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Evaluation of exclusive bus lanes in a tri-modal road network incorporating carpooling behavior

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ABSTRACT

This paper considers the evaluation of exclusive bus lanes (EBLs) in the road network with three travel modes: bus, solo driving, and carpooling. A tri-modal transportation network equilibrium model is developed to analyze the effects of EBLs under three different policies: (i) no EBLs (called Policy 1); (ii) EBLs can only be used by bus (called Policy 2); and (iii) EBLs can be used by both bus and carpooling modes (called Policy 3). By taking into account both EBLs setting scheme and bus frequencies, a combinatorial optimization model is proposed to test the performance of the tri-modal transportation system. In a traffic corridor case with single O-D pair, numerical results show that travel demand levels will remarkably influence the total system costs under different policies. The effects of average carpooling occupancy and mode choice parameters on travelers' choice behavior are analyzed. Finally, a tri-modal network with nineteen links is used to illustrate that the system could be more efficient when different EBLs policies are adopted on different links.

1. Introduction

Traffic congestion is becoming more and more ubiquitous in metropolitan areas all over the world due to the ever-increasing car ownerships. Therefore, besides traditional public transportation, new travel modes and traffic management methods have been developed to alleviate the urban congestion. Among them, exclusive bus lanes (EBLs) and carpooling are two common and effective methods. High occupancy vehicle (HOV) lane, which is usually used in freeways in the United States to encourage travelers to choose carpooling instead of solo driving, has also been attempted in the urban area of Shenzhen City in China recently ("Congested Chinese city to open carpool lane," 2016). Some cities share HOV and EBLs in one lane, such as Interstate 5 in Seattle, and route 116 in Lévis, Quebec ("High-occupancy vehicle lane," 2017). It is clear that re-assignment of road resources has become a major control measure/policy to increase the share of bus and carpooling modes to reduce traffic congestion.

EBLs is a topic that has been discussed by many researchers (Shalaby, 1999; Viegas and Lu, 2004; Eichler and Daganzo, 2006; Abdelghany et al., 2007; Arasan and Vedagiri, 2008, 2009; 2010; Vedagiri and Arasan, 2009; Li and Ju, 2009; Chen et al., 2010; Zhu, 2010; Basso et al., 2011; McDonnell and Zellner, 2011; Yao et al., 2012, 2015; Yu et al., 2015; Wu et al., 2017) in the past two decades. Most of them did not consider modal split and route choice qualitatively or only considered two modes of bus and car in their mathematical models. Besides, as another major way to improve the efficiency of urban transportation, carpooling behavior is firstly considered as the way of saving fuel and reducing operating cost (Ronald et al., 1974; Kocur and Hendrickson, 1983; Bento et al., 2013), and then as the way of relieving traffic congestion (Yang and Huang, 1999; Huang et al., 2000; Li et al., 2007; Konishi and Mun, 2010; Agatz et al., 2011, 2012; Burris et al., 2014; Xu et al., 2015a; b; Stiglic et al., 2016) and reducing vehicle emissions (Erdoğan et al., 2015). There are some qualitative (Horowitz, 1976; Tischer and Dobson, 1979; Wang, 2011) and quantitative researches (Habib et al., 2011; Qian and Zhang, 2011; Vanoutrive et al., 2012; Neoh et al., 2017) incorporating bus transit, solo driving and carpooling modes. However, they have not considered EBLs setting and carpooling behavior simultaneously.

Relatively little attention has been paid to the evaluation of EBLs implementation policies in a road network with three travel modes: bus, solo driving, and carpooling. To fill up the gap mentioned above, this paper aims to address the following questions: (a) How to formulate a network equilibrium model incorporating both EBLs and carpooling behavior? (b) How to test and optimize the performance of transportation system under the tri-modal equilibrium model? (c) What is the best implementation policy of EBLs in a tri-modal road network? (d) What are the impacts of travel demand, choice behavior, and other factors on the share and cost of each travel mode?

