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An informed user equilibrium dynamic traffic assignment problem in a multiple origin-destination stochastic network

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ABSTRACT

We develop in this paper a comprehensive linear mathematical framework to study the benefit of real-time information and the impact of resulting user adaptive route choice behaviours on network performance. The framework formulates the information-based stochastic user equilibrium (ISUE) dynamic traffic assignment (DTA) problem for a multiple origin-destination (OD) network. Using the framework, we prove the linkage between the user equilibrium (UE) and system optimal (SO) solutions underpinned by the first-in-first-out (FIFO) principle. This important property then enables us to develop an incremental loading method to obtain the ISUE solutions efficiently by solving a sequence of linear programs. Moreover, the proposed method is more scalable that avoids a huge enumeration of paths in large-scale networks as done in path-based methods of the existing literature on this topic. We show via numerical examples the impact of information on both route choices and network performance, and demonstrate the significant improvements in the obtained ISUE solution both in terms of accuracy and computational complexity.

1. Introduction

Traditional dynamic traffic assignment problem assumes the deterministic network conditions, therefore travellers know exactly their travel cost in the user equilibrium solution. Herein, we study a more general problem where users only know the most recent update of the probabilistic traffic demand and network capacity before they enter the network. With the advancement of technologies, information becomes more accessible with improved quality and diversity (e.g. via sensors, phones and smart devices, or social networks, etc.). Increasingly, information is being used to enhance travellers' experience and to improve traffic flows in the transportation networks, for example, traffic condition can now be provided for road users to make informed routing decisions in real-time (Chorus et al., 2006). For this reason, the value of information and its impact on users' behaviour and network performance is a very important topic and has been researched intensively in the literature. In the following, we summarise the research papers that study the informed adaptive route choices in stochastic dynamic networks and motivate the development of a novel linear framework for the information-based stochastic user equilibrium (ISUE) in dynamic traffic assignment (DTA) problem.

Studying the impact of information services, such as the advanced traveller information systems (ATIS), on the system performance is usually based on the observation that the available information helps to reduce the uncertainty of the per-

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ceived travel cost for users equipped with ATIS. Hall (1996) studied this impact on different types of users and shown a simple two-route example that information cannot degrade network performance. He also suggested the use of ATIS to achieve the user equilibria instead of shaping the traffic toward system optimal point because users "certainly will not rely on sources that run counter to their own observations." Using a more advanced traffic model based on the cell transmission model, Lo and Szeto (2004) developed a complementary formulation for the stochastic UE route choice and compared the results between static and dynamic paradigms. Bifulco et al. (2016) focused on the stability of UE under ATIS in the day-to-day dynamics of the traffic network. The literature on this direction of research is extensive, for more details, see Chorus et al. (2006); De Palma et al. (2012); Huang et al. (2008); Lam et al. (2008).

Given an up-to-date information, travellers adapt their decision of route choices according to the current network state. Particularly, Polychronopoulos and Tsitsiklis (1996), then followed by those in Gao and Chabini (2006); Gao and Huang (2012); Gao (2012), introduced the concept of learning where users could eliminate infeasible realisations of link cost via the knowledge gained as they traversed the network. To investigate the network-level impact of information using DTA, Gao (2012) developed a fixed-point framework in which the information is the link travel time distribution inputting into their route choice model.

Similarly, with stochastic and flow dependent arc cost, Unnikrishnan and Waller (2009) assumed that users know the link travel costs but only when they arrive at the upstream node of these links, which enables them to choose the best next link before continuing their journey. Other studies by Kim et al. (2005); Xiao and Lo (2014); Dong et al. (2013) relied on the knowledge of road state transition (or link costs correlation) to reduce the uncertainty of travel time estimation in routing. In transit networks, Hamdouch et al. (2004, 2014) studied the strategic decisions aided by the link access probability due to incidents or supply capacity drop. Their problem was formulated in the form of variational inequalities to achieve the user equilibrium solutions.

Instead of studying the benefit of information to individual user route choice, Waller et al. (2013) modelled the system optimal (SO) path choice based on the historical (a priori) information from the network's perspective. In terms of route guidance, the works of Paz and Peeta (2009); Balakrishna et al. (2005); Peeta and Zhou (2002); Mahmassani (2001) steer the network towards SO solutions via information provision. In their work, they approached this problem by developing the rolling-horizon framework for updating real-time information and using fuzzy-logic approach for route choice.

In all the above works, the UE condition was programmed as a constraint in the mathematical formulation and solved by different methods such as variational inequality (VI) models (Han, 2003; Hamdouch et al., 2004), fixed-point models (Bifulco et al., 2016; Long et al., 2015; Gao and Huang, 2012) or non-linear complementarity problem (NCP) (Lo and Szeto, 2004). Due to the difficulty of solving these models, there have been a number of heuristic algorithms or approximated solution methods proposed, e.g., fixed-point algorithms, the method of successive averages (MSA), alternating direction method, projection method, etc. The performance of these iterative methods, e.g., their speed of convergence, partially depends on the chosen initial solutions and other parameter settings. A performance comparison among the existing methods can be found in Carey and Ge (2012).

In this paper, we consider the stochasticity in terms of traffic demand and network capacity (or supply) where their joint probabilistic distribution is assumed to be known in our modelling framework. In the literature, demand uncertainty has been studied from different perspectives, e.g., from statistically collected data to stochastic user route choices (Clark and Watling, 2005; Yang et al., 2018). It is well recognised that travel demand varies from day to day. As for the supply side, its variation or uncertainty might be caused by recurrent (e.g., road capacity and behavioural issues, see Bifulco et al., 2016; Ettema and Timmermans, 2006) or non-recurrent conditions (e.g., incidents, see Emmerink et al., 1995). Furthermore, Kim et al. (2013); Chung et al. (2005) showed that inclement weather events (e.g., heavy snow or rain) impact on both demand and supply. We hence model demand and supply as forming a joint probability distribution. Given this joint distribution, as information is collected and updated over time, travellers make route choices at their departure time as well as reroute while en route in order to minimise their expected travel cost.

In practice, however, this joint distribution can often be approximated as a product of the marginal distributions of the demand and supply assuming their independence. The individual marginal distribution can then be estimated based on the available information such as sensor data and measurements. There are several sources of such information ranging from mobile GPS, route guidance systems (e.g., Tomtom) to day-to-day data collected by road-side units (e.g., Bluetooth) etc., that would be useful in determining the O-D demand (Zhou and Mahmassani, 2007; Balakrishna et al., 2007) or network supply (Mahmassani et al., 2012; Qu et al., 2015). In the near future, with the introduction of autonomous vehicles (AVs) in the traffic streams, the advanced technology will enable a more accurate estimation of traffic demand (e.g., Duell et al., 2016) and that of network supply (e.g., Fakharian Qom et al., 2017).

Our approach departs from existing research in several ways. From the aspect of modelling user equilibrium route choice, the previous works developed the constrained-based models for UE conditions. In contrast, we propose in this paper an objective-based model for the information-based user equilibrium path choice in a stochastic dynamic network where the actual or predictive path travel time is considered. In Lin and Lo (2000), they showed an extension of Beckmann's formulation that is failed to represent UE solutions in a dynamic multiple OD network. It is because the separability of link cost functions without any interaction among them (in the original Beckmann's formulation) is not valid in the dynamic scenarios (i.e., DTA problem) due to the complexity of traffic propagation over both time and space. In our proposed framework, rather than using link costs, we introduce a concept of trips that captures the whole vehicle trajectory in both time and space, and thus enables the separation of path travel costs.