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A dynamic taxi traffic assignment model: A two-level continuum transportation system approach

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ABSTRACT

This paper proposes a two-level continuum transportation system approach to modeling a dynamic taxi traffic assignment (DTTA) problem in a dense network with real-time traffic information provision and three types of vehicles, including private cars, occupied taxis, and vacant taxis. The proposed approach treats the dense network as a continuum in the first level, in which private car and occupied taxi drivers are free to choose their paths in a two-dimensional continuous space. The proposed approach also divides the modeling region into many identical squares to form a cell-based network in the second level, in which the cells are classified into two categories: target cell with an acceptable expected rate of return (EROR) to vacant taxi drivers and non-target cell with an unacceptable EROR. The EROR associated with a cell is the ratio of the cumulative expected profit of a taxi driver who successfully picks up a customer during the customer search that starts from that cell to the sum of expected search time for this customer and expected occupied travel time to serve this customer. Based on the cell-based network, we develop a cell-based intervening opportunity model to capture the fact that vacant taxi drivers can meet a customer on the way to their destination zones and estimate the EROR. Each vacant taxi driver has a mixed strategy to determine his/her customer-search direction according to the EROR: Each vacant taxi driver in a target cell selects its neighbor cells with maximum EROR, and each vacant taxi driver in a non-target cell selects the travel time-based shortest path to his/her target cell. Meanwhile, each private car driver chooses the path that minimizes his/her own generalized travel cost, and each occupied taxi driver chooses the path that minimizes his/her customer's generalized in-vehicle travel cost. In our model, traffic density in the system is governed by the conservation law (CL), and the flow directions of different vehicles are determined by the path-choice strategies of their drivers, which are captured by Hamilton–Jacobi (HJ) equations. Both the proposed CL and HJ equations can be solved by the Lax–Friedrichs scheme, which forms the backbone of the developed solution algorithm. Finally, numerical examples and a case study are used to demonstrate the properties of the model, the performance of the solution algorithm, and the value of using our methodology for estimating network performance.

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1. Introduction

As an important transportation mode, taxis offer speedy, comfortable, and direct transportation services. However, they tend to circulate around a city to search for customers and can consequently use up significant amount of road capacity and worsen traffic congestion and roadside air quality. To tackle these problems, advanced technologies (e.g., Horn, 2002; Lee and Cheng, 2008; Conway et al., 2012; da Costa and de Neufville, 2012; Miwa et al., 2013; Jung et al., 2014) are often used, and taxi regulation policies (e.g., De Vany, 1975; Schroeter, 1983; Arnott, 1996; Cairns and Liston-Heyes, 1996; Yang et al., 2000, 2002, 2005, 2010; Fernández et al., 2006; Moore and Balaker, 2006; Wong et al., 2014b) are established. The effectiveness of these methods can be evaluated by a taxi traffic assignment model.

Taxi traffic assignment aims to predict taxi traffic flow on each link or in each region, and can be used for both offline taxi regulation policy evaluation and real-time taxi operation and management. Taxi traffic assignment is an extension of traditional traffic assignment problems (TAPs), which have been widely studied for a long time and can be classified into two categories: static TAPs (e.g., Beckmann et al., 1956; Daganzo and Sheffi, 1977; Bar-Gera, 2002; Nie, 2010) and dynamic traffic assignment (DTA) problems (e.g., Yagar, 1971; Merchant and Nemhauser, 1978a,b; Friesz et al., 1989; Ran et al., 1993; Huang and Lam, 2002; Lo and Szeto, 2002; Ban et al., 2008; Long et al., 2013, 2015, 2016; Han et al., 2015). As the temporal variation of flow and cost are not considered in the static models, they cannot be used to model travelers' departure/arrival time choices or dynamic traffic management and control. DTA can address these problems and has received much attention in recent decades (e.g., Merchant and Nemhauser, 1978a,b; Friesz et al., 1989; Ran et al., 1993; Lo and Szeto, 2002; Long et al., 2013; Du et al., 2013, 2015; Jiang et al., 2017). Different from the fast development of TAP models, the development of taxi traffic assignment models is still in its early stage. Most existing taxi traffic assignment models are static (e.g., Yang and Wong, 1998; Wong et al., 2008; Yang et al., 2010). Therefore, they cannot capture the time-varying customer demand and the situation that taxi drivers change their customer search choices en-route when they receive real-time traffic and customer demand information regularly. Consequently, the taxi customer-search efficiency and the congestion impacts caused by taxi cruising and circulation during the studied horizon cannot be accurately evaluated by these models.

