Transportation Research Part C 68 (2016) 333–349

Contents lists available at ScienceDirect

Transportation Research Part C

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

Dynamics of modal choice of heterogeneous travelers with responsive transit services

Xinwei Li *, Hai Yang

Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong, PR China

ARTICLE INFO

Article history:
Received 9 January 2016
Received in revised form 18 April 2016
Accepted 18 April 2016

Keywords:
Dynamic modal choice
Responsive transit strategy
Equilibrium
Stability
Profit

ABSTRACT

In this paper, we investigate travelers' day-to-day modal choice in a bi-modal transportation system with responsive transit services under various economic objectives. A group of travelers with heterogeneous preferences adjust their modal choice each day based on their perceived travel cost of each mode, aiming to minimize their travel cost. Meanwhile, the transit operator sets frequency each period according to the realized transit demand and previous frequency, trying to achieve different profit targets. For a given profit target, the fixed point of equilibrium may not be unique. We establish the condition for existence of multiple fixed points and examine the stability of the fixed points in each case. Furthermore, in view of a socially desirable mode choice, we also investigate the impacts of total travel demand and bus size on the convergence of the system to various fixed points associated with different targeted mode split. Finally, we use several numerical examples to illustrate the theoretical results and their practical implications for the transit operator to design appropriate transit schemes in a dynamic transportation environment.

1. Introduction

A large pool of literature relies on the steady-state equilibrium paradigm to provide theoretical basis for the transport planners through the deterministic user equilibrium (DUE) or stochastic user equilibrium (SUE) approach. However, the steady-state analysis is limited for it only shows an end result rather than the choice adjustment process. The dynamic transportation approach can characterize the evolution of traffic states over time and its value of modeling the traffic system is well acknowledged. There are two major categories of dynamic approaches. One is within-day dynamic (e.g. Friesz et al., 1993; Lam and Huang, 1995; Ran et al., 1996), which focuses on dynamic traffic assignment (DTA) research and assumes the system is unchanging over days. The other one is day-to-day dynamics approach with dynamics between-day scale and constant within-day scale. Day-to-day dynamics approach can date back to the works of Horowitz (1984), Smith (1984) and Cascetta (1987, 1989); the present paper also lies in this research area.

A bi-modal system is often as an example to analyze the interaction between private cars and public transits in the literature. For instance, Arnott and Yan (2000) and Kraus (2003) indicated the underpricing of auto travel is a source of market distortion and a resource waste in transportation system with private and public transport modes. Li et al. (2012) investigated the intermodal equilibrium with two alternative modes. David and Foucart (2014) provided a game-theoretical model

* Corresponding author.
E-mail address: xliaz@ust.hk (X. Li).

http://dx.doi.org/10.1016/j.trc.2016.04.014

in which travelers have heterogeneous preferences choose rationally between using the car or public transportation. Zhang et al. (2014) studied the conditions for occurrence of the Downs-Thomson Paradox under different economic objectives.

However, these studies are concerned with a steady state analysis; neither travelers' day-to-day mode choice nor transit operator's periodic operating strategy are considered. It is known that more (fewer) transit passengers lead to more (less) frequent service, which leads to even more (fewer) passengers. This so-called "Mohring effect", named for the well-known economist Herbert Mohring, can be better analyzed in a dynamic environment. A few recent studies are carried out on the dynamic bi-modal problem in the literature. Cantarella et al. (2013) conducted an analysis of day-to-day dynamic mode choice in a transportation system with homogeneous travelers; bus operating strategies are demand-responsive but with a fixed fleet size. Bar-Yosef et al. (2013) examined the phenomena of a vicious cycle of a bus service line; nevertheless, mode choice of non-captive travelers is based only on the willingness-to-wait for the bus rather than the total trip cost. Besides, neither of the two studies take account of the operation cost and specific transit operating schemes. Three recent dynamic modeling approaches are relevant but purely in the context of congestion pricing. Tan et al. (2015) proposed a discrete-time tolled scheme by using the implicit Runge–Kutta method with heterogeneous users and investigated the equilibrium properties of the dynamic system. Farokhi and Johansson (2015) considered a piecewise-constant congestion taxing policy for repeated routing games of fixed demand. Ye et al. (2015) investigated the convergence of the trial-and-error tolling procedure for achieving system optimum with day-to-day flow dynamics when the observed link flow pattern is in disequilibrium. In the latter two studies, the link toll is constant in each period and calculated based on marginal cost pricing with the flow observed at the beginning of the tolling period. In the same spirit, we assume that the transit operator adjusts the transit frequency from period to period and keeps the frequency unchanged throughout each period. Transit frequency is reset at the beginning of each period based on the realized transit demand at the end of the previous period.

