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Evaluation of exclusive bus lanes in a bi-modal degradable road network

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ABSTRACT

In this paper, we proposed an evaluation method of exclusive bus lanes (EBLs) in a bi-modal degradable road network with car and bus transit modes. Link travel time with and without EBLs for two modes is analyzed with link stochastic degradation. Furthermore, route general travel costs are formulated with the uncertainty of link travel time for both modes and the uncertainty of waiting time at a bus stop and in-vehicle congestion costs for the bus mode. The uncertainty of bus waiting time is considered to be relevant to the degradation of the front links of the bus line. A bi-modal user equilibrium model incorporating travelers' risk adverse behavior is proposed for evaluating EBLs. Finally, two numerical examples are used to illustrate how the road degradation level, travelers' risk aversion level and the front link's correlation level with the uncertainty of the bus waiting time affect the results of the user equilibrium model with and without EBLs and how the road degradation level affects the optimal EBLs setting scheme. A paradox of EBLs setting is also illustrated where adding one exclusive bus lane may decrease share of bus.

1. Introduction

An urban transportation system usually includes multiple travel modes where car and bus are major modes for long-distance travel. Increasing car ownership has made traffic congestion more and more serious in urban areas. Thus, how to assign road resources so as to improve the operational efficiency of transportation has become a frontier research topic. As a major bus priority measure, exclusive bus lanes (EBLs) have been recognized as a key measure to relieve traffic congestion. They have a significant effect on improving bus operation efficiency and service quality, strengthening the attractiveness of the bus system and increasing the share of people using the bus.

Many researchers have evaluated effect of exclusive bus lanes by microscopic simulation (Shalaby, 1999; Arasan and Vedagiri, 2008, 2009, 2010; Chen et al., 2010). For the case of low bus frequency, Viegas and Lu (2004), Eichlerand and Daganzo (2006) and Zhu (2010) discussed the concept of an intermittent bus lane. Abdelghany et al. (2007) proposed a dynamic traffic assignment and simulation model to support evaluation and planning of BRT services. Vedagiri and Arasan (2009) evaluated the improvement of the bus service caused by EBLs and how it affected the share of people using the bus. Li and Ju (2009) proposed a bi-modal dynamic traffic assignment based on stochastic user equilibrium to analyze EBLs where two extreme situations, with and without EBLs for all lines, were considered and a fixed link travel time and

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bus frequency were assumed. Basso et al. (2011) analyzed bus corridor optimization with interactions among cars, buses and other travel modes. McDonnell and Zellner (2011) developed an agent-based model to evaluate how BRT effects travel time and modal split. Mesbah et al. (2011) proposed a bi-level model to optimize EBLs based on multi-modal traffic network equilibrium with fixed bus frequencies. Yