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An intersection-movement-based stochastic dynamic user optimal route choice model for assessing network performance

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ABSTRACT

Different from traditional methods, this paper formulates the logit-based stochastic dynamic user optimal (SDUO) route choice problem as a fixed point (FP) problem in terms of intersection movement choice probabilities, which contain travelers' route information so that the realistic effects of physical queues can be captured in the formulation when a physical-queue traffic flow model is adopted, and that route enumeration and column generation heuristics can be avoided in the solution procedure when efficient path sets are used. The choice probability can be either destination specific or origin–destination specific, resulting into two formulations. To capture the effect of physical queues in these FP formulations, the link transmission model is modified for the network loading and travel time determination. The self-regulated averaging method (SRAM) was adopted to solve the FP formulations. Numerical examples were developed to illustrate the properties of the problem and the effectiveness of the solution method. The proposed models were further used to evaluate the effect of information quality and road network improvement on the network performance in terms of total system travel time (TSTT) and the cost of total vehicle emissions (CTVE). Numerical results show that providing better information quality, enhancing link outflow capacity, or constructing a new road can lead to poor network performance.

1. Introduction

Traffic congestion and emissions are major problems in Hong Kong and many other urban cities. These problems can be handled by appropriate transportation planning and traffic management, with the use of Dynamic Traffic Assignment (DTA) models.

DTA models can be developed by either the simulation-based approach (e.g., Yagar, 1971; Mahmassani, 2001; Florian et al., 2008; Tian and Chiu, 2014) or the analytical approach (see Peeta and Ziliaskopoulos (2001) and Jiang et al. (2011)

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for comprehensive reviews). The simulation approach focuses on enabling practical deployment of the DTA models for realistic highway networks, the applicability of the models in real-life highway networks, and the ability of the models to adequately capture traffic dynamics and microscopic driver behavior such as lane changing. However, the solution properties of the models, such as solution existence and uniqueness, are not guaranteed and cannot be determined in advance. The analytical approach often formulates DTA problems in terms of 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; Waller and Ziliaskopoulos, 2006b; Nie, 2011; Waller et al., 2013), optimal control problems (e.g., Friesz et al., 1989; Ran et al., 1993), variational inequality (VI) problems (e.g., Friesz et al., 1993; Ran and Boyce, 1996; Chen and Feng, 2000; Huang and Lam, 2002; Han, 2003), 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), differential complementarity systems (e.g., Ban et al., 2012), and differential VI problems (e.g., Friesz et al., 2001; Han et al., 2013c). Different from the simulation-based DTA models, the solution properties can be determined beforehand.

DTA models have two fundamental components: the travel choice principle and the traffic flow component (Szeto and Lo, 2006). The travel choice principle depicts travelers' propensity to travel, e.g., how they select their routes, departure times, modes, or destinations. Travel time is one important element in such choices. Commonly adopted travel choice principles include the dynamic user optimal (DUO) principle (e.g., Friesz et al., 1993, 2013; Ran and Boyce, 1996; Yang and Meng, 1998; Huang and Lam, 2002; Lo and Szeto, 2002a,b; Waller and Ziliaskopoulos, 2001, 2006a; Golani and Waller, 2004; Han, 2007; Ng and Waller, 2012; Ukkusuri et al., 2012; Iryo, 2013; Blumberg-Nitzani and Bar-Gera, 2014), the stochastic dynamic user optimal (SDUO) principle (e.g., Ran and Boyce, 1996; Chen and Feng, 2000; Han, 2003; Lim and Heydecker, 2005; Szeto et al., 2011), and the dynamic system optimal (DSO) principle (e.g., Merchant and Nemhauser, 1978a,b; Carey, 1987; Li et al., 1999; Carey and Subrahmanian, 2000; Ziliaskopoulos, 2000; Nie, 2011; Doan and Ukkusuri, 2012; Carey and Watling, 2012; Qian et al., 2012; Han et al., 2013a,b; Ma et al., 2014; Mesa-Arango and Ukkusuri, 2014; Shen and Zhang, 2014). The DUO/SDUO/DSO principle assumes that travelers select their routes and/or departure times to minimize their individual actual/perceived/marginal travel cost, such as travel time.

The traffic flow component depicts how traffic propagates inside a traffic network and hence governs the network performance in terms of travel time (see e.g., Szeto, 2008; Sumalee et al., 2011; Ngoduy, 2013; Zhang et al., 2013; Zhong et al., 2013; Zhu et al., 2013; Balijepalli et al., 2014; Chen et al., 2014; Chiabaut et al., 2014). This is sometimes referred to as a dynamic network loading (DNL) model. The existing approaches for developing DNL models can be broadly classified into two categories: non-physical queue models and physical queue models. Exit functions (e.g., Merchant and Nemhauser, 1978a,b; Carey, 1987, 1990; Carey and Srinivasan, 1993), link performance functions (e.g., Ran and Boyce, 1996; Chen and Hsueh, 1998; Ban et al., 2008), and the point queue models (e.g., Huang and Lam, 2002; Nie and Zhang, 2005) can be put under the first category. These models have a simpler calculation but fail to capture some fundamental traffic dynamics such as queue spillback. The second category includes advanced exit flow models which are developed based on either Daganzo's (1994, 1995) solution scheme (i.e., Cell Transmission Model (CTM)) or Newell's (1993) solution scheme to the Lighthill and Whitham (1955) and Richards (1956) (LWR) hydrodynamic model of traffic flow (see Kuwahara and Akamatsu, 2001; Lo and Szeto, 2002a,b for example). They can describe traffic dynamics on a road network, including shock waves and queue spillback over multiple links, and are popularly applied to calculate travel times for DTA models in the past decade (e.g., Kuwahara and Akamatsu, 2001; Lo and Szeto, 2002a,b; Szeto and Lo, 2004; Szeto et al., 2011). Recently, Yperman (2007) proposed the link transmission model (LTM) which can be considered as a combination of Daganzo's (1994, 1995) CTM with a triangular fundamental diagram and Newell's (1993) solution scheme. Since each whole link is treated as one cell, the LTM's computational efficiency is much higher than that of classic numerical solution schemes for the LWR model, while retaining the same accuracy when the true fundamental diagram is triangular.

The success of the resultant analytical DTA model in capturing the effect of queue spillback depends on not only the choice of traffic flow models but also the choice of decision variables used in the formulation. Traditionally, either link or path inflow variables are used in the model and the corresponding models are referred to as link-based models (e.g., Friesz et al., 1989; Ran and Boyce, 1996; Wie et al., 2002; Ban et al., 2008) and path-based models (e.g., Friesz et al., 1993; Chen and Feng, 2000; Huang and Lam, 2002; Lo and Szeto, 2002a,b; Szeto and Lo, 2004, 2006; Lim and Heydecker, 2005; Szeto et al., 2011; Meng and Khoo, 2012). Link-based models do not require having the path set information in advance, in which the path set can be large even for a medium-scale highway network. Hence, these models can avoid path enumeration and path set generation heuristic in the solution procedure and have the potential to be applied to large-scale highway networks. Link-based DTA models cannot, however, capture queue spillback since the link flow variables cannot model traffic at intersections.

In contrast, path-based models have important information, such as path inflows and the path set, to model traffic at diverges and merges. Path-based models can, therefore, track spillback queues when a realistic traffic flow or DNL model is used. Path-based models also have the advantage that stochastic assignment using logit-type models can be applied easily, ensuring much faster convergence to an equilibrium than a deterministic approach. Nevertheless, the main disadvantage of such models is that they require explicit enumeration of the path choice set, which can be very time consuming, even for medium networks. Hence, for large-scale network applications, path enumeration has not been used to obtain the path set. Instead, path-set generation (e.g., Bliemer et al., 2004) has been used in these applications, which have generated paths when needed. Also, unused paths can be deleted. However, this path set generation and deletion procedure is a heuristic and solution convergence may not be guaranteed. Some smarter ways of using route sets, such as the concept of subpaths, were