This paper is intended to fill a gap in the literature of bi-modal problems by examining the double dynamics of heterogeneous travelers' day-to-day modal choice and transit operator's periodic operating policy. Transit operator adjusts service frequency to drive the dynamic system towards a desired equilibrium while achieving a profit target. For various combinations of economic objectives and operating schemes, the interactions between travelers and transit operator are investigated in a dynamic environment. Existence, uniqueness and stability of the equilibrium fixed point of the double dynamic system are established. Particularly, occurrence of the vicious cycle considered by Bar-Yosef et al. (2013) is analyzed under different levels of travel demand and bus capacity.

The rest of the paper is organized as follows. Section 2 introduces the bi-modal transportation system with heterogeneous travelers. Section 3 analyzes the bi-modal system in a period with given transit frequency, and shows the existence, uniqueness and stability of user equilibrium. Inter-period dynamic frequency adjustment of a responsive transit operator is considered under different economic objectives in Section 4. The impacts of travel demand and bus capacity on the system performance and the occurrence of the vicious cycle are examined in Section 5. Section 5 provides a numerical example and Section 6 draws the conclusions and highlights avenue for future research.

2. Model formulation

We consider one origin–destination (OD) pair connected by a congested highway running in parallel to an exclusive transit line. On a typical day, the total travel demand for this OD pair is fixed at d. Travelers have to make a discrete choice between using a private transport (auto) and public transit (bus). For simplicity, the occupancy of each private car is assumed to be 1. Travelers are heterogeneous as they have different intrinsic preferences for the use of private transport relative to public transit. The share of auto users is represented by z, then the share of public transport users is $1 - z$.

Transit users have to pay for the transit fare, spend time in waiting and riding. Following the model in David and Foucart (2014), the travel cost of commuters by each mode consists of the travel time cost and the monetary cost and the disutility of a traveler i is specified as follows:

$$p_i^t = w(f) + \tau + \frac{\varepsilon_i}{2}$$

and

$$p_i^c = t(z) - \frac{\varepsilon_i}{2},$$

where p_i^t stands for public transit cost and p_i^c for private car cost, f and τ denote the transit frequency and uniform ticket price (transit fare), respectively. The function $w(f)$ represents the travel time cost of public transport as a function of service frequency. It is assumed to be strictly decreasing and differentiable with respect to transit frequency f, i.e., $w' = w'(f) < 0$. The function $t(z)$ represents the travel cost of private car, including both travel time cost and monetary cost, it is assumed to be strictly increasing and differentiable with respect to auto share z, i.e., $t' = t'(z) > 0$ and $t(0) > 0$ at free flow. We also assume that w' is bounded for all $f > 0$ and t' is bounded for any $z \in [0, 1]$.

The commuter-specific parameter, ε_i, reflects individual preference between private car and public transit, it is continuously distributed with a cumulative distribution function $\varepsilon \sim G(\varepsilon)$, where G is assumed to be strictly increasing, continuous and differentiable over its support $(-\infty, +\infty)$. The support implies that some individuals prefer the private transport so