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Interactive travel choices and traffic forecast in a doubly dynamical system with user inertia and information provision

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ABSTRACT

This study models the joint evolution (over calendar time) of travelers' departure time and mode choices, and the resulting traffic dynamics in a bi-modal transportation system. Specifically, we consider that, when adjusting their departure time and mode choices, travelers can learn from their past travel experiences as well as the traffic forecasts offered by the smart transport information provider/agency. At the same time, the transport agency can learn from historical data in updating traffic forecast from day to day. In other words, this study explicitly models and analyzes the dynamic interactions between transport users and traffic information provider. Besides, the impact of user inertia is taken into account in modeling the traffic dynamics. When exploring the convergence of the proposed model to the dynamic bi-modal commuting equilibrium, we find that appropriate traffic forecast can help the system converge to the user equilibrium. It is also found that user inertia might slow down the convergence speed of the day-to-day evolution model. Extensive sensitivity analysis is conducted to account for the impacts of inaccurate parameters adopted by the transport agency.

1. Introduction

The within-day dynamic traffic patterns have been essentially characterized by the travelers' trip-timing choices and much has been modeled in the framework of the bottleneck model firstly proposed by Vickrey (1969). Later, Smith (1984) and Daganzo (1985) respectively established the existence and uniqueness of the user equilibrium solution in the presence of a single bottleneck, and Arnott et al. (1990) analyzed the departure/arrival equilibrium with piece-wise linear schedule delay cost functions. The original bottleneck model has been extended in a broad range of directions to incorporate exogenous factors such as user heterogeneity, demand and capacity uncertainty, and carpooling (Arnott et al., 1994; Xiao et al., 2013, 2016), congestion and/or parking pricing (Laih, 1994), or to cater for traffic complications such as hyper-congestion and capacity drop (Liu and Geroliminis, 2016; Liu et al., 2015) (one may refer to Small, 2015 for a recent review). In particular, the bottleneck model has been embedded into the bi-modal transportation system to simultaneously model travelers' mode-shifting and trip-timing choices. In this context, various regulatory issues have been considered, including road pricing (Tabuchi, 1993; Wu and Huang, 2014), parking space limitation (Yang et al., 2013; Liu et al., 2014), and preventing the counterproductive Downs-Thomson Paradox (Wang et al., 2017).

The day-to-day traffic dynamics, however, refer to the system variations that occur between successive reference periods, which can be either the whole day or one part of a day, e.g., the morning peak period (Cascetta and Cantarella, 1991). The literature has

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established evidences for traffic variations from day to day, for example, Guo and Liu (2011). This raises the interest to model the day-to-day traffic evolution dynamics in the transportation systems. As summarized by Yang and Zhang (2009), the five major dynamical systems to formulate the day-to-day traffic dynamics are the proportional swap system, the network tatonnement process, the simplex gravity flow dynamics, the projected dynamical system, and the evolutionary traffic dynamics. As mentioned in Guo and Huang (2016), the day-to-day models have been considered in the context of Wardrop user equilibrium, Logit-based stochastic user equilibrium, or boundedly rational user equilibrium. The day-to-day dynamical system can capture the evolution process of traffic dynamics, and thus can help observe and uncover features not available in stationary models. Many studies also proposed strategies to accommodate the day-to-day traffic dynamics and thus improve system traffic efficiency (Sandholm, 2002; Smith and Mounce, 2011; Guo et al., 2015; Tan et al., 2015; Ye et al., 2015; Xu et al., 2016).

Some researchers have integrated the bottleneck model into the day-to-day framework, and developed a so-called doubly dynamical system (Ben-Akiva et al., 1984, 1986; Iryo, 2008; Wu, 2009; Guo et al., 2017a). The doubly dynamical system can describe the day-to-day evolution of the within-day dynamic traffic patterns. However, little has been said about the convergence of the evolution process to the dynamic user equilibrium. Recently, the non-convergence of the proportional swap system when it is applied to a bottleneck model based doubly dynamical system was shown by both Iryo (2008) and Guo et al. (2017a). Their analyses, while providing interesting insights, fail to capture several important aspects of a real transportation system including, but not limited to, how information provision or traffic forecast can affect users' travel behavior and the system dynamics; how the potentially existing user inertia might play a role in traffic evolution; and more importantly, how the multi-modality could influence users' choices and the system dynamics. While the existing studies on the day-to-day dynamical systems (include those for the doubly dynamical systems) often focus on an isolated highway system, the mode-shifting dynamics have received very little attention except from Cantarella et al. (2015), Li and Yang (2016) and Liu and Geroliminis (2017), in which the trip-timing decision is, however, not considered.

