Day-to-day modal choice with a Pareto improvement or zero-sum revenue scheme

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ABSTRACT

We investigate the day-to-day modal choice of commuters in a bi-modal transportation system comprising both private transport and public transit. On each day, commuters adjust their modal choice, based on the previous day's perceived travel cost and intraday toll or subsidy of each mode, to minimize their perceived travel cost. Meanwhile, the transportation authority sets the number of bus runs and the tolls or subsidies of two modes on each day, based on the previous day's modal choice of commuters, to simultaneously reduce the daily total actual travel cost of the transportation system and achieve a Pareto improvement or zero-sum revenue target at a stationary state. The evolution process of the modal choice of commuters, associated with the strategy adjustment process of the authority, is formulated as a dynamical system model. We analyze several properties of the dynamical system with respect to its stationary point and evolutionary trajectory. Moreover, we introduce new concepts of Pareto improvement and zero-sum revenue in a day-to-day dynamic setting and propose the two targets' implementations in either a prior or a posterior form. We show that, although commuters have different perceived travel costs for using the same travel mode, the authority need not know the probability distribution of perceived travel costs of commuters to achieve the Pareto improvement target. Finally, we give a set of numerical examples to show the properties of the model and the implementation of the toll or subsidy schemes.

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1. Introduction

In most cities around the world, multiple transport modes exist to provide substitutable transportation services for people, e.g., people can choose either private cars or public transit to travel from an origin to a destination. Thus, there is a problem, i.e., how to plan and manage a congested transport system with multiple modes so as to improve its system performance, which can be evaluated by travel time, transport safety, fuel consumption, environmental pollution, and so on. This paper considers a bi-modal transportation system comprising both private transport and public transit, in which travelers adjust their individual travel mode choice from day to day. This study is important because it gives new insights into the management of a transport system with multiple modes from the dynamic and evolutionary viewpoint.

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Existing studies on the multi-modal problem extend mainly along two lines. Along the first line, researchers follow with interest the distribution of traffic flows among travel modes at a static state, i.e., which mode travelers choose (e.g., Cantarella, 1997; Arnott and Yan, 2000; Ahn, 2009; Li et al., 2012; Tirachini and Hensher, 2012; David and Foucart, 2014; Zhang et al., 2014). The distribution of flows among travel modes is generally evaluated under static user equilibrium (UE) or system optimum (SO). Along the other line, researchers focus on not only the distribution of traffic flows among travel modes but also the within-day dynamics of traffic flows, i.e., how and when people travel (e.g., Huang, 2000, 2002; Kraus, 2003; Huang et al., 2007; Gonzales and Daganzo, 2012; van der Weijde et al., 2013; van den Berg and Verhoef, 2014; Wu and Huang, 2014; Gonzales, 2015; Tian and Huang, 2015; Liu et al., 2016). The distribution of flows along the temporal dimension and among travel modes is generally evaluated under dynamic UE or SO. The within-day dynamics of traffic flows is generally formulated by the bottleneck model proposed by Vickrey (1969).

The above two categories of studies only show an end result rather than the choice adjustment process of traffic states. It is well known that, in realistic traffic systems, commuters adjust their travel modes or routes from day to day with their experiences or information provided by an advanced traffic information system (ATIS), and the resultant traffic flows evolve over days before reaching an equilibrium state. On one hand, the exploration of the day-to-day dynamics is useful for better understanding various processes of forming traffic jam and better using an ATIS from either a theoretical or practical standpoint. On the other hand, the exploration of the day-to-day dynamics opens up another avenue for improving total travelers' utility (e.g., decreasing traffic congestion or total travel cost) in traffic systems.

