assumptions such as drivers "transitioning" from driving towards the destination to searching for parking. Fourth, the introduction of an equilibrium concept captures the dependency between searching strategies and parking availability.

To accomplish this, a network transformation is introduced to distinguish between drivers searching for parking on a link and drivers merely passing through. The dependence of parking probability on flow rates results in a set of nonlinear flow conservation equations. Nevertheless, as shown below, under relatively weak assumptions the existence and uniqueness of the network loading can be shown, and an intuitive "flow-pushing" algorithm can be used to solve for the solution of this nonlinear system. Built on this network loading algorithm, travel times can be computed. The equilibrium is formulated as a variational inequality, and a heuristic algorithm is presented to solve it.

The remainder of the paper is organized as follows. Section 2 reviews relevant literature on the impact of parking in urban areas, along with network modeling approaches which have been proposed. Section 3 introduces the network transformation used to represent the stochastic nature of the parking search and notation which will be used throughout. Network loading and flow conservation are described in Section 4, along with the flow-pushing algorithm; this section describes the impact of travel choices on parking availability and link flows. Next, Section 5 introduces the complementary perspective of the impact of parking availability on travel choices, leading to an equilibrium definition to reconcile both perspectives. A solution heuristic is presented in this section as well. Section 6 demonstrates the algorithm's performance numerically and conducts sensitivity analyses, while Section 7 concludes and discusses future directions.

2. Literature review

Parking imposes significant demands on urban transportation networks. Drivers "cruising" or searching for parking increase roadway volumes, exacerbating congestion and emissions. A meta-analysis by Shoup (2006) finds that approximately 34% of congestion in urban areas results from cruising for parking, and a study in Frankfurt, Germany indicates that up to 40% of total travel time consists of searching for a parking space, for peak-period trips to the city center (Axhausen et al., 1994). As a result, many cities are focusing attention on parking management, including data collection, real-time dynamic pricing, and other strategies; such cities include San Francisco (Pierce and Shoup, 2013), Boston (Ross, 2013), Seattle, and Washington, DC (Greenberg, 2012).

Network models that incorporate parking can be broadly classified into simulation-based approaches and analytic approaches. Simulation approaches include the study of Thompson and Richardson (1998), in which drivers choose parking spaces based on a disutility function incorporating time and cost variables, and agent-based approaches (Benenson et al., 2008; Gallo et al., 2011; Dieussart et al., 2009) in which drivers are assigned behavioral rules. While simulation has the advantage of explicitly modeling parking dynamics and accommodating behavioral heterogeneity, they are limited in their ability to model large networks and are generally not amenable to exact results regarding the network loading and the equilibrium state. A further limitation is that in the absence of field data, there is an arbitrary element to the behavior rules, such as assuming that drivers will not cruise for parking if vacant spaces are available (Arnott et al., 1991), or that drivers will route deterministically to a preferred parking location; if that choice is unavailable, they will proceed to a second choice, third choice, and so on (Leurent and Boujnah, 2012). While some degree of arbitrariness is inevitable without field data, we prefer to build a model on a more fundamental principle. As described below, in our model the route choice and choice whether to take an available space if one exists are both governed by the principle of expected cost minimization, without the need to introduce a distinction between "driving toward the destination" and "searching for a parking space."

Analytical approaches, by contrast, are based on traffic assignment concepts and transform the network by adding new links to represent parking options. Typically these links are equipped with an impedance function to reflect delay due to parking search as more drivers attempt to park on that link. These approaches include Eldin et al. (1981), Lam et al. (2002, 2006), and Li et al. (2007), and incorporate features such as endogenous mode choice accounting for parking, bilevel models for parking price. The main advantage of these approaches is their tractability, and ability to incorporate well-known results from the traffic assignment literature. However, by assuming a deterministic impedance for parking, the models are unable to reflect additional delay or volume on specific network links as drivers search for parking (possibly traversing a link multiple times as they cycle). Discrete choice concepts have also been used to study parking choice (Hunt and Teply, 1993), without explicit reference to a network, but using a nested logit model to account for similarities in on-street and off-street alternatives.

By contrast, the model described in this paper is explicitly stochastic and can be used to identify specific links with increased volume due to parking search. Furthermore, the network loading can be described analytically, and the equilibrium principle can be formulated mathematically. Furthermore, the behavior model relies on a fairly simple principle