This study aims to fill these research gaps by considering a multi-modal transport system where the travelers adjust their choices of both departure time and travel mode from day to day. Particularly, we have modeled and analyzed how information provision/traffic forecast (from transport agency) and user inertia could affect travelers' choice in a day-to-day context. Note that advanced traveler information systems were considered by Huang et al. (2008) in a day-to-day context, where the main focus washow pre-trip information could help reduce the drivers' travel time uncertainty. Differently, in this paper in order to characterize the impact of traffic forecast on travel behavior, a more general learning process has been proposed with respect to that in Bie and Lo (2010) and Watling (1999). In such a process, the forecast travel costs provided by a transport agency are referred to in the travelers' perception updating. Furthermore, a proportional-swap-based dynamical system is developed to describe the day-to-day flow adjustment. Besides, user inertia is captured by imposing constraints on the proportional-swap system, under which users can only change their departure time within a certain amount of time between any two consecutive days. The convergence of the dynamical system described in the above towards the bi-modal dynamic user equilibrium has been explored and compared with the observations in Iryo (2008) and Guo et al. (2017a).

As mentioned in the above, user inertia is considered in the decision process for the travelers. In the context of social and behavioral sciences, inertia is generally regarded as the endurance of stable relationships or reluctance in adjustment of status quo. "Absent other forces, inertia describes the tendency to remain with the status quo and the resistance to strategic renewal outside the frame of current strategy" (Huff et al., 1992). Recent studies have looked into the user inertia in route choices of travelers (Zhang and Yang, 2015), where travelers' route sets might be smaller than the set of all possible routes. This paper considers a similar concept that travelers departing at a time point may only shift to a departure time that belongs to a subset of all feasible departure times in the next day. The user inertia is related to user bounded rationality (Zhang and Yang, 2015), where bounded rationality refers to that when making decisions, individual's rationality is limited due to many factors. However, the modeling of user inertia in this paper is different from the boundedly rational user equilibrium considered in the literature (Di et al., 2013). In those papers, travelers' choices are bounded rational for that some indifference bands exist between the costs of their own choice and the shortest route. However, travelers' choices are not limited to a subset that is specified in the first place (or predetermined), which is the key difference from the inertia model. In summary, user inertia and bounded rationality are inter-correlated but not equivalent. A route choice model trying to incorporate different behavior assumptions is presented in Xu et al. (2017).

Furthermore, the traffic forecast of the transport agency is based on an auxiliary day-to-day learning model and a traffic simulator with the observed data being the input and the cost estimates for travelers being the output. This learning model coupled with a simulator are developed to mimic how transport agency learns from historical data and generates traffic forecast. Properties of such a learning model are also analyzed and discussed. Impacts of adopting inaccurate parameters for the transport agency have been examined numerically. Note that the learning and simulating framework developed in this paper might be further integrated into a detailed simulation for large-scale networks in the future (such as that in Hu and Mahmassani, 1997).

The rest of the paper is organized as follows. Section 2 describes the bi-modal commuting problem, provides cost formulations for travelers, and revisits the bi-modal user equilibrium. In Section 3, the day-to-day learning behaviors of the travelers and the traffic information agency are modeled and illustrated. Section 4 numerically illustrates the dynamic traffic evolution and verifies the applicability of the proposed model. Particularly, impacts of traffic forecast and user inertia are examined and a sensitivity analysis regarding a number of key parameters in the paper is conducted. Finally, Section 5 concludes the paper.

2. Formulation for user equilibrium

We start with a thumbnail description of the rush-hour commuting problem with both departure time and travel mode choices,