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Stochastic user equilibrium traffic assignment with equilibrated parking search routes

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ABSTRACT

In this paper we define and formulate the concept of parking search routes (PSR) where a driver visits a sequence of parking locations until the first vacant parking spot is found and in doing so may account for (expected) parking probabilities. From there we define and formulate the stochastic user equilibrium (SUE) traffic assignment in which no driver, by unilaterally changing its PSR, can lower its perceived expected generalized costs. Recognizing the interdependency between PSR flows, travel times and parking probabilities, we propose a queuing model in order to compute endogenous parking probabilities accounting for these factors as well as maximum admissible search times. To solve the SUE assignment with equilibrated PSR we propose a solution algorithm, including a method for PSR choice set generation. The model is implemented and applied both to a number of experimental cases to verify its properties and to a real-life setting to illustrate its usefulness in parking-related studies.

1. Introduction

Parking is an essential component in every car trip especially in the urban context, and as such has been studied regarding, for example, how it affects mode choice, location accessibility, and network performance due to cruising traffic. In particular considering cruising traffic, various studies have quantified this with estimates of about 30% of the urban traffic flows being cruising traffic (e.g., Shoup, 2006, and Van Ommeren et al., 2012) and of about 30–50% of the travel time within the city being spent on searching for a parking spot (e.g., Bonsall and Palmer, 2004, and Tang et al., 2014).

Apart from the sheer amount of cruising traffic, parking in the urban context is also an interesting topic for research due to fast developments nowadays in the parking system. In more and more cities worldwide, including the majority of cities in the Netherlands, on-street paid parking is regulated by registration of the car number plate, instead of the traditional pay-and-display system where a parking ticket is bought. The main reason for implementing this payment system is that it enables automated parking control, using a special control car with mounted automatic number plate recognition camera that is connected with the back office system to check for any non-registered parked cars. This online payment system has led to the introduction of several smartphone applications where users no longer need to pay in advance for a pre-specified amount of parking time, but simply register their car upon arrival at a parking location and subsequently unregister upon departure, thus only paying for the parking time actually used. Given that parked cars are now registered, this means that there is real-time information on the occupancy at parking locations. This information was already available for off-street

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parking, but is generally only displayed at roadside panels that are typically located at motorway exits and along the urban ring road for purposes of parking route guidance. Now with information on-street parking occupancies as well and with smartphone applications, this parking occupancy information may soon become available to drivers everywhere and in real-time. Furthermore, this may enable parking reservation in advance. Such a reservation system is not yet available for public parking space, although a few of the Dutch smartphone applications do already offer this service for private parking space offered by, for example, companies and hotels.

Earlier studies on parking location choices of drivers show that this predominantly depends on the factors of access time to parking location, parking fees, walking distance to final destination, and a number of socio-economic characteristics of the driver. In a recent stated preference survey by the authors (Chaniotakis and Pel, 2015) we show that uncertain parking availability ranks as second most important factor in determining drivers' parking location decisions, and is only dominated by parking fees. This is relevant because the parking availability and associated search time is evidently precisely what will be affected by the aforementioned new technologies, while the other factors will remain mostly unaffected. Furthermore, earlier studies on parking information and guidance systems show that the effects hereof are rather limited when the parking information provided via roadside panels tended to be outdated and unreliable, especially in more congested circumstances (see e.g., Waterson et al., 2001, and Geng and Cassandras, 2012).

In this paper we propose a model for the dynamic traffic assignment problem that incorporates drivers' parking search routes in a way that allows to simulate the effects of uncertain parking availability and parking reservation, and thus enables evaluating various parking information technologies and policies. According to Martens and Benenson (2008) this model would be classified as a spatially explicit parking model, as opposed to a spatially implicit model that only considers parking location without accounting for the traffic network effects. Examples of spatially implicit models are: the bottleneck model proposed by Yang et al. (2013) that is used by Liu et al. (2016) to analyze the effects of parking pricing and regulation on departure times in the morning commute; the network fundamental diagram model proposed by Geroliminis (2015) and Liu and Geroliminis (2016) that is used to analyze the relationships between time-varying tolls, departure times, and cruising times of morning commute traffic; and the probabilistic system dynamics model proposed by Cao and Menendez (2015) that is used to analyze the interactions between traffic flows, parking supply, and cruising times. On the other hand, considering spatially explicit parking models, also various approaches have been proposed in the literature. For example, a number of simulation models have been proposed to describe parking traffic, in particular the on-street search process where drivers cruise in a myopic semi-random manner searching for a vacant parking spot (e.g., Kaplan and Bekhor, 2011, Van der Waerden, 2012, Guo et al., 2013, and Boyles et al., 2014). Along a similar line of reasoning, a number of agent-based simulation models have been appended with decision rules for parking choices (e.g., Benenson et al., 2008, and Waraich and Axhausen, 2012). Other studies have considered strategic parking search behavior within an equilibrium context and use network assignment models. For example, Bifulco (1993) solves the stochastic user equilibrium assignment where route costs include parking search costs that are approximated as a function of parking occupancy. Lam et al. (2006) solve the traffic assignment problem with departure time and parking location choice where parking availability is approximated via a BPR-like cost function. Li et al. (2008) solve the traffic assignment problem under the assumption of time-dependent Normal-distributed uncertain travel times and parking search times in order to investigate the impact on network reliability. Leurent and Boujnah (2014) solve the static user equilibrium assignment with route and parking location choice, where drivers divert to other parking locations when not being able to find a vacant parking spot, such that parking search routes emerge. Boyles et al. (2015) model strategic parking routes within the cell transmission model by incorporating parking search policies defined in terms of stochastic decision processes. Their approach computes the user equilibrium traffic assignment that minimizes travel times (including driving time and walking time towards the destination) with endogenous parking availabilities.

All of these model studies in one way or another account for uncertain parking availability and the parking search process, whereas the majority of parking models (used to study e.g., parking pricing and regulation) would typically model parking availability as deterministic. Although these models may certainly be applicable for specific studies, they also have their limitations within the context of evaluating the impact of all kinds of parking-oriented traffic information and management strategies (such as parking information systems, parking guidance systems, parking reservation systems, and all sorts of parking policies targeted towards reducing cruising traffic). The latter scope of model applications requires (1) a spatially explicit parking model as part of a traffic assignment model, (2) including drivers' choice behavior (pre-trip and on-trip) among parking locations, and the effect of probabilistic parking availability and search times, (3) as well as time dynamics of traffic flows and parking availabilities, (4) and where the interdependencies between parking search route flows, travel times, and parking probabilities are endogenously determined in a rigorous manner. To the best of the authors' knowledge no model to date meets all of these requirements.

In this paper we propose a model that does meet these requirements. It does so by distinguishing itself particularly in two ways. First, our model has a clear theoretical foundation where parking search route choice follows Random Utility Maximization choice theory, and the (stochastic) user equilibrium assignment with equilibrated parking search routes is a generalization of the Wardrop equilibrium concept. Second, the rigorous model formulation includes the interdependencies between parking search route flows, travel times, and parking probabilities, and hence these three factors are all endogenously determined. As such, the model adheres to general requirements for (traffic assignment) planning models.

The contributions of the paper are: (1) we define and formulate the concept of parking search routes (PSR) that drivers may follow in order to find a vacant parking spot while accounting for parking probabilities; (2) we propose a queuing