Transportation Research Part C 91 (2018) 77–98

Contents lists available at ScienceDirect

Transportation Research Part C

journal homepage: www.elsevier.com/locate/trc

Traffic dynamics in a bi-modal transportation network with information provision and adaptive transit services

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ARTICLE INFO

Keywords:
Day-to-day
Predicted travel cost
Stability
Adaptive transit service
Transit profit

ABSTRACT

This paper has two major components. The first one is the day-to-day evolution of travelers' mode and route choices in a bi-modal transportation system where traffic information (predicted travel cost) is available to travelers. The second one is a public transit operator adjusting or adapting its service over time (from period to period) based on observed system conditions. Particularly, we consider that on each day both travelers' past travel experiences and the predicted travel cost (based on information provision) can affect travelers' perceptions of different modes and routes, and thus affect their mode choice and/or route choice accordingly. This evolution process from day to day is formulated by a discrete dynamical model. The properties of such a dynamical model are then analyzed, including the existence, uniqueness and stability of the fixed point. Most importantly, we show that the predicted travel cost based on information provision may help stabilize the dynamical system even if it is not fully accurate. Given the day-to-day traffic evolution, we then model an adaptive transit operator who can adjust frequency and fare for public transit from period to period (each period contains a certain number of days). The adaptive frequency and fare in one period are determined from the realized transit demands and transit profits of the previous periods, which is to achieve a (locally) maximum transit profit. The day-to-day and period-to-period models and their properties are also illustrated by numerical experiments.

1. Introduction

Traditional steady-state equilibrium paradigm has been providing theoretical basis for the transport planners and operators during the past few decades. However, steady-state analysis, while insightful, ignores user behavior and traffic adjustment process. In practice, traffic networks are not always in steady-state. Travelers can adjust their mode choice and/or route choice from time to time. This raises the interest to study the traffic dynamics and evolution in the transportation systems. There are two major categories of approaches to model transportation system dynamics. One is the within-day dynamics (e.g. Friesz et al., 1993; Lam and Huang, 1995; Ran et al., 1996), which is alternatively termed as the dynamic traffic assignment (DTA) and assumes that the system is unchanging over days but evolving over clock time. The other one is the day-to-day dynamical approach with between-day traffic variations. Pertaining to the current study, there is a large pool of studies focusing on the day-to-day evolution process, e.g., Smith

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https://doi.org/10.1016/j.trc.2018.03.026
Received 12 April 2017; Received in revised form 28 March 2018; Accepted 28 March 2018
0968-090X/

(1984); Horowitz (1984); Friesz et al. (1994); Cantarella and Cascetta (1995); Zhang and Nagurney (1996); Watling (1999); Watling and Hazelton (2003); Yang and Zhang (2009); Bie and Lo (2010); He and Liu (2012); Guo et al., (2013); Guo et al., (2015); Smith and Watling (2016). A few studies are carried out on the bi-modal commuting problem with day to day traffic variation, e.g. Cantarella et al. (2015); Li and Yang (2016). However, these bi-modal researches usually consider an isolated single Origin-Destination (OD) pair network without route choice for analytical tractability.[1]

The development of information and communication technologies and the widespread use of navigation services now provide advanced platforms for travelers to access traffic information and predicted/forecast conditions. These information services might affect travelers' behavior and decision significantly, which could further complicate the dynamical evolution of traffic and user choices in multi-modal transportation systems. Some laboratory experiments and statistical analysis are conducted (e.g., Ben-Elia et al., 2013; Tanaka et al., 2014; Tsirimpa et al., 2007) to explore the ability of information services to influence travelers' behavior. However, only a few researches are focused on the theoretical explanation of the properties of the day-to-day network traffic evolution under information provision. Xiao and Lo (2016) recently examined how information sharing through the social network would affect travelers' day to day choices of departure time. Bifulco et al. (2016) indicated that, accurate information is able to stabilize systems that maybe otherwise unstable. More recently, Liu and Geroliminis (2017) proposed a new model for traveler learning, where the perceived travel cost is not only dependent on previous perceived and experienced travel cost, but also relying on real-time traffic conditions. They numerically indicated that the real-time information can help stabilize the dynamical system even though it does not fully capture the experienced conditions during the whole journey.

This paper develops a general deterministic dynamical model to study how information provision might affect the multi-modal systems' user learning and traffic dynamics. Both mode and route choices are considered and impact of information inaccuracy is theoretically explored. Different from a bunch of studies adopting the exponential smoothing approach to model both user cost and choice updating process (e.g., Cantarella and Cascetta, 1995; Watling, 1999; Bie and Lo, 2010), we intend to capture the impact of the predicted travel cost (based on information provision) on travelers' behavior. The issues regarding existence, uniqueness, stability and convergence of the equilibrium state are analyzed. Several theoretical results about the impact of information provision on the stability of the dynamical system are presented. We notice that our study exhibits some similarities with Bifulco et al. (2016) in the sense that we both consider impacts of information provision. However, this paper is fundamentally different from Bifulco et al. (2016) as the modeling of user behavior and learning are completely different. We consider that the travelers can learn from their experiences and information provision simultaneously. However, Bifulco et al. (2016) assumes two extreme cases: travelers either fully rely on information or fully rely on own expectation. Moreover, this paper explores and analyzes the theoretical properties of the dynamical process under non-fully accurate information.

Besides modeling the day to day traffic dynamics in the bi-modal general network, we examine an adaptive transit operator, who may make adjustments on the transit frequency and fare from period to period to achieve its target. As mentioned earlier, Cantarella et al. (2015) and Li and Yang (2016) conducted some relevant analyses of day-to-day mode choice with responsive transit service frequency. However, neither of these two studies takes account of responsive transit fare. Also, they are based on simplified networks. There is a branch of studies looking into transit frequency and fare for public transportation under steady-state, e.g., Mohring (1972), Nash (1978), Jansson (1980), Jara-Díaz and Gschwender (2003), Pedersen (2003). However, most studies are restricted to the service supply side and do not consider the interaction between fare, frequency and transit demand. Differently, our approach is dynamic and adaptive, given that traffic also evolves over time. Specifically, we consider that the transit operator can update their operation strategy regularly (from period to period, and each period contains a certain number of days). Also, we explore how the transit operator may take advantage of the system states observed (such as transit demand fluctuations in the system), and thus can adjust its frequency and fare accordingly. This adaptive strategy can help drive the bi-modal system to the state with the (locally) maximum transit profit.

The rest of the paper is organized as follows. Section 2 introduces the dynamical system of the bi-modal transportation network with given transit frequency and fare. The existence, uniqueness and stability of the fixed point are analyzed. Inter-period frequency and fare adjustment of an adaptive transit operator is then formulated and analyzed in Section 3. Section 4 further numerically illustrate the properties of the intra-period dynamical model and the implementation of the inter-period responsive transit strategy. Section 5 concludes the paper.

Before moving further, we list the main notations in Table 1.

2. Intra-period day to day dynamical model with given transit frequency and fare

Consider a general network with two modes (the public transit and private car) to provide transportation services from origins to destinations. "Mode 1" represents the public transit and "Mode 2" represents the private car mode. On a typical day, a certain number of travelers have to choose between driving and taking public transit based on the perceived travel cost of each option. We assume that the total number of travelers for each origin–destination (OD) pair d_i is fixed every day.

For the transit side, we further assume that each OD pair is connected by an exclusive transit line and the transit capacity is virtually unlimited. Therefore, the transit line has no direct flow interaction with the car traffic, and the in-vehicle transit travel time

[1] For the bi-modal problem, there is indeed a substantial literature with either dynamic or static traffic models, e.g., Small (1992); Arnott and Yan (2000); Kraus (2003); Small and Verhoef (2007); Ahn (2009); Yang et al. (2013); Zhang et al. (2014, 2016); Liu et al. (2016); Chen et al. (2017). Yet, these studies generally evaluate the distribution of traffic flows among each mode in static state and travelers' day-to-day mode variation is not considered.