So far, there are a number of studies focusing on the day-to-day evolution of traffic flows in a single-modal system, e.g., Smith (1984), Friesz et al. (1994), Cantarella and Cascetta (1995), Zhang and Nagurney (1996), Watling (1999), Yang and Zhang (2009), He et al. (2010), Smith and Mounce (2011), He and Liu (2012), Cantarella and Watling (2016), He and Peeta (2016), Hazelton and Parry (2016), Rambha and Boyles (2016), Wang et al. (2016), Wei et al. (2016), Xiao and Lo (2016), Xiao et al. (2016), Guo et al. (2017), and Han et al. (2017). Readers may refer to Watling and Cantarella (2013, 2015) for a comprehensive review of the day-to-day dynamics of traffic flows. Recently, Cantarella et al. (2015), Li and Yang (2016), Liu and Geroliminis (2017), and Liu et al. (2017) concerned the day-to-day dynamics of traffic assignment in bi-modal or multi-modal transport systems.

In this paper, we also focus on the day-to-day modal choice of commuters in a transportation system comprising both private transport and public transit. Despite that Cantarella (1997), Cantarella et al. (2015), Li and Yang (2016), Liu and Geroliminis (2017), Liu et al. (2017), and our study all focus on the subject of bi-modal or multi-modal choice, the specific issues involved in these works are essentially different. Cantarella (1997) proposed a fixed-point formulation of multi-mode equilibrium assignment with elastic demand and analyzed the properties of the equilibrium, which can be considered to be the stationary state of a day-to-day dynamical system. They further established the theoretical conditions of the existence and uniqueness of equilibrium for stationary multi-mode systems. Cantarella et al. (2015) proposed a dynamical system of formulating the joint adjustment of modal choice and transit operation from day to day in a bi-modal transport system. In the system, the frequency of bus runs is prefixed to meet the demand with all the buses available or is daily updated to meet the demand with the minimum number of buses needed to avoid oversaturation. They also showed the non-uniqueness of equilibrium by a numerical example. Li and Yang (2016) proposed a dynamical system model of formulating travelers' day-to-day modal choice in a bi-modal transportation system with responsive transit services. In their model, the frequency of bus runs is adjusted from period to period so that a given target profit of the transit operator is achieved at a stationary state. Liu and Geroliminis (2017) modeled and controlled a multi-region and multi-modal transportation system, in which the travelers adjust their mode choices from day to day and also the within-day traffic dynamics evolve over days. They developed an adaptive mechanism to update parking pricing from period to period so as to improve the system's efficiency. Liu et al. (2017) modeled the joint evolution of travelers' departure time and mode choices in a bi-modal transportation system by considering the impact of user inertia. They also analyzed the dynamic interactions between transport users and the traffic information provider.

Different from Cantarella (1997), Cantarella et al. (2015), Li and Yang (2016), Liu and Geroliminis (2017), and Liu et al. (2017), we concern the issue of Pareto improvement or zero-sum revenue associated with day-to-day modal choice, introduce new concepts of Pareto improvement and zero-sum revenue in a day-to-day dynamic setting, and propose the two targets' implementations in either a prior or a posterior form. We propose a control scheme implemented from the government's standpoint. The transportation authority adjusts not only the number of bus runs but also the tolls/subsidies of both car and bus users from day to day so as to simultaneously reduce the daily total actual travel cost of the transportation system and achieve either a Pareto improvement or zero-sum revenue target. In this way, both society and individual commuters become better off under the implementation of the scheme.

The tolls or subsidies herein imply that all commuters using a travel mode may be charged on some days and may be subsidized on other days. The utilities of some commuters may decrease under the implementation of the control (and redistribution) scheme. With proper subsidies to them, their utility losses can be compensated.

The Pareto improvement refers to that the net travel cost of each commuter is reduced under the implementation of the control scheme, compared with the initial state, i.e., each commuter becomes better off. Such a Pareto-improvement can make the control scheme as a policy more acceptable to commuters because everyone is a winner under such a policy (Guo and Yang, 2010). Some researchers, e.g., Daganzo (1995), Eliasson (2001), Song et al. (2009), Guo and Yang (2010), and Lawphongpanich and Yin (2010), proposed their toll or subsidy schemes (or pricing and revenue refund schemes) implemented at the steady state to realize a Pareto-improvement target. Different from these toll or subsidy schemes, our toll