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Thus, in this paper, a tri-modal transportation network equilibrium model with EBLs is established. Two numerical cases are carried out by the proposed model to analyze the system performances under different policies: (i) no EBLs (called Policy 1); (ii) EBLs can only be used by bus (called Policy 2); and (iii) EBLs can be used by both bus and carpooling modes (called Policy 3).

The remainder of the paper is organized as follows. In Section 2, the tri-modal transportation network equilibrium model incorporating both carpooling behavior and EBLs setting schemes is established. Section 3 elaborates the evaluation methodology of EBLs based on the model proposed in Section 2. Based on the proposed model, in Section 4, how travel demand and choice preference affect optimal policies, share and cost of each travel mode are analyzed in a traffic corridor example. The sensitivities of average carpooling occupancy, and choice behavior parameters are also analyzed. Further, how the combinational usage of multiple policies in different links affects the overall system efficiency is discussed in Section 4. Finally, general conclusions and future studies are summarized in Section 5.

2. Tri-modal transportation network equilibrium analysis incorporating carpooling behavior and EBLs setting schemes

2.1. Tri-modal transportation network introduction

When choosing between bus, solo driving and carpooling, travelers' final decision is correlated with general travel costs. The general travel costs of solo driving include travel time, fuel cost, congestion toll, parking toll and etc. Carpoolers share fuel cost, congestion toll and parking toll, but they have extra costs in coordinating travelling schedules, origins and destinations. The extra costs are referred to carpooling coordination cost. The general travel costs for bus passengers include walking cost, transferring cost, in-vehicle travel cost and in-vehicle congestion cost. For no EBLs case, all vehicles run simultaneously in the road. When setting EBLs, bus can use EBLs independently or use EBLs with carpooling vehicles simultaneously.

Considering the road transportation network (V, A), V and A denote the node set and the link set respectively. $rs \in RS \subset V \times V$ denotes the origin-destination (O-D) pairs from origin r to destination s. G denotes the bus line set, $g \in G$ is bus line number. Let C_a denote the capacity of single lane in link a, n_a denote the number of lane in link a. For convenience, similar with Konishi and Mun (2010), m carpoolers share one car. Let Q_{rs}, q_{rs}^c, q_{rs}^{c1}, q_{rs}^{c2} and q_{rs}^b denote travel demand of all travelers, automobile travelers, solo drivers, carpoolers and bus passengers respectively in O-D pairs rs, they satisfy:

$$Q_{rs} = q_{rs}^c + q_{rs}^b = q_{rs}^{c1} + q_{rs}^{c2} + q_{rs}^b, \quad rs \in RS \tag{1}$$

Let P_{rs}^c to be the route set of automobile, f_p^{c1} and f_p^{c2} denote the number of solo drivers and carpoolers on route p $(p \in P_{rs}^c)$ respectively. y_a^{c1} and y_a^{c2} are the number of solo drivers, and carpoolers in link a $(a \in A)$ respectively. They satisfy:

$$y_a^{ci} = \sum_{rs \in RS} \sum_{p \in P_{rs}^c} \delta_p^a f_p^{ci}, \quad a \in A,\ i \in \{1,2\} \tag{2}$$

where $\delta_p^a = 1$ if route p passes link a, otherwise $\delta_p^a = 0$.