In the literature, there are two approaches to modeling TAPs: discrete (e.g., Friesz et al., 1993; Huang and Lam, 2002; Lo and Szeto, 2002; Lim and Heydecker, 2005; Long et al., 2013, 2015, 2016; Jiang et al., 2016) and continuum (e.g., Hoogendoorn and Bovy, 2004; Jiang et al., 2011, 2017; Du et al., 2013, 2015). The discrete modeling approach assumes that road links are separated but connected by nodes, and traffic demands are concentrated at hypothetical zone centroids. Discrete traffic equilibrium assignment problems are usually formulated as certain well-known mathematical problems, such as mathematical programming problems (e.g., Merchant and Nemhauser, 1978a,b; Carey, 1987; Carey and Subrahmanian, 2000; Ziliaskopoulos, 2000; Nie, 2011; Waller et al., 2013), optimal control problems (e.g., Friesz et al., 1989; Ran et al., 1993; Ma et al., 2014), variational inequality (VI) problems (e.g., Friesz et al., 1993; Ran and Boyce, 1996; Huang and Lam, 2002; Han, 2003; Long et al., 2013), nonlinear complementarity problems (NCP) (e.g., Wie et al., 2002; Ban et al., 2008), fixed-point problems (e.g., Smith, 1993; Lim and Heydecker, 2005; Szeto et al., 2011; Long et al., 2015), etc. The solution properties such as the existence and uniqueness of solution to the analytical DTA models can be determined beforehand and the existing solution algorithms can be used to solve them. However, it is challenging to model a large-scale congested urban traffic network with a large number of highways, intersections, interchanges, and severe congestion with queues and their spillbacks.

The continuum approach approximates a dense network as a continuum in which travelers are free to choose their paths in a two-dimensional continuous space. This allows that the characteristics of a network, such as its flow intensity, demand, and travel cost, can be represented by smooth mathematical functions (Vaughan, 1987). Hence, fewer data are required for the model setup process, and the problem size can be reduced for large dense transportation networks. This can potentially save computational time and memory. This approach also includes a special case where a single corridor is modelled as a continuum (e.g., Wang and Du, 2013; Du and Wang, 2014). The continuum modeling approach has been widely applied to model various highly dense transportation systems (e.g., Wong et al., 1998; Yang and Wong, 2000; Ho et al., 2006, 2013; Hoogendoorn and Bovy, 2004; Jiang et al., 2011; Du et al., 2013, 2015). Early studies use static continuum equilibrium models to determine facility locations and perform policy (e.g., Yang and Wong, 2000; Ho et al., 2006), environmental (e.g., Yin et al., 2013) and socio-economic analyses (e.g., Ho et al., 2013). These static models can predict a long-term traffic state for transportation planning and network design, but should only be used when traffic flow variation is small. To overcome this shortcoming, continuum static equilibrium models have been extended to continuum DTA models for pedestrian flow (e.g., Xia et al., 2008; Huang et al., 2009; Jiang et al., 2009) and urban road traffic flow (e.g., Hoogendoorn and Bovy, 2004; Jiang et al., 2011; Du et al., 2013, 2015; Wang and Du, 2016). However, to the best of our knowledge, continuum DTA models for taxi traffic flow has not been proposed in the literature.

The taxi route choice principle is a fundamental component of taxi traffic assignment models. It depicts how taxi drivers select their routes. The routing strategy of a taxi driver depends on taxi occupation status. If a taxi is occupied by customers, then the minimum cost path is usually assumed to be used (e.g., Yang and Wong, 1998; Yang et al., 2002; Wong et al., 2001, 2008). If not, the main principle used to depict the route choice of a vacant taxi driver varies from study to study, and includes minimizing the expected search time for customers (Hu et al., 2012), maximizing weighted expected profit minus search cost (Wong et al., 2003), maximizing profit per unit time (Yang et al., 2010), etc. However, all of these route choice principles ignore the fact that vacant taxi drivers can meet a customer on the way to their destination zones. To capture this intervening opportunity feature, Wong et al. (2015b) considered the sequential customer-search decisions of vacant taxi