For bus mode, P_{rs}^b is the set of all bus travel routes from origin r to destination s, note that different bus transfer schemes on the same path belong to different bus travel routes. Let f_p^b to be the number of bus passengers by route p $(p \in P_{rs}^b)$, and y_a^g denotes the number of passengers of bus line g in link a. Their relations are as follows:

$$y_a^g = \sum_{rs \in RS} \sum_{p \in P_{rs}^b} \delta_p^{ga} f_p^b, \quad a \in A,\ g \in G \tag{3}$$

$$y_a^b = \sum_{g\ in\ a} y_a^g, \quad a \in A,\ g \in G \tag{4}$$

where $\delta_p^{ga} = 1$ if route p passes link a using bus line g, otherwise $\delta_p^{ga} = 0$, y_a^b is the total number of bus passengers in link a.

x_a^{c1}, x_a^{c2} represent vehicle flow of solo driving and carpooling modes in link a respectively. It is assumed that only one person in a solo driving car and m people in a carpooling vehicle, then $x_a^{c1} = y_a^{c1}$ and $x_a^{c2} = y_a^{c2}/m$. For bus vehicle flow in link a, x_a^b satisfies

$$x_a^b = \sum_{g \in G} \delta_g^a F_g, \quad a \in A \tag{5}$$

where F_g is the frequency of bus line g, $\delta_g^a = 1$ only when bus line g passes link a, otherwise $\delta_g^a = 0$.

2.2. Link travel time analysis of three modes with different EBLs' setting schemes

Three policies of road resource assignment are considered in this paper. Policy 1: No EBLs, all vehicles use road resource simultaneously; Policy 2: Setting EBLs and only bus can use them; Policy 3: Setting EBLs and both bus and carpooling vehicles can use them simultaneously.

With Policy 1, vehicles of three modes run simultaneously, the travel time for the two automobile modes are the same. Their link travel time on link a can be written by US Bureau of Public Roads (BPR) function as follows:

$$t_a^{ci1} = t_{a0}^c \left(1 + \alpha^c \left(\frac{y_a^{c1} + \frac{1}{m} y_a^{c2} + K x_a^b}{n_a C_a}\right)^{\beta^c}\right), \quad a \in A,\ i \in \{1,2\} \tag{6}$$

where K is the vehicle conversion factor for bus, t_{a0}^c is the free flow travel time of automobile on link a, α^c and β^c are BPR function parameters for automobile mode. Travel time for bus mode in link a can be written as:

$$t_a^{b1} = t_{a0}^b \left(1 + \alpha^b \left(\frac{y_a^{c1} + \frac{1}{m} y_a^{c2} + K x_a^b}{n_a C_a}\right)^{\beta^b}\right), \quad a \in A \tag{7}$$

where t_{a0}^b is the free flow travel time of bus on link a, α^b and β^b are BPR function parameters for bus mode.

For Policy 2, the travel times for the two automobile modes are also the same and can be written as:

$$t_a^{ci2} = t_{a0}^c \left(1 + \alpha^c \left(\frac{y_a^{c1} + \frac{1}{m} y_a^{c2}}{(n_a - 1) C_a}\right)^{\beta^c}\right). \quad a \in A,\ i \in \{1, 2\} \tag{8}$$

The travel time for bus mode could be:

$$t_a^{b2} = t_{a0}^b \left(1 + \alpha^b \left(\frac{K x_a^b}{C_a}\right)^{\beta^b}\right). \quad a \in A \tag{9}$$

For Policy 3, it is assumed that carpoolers always choose the fastest lane. In the vast majority of practical circumstances and all the cases presented in this paper, EBLs are less congested than common lanes. Under very high bus frequency or share of carpooling proportion, EBLs could be worse than common lanes. Then, some carpoolers would choose common lanes until the travel costs of two kinds of lanes reach to an equilibrium. Denote y_{a1}^{c2} and y_{a2}^{c2} to be the number of carpoolers on link a use EBLs and common lanes respectively. They satisfy $y_{a1}^{c2} + y_{a2}^{c2} = y_a^{c2}$. The travel time for solo driving mode in link a could be:

$$t_a^{c13} = t_{a0}^c \left(1 + \alpha^c \left(\frac{y_a^{c1} + \frac{1}{m} y_{a2}^{c2}}{(n_a - 1) C_a}\right)^{\beta^c}\right). \quad a \in A,\ i \in \{1, 2\} \tag{10}$$

The travel time for bus mode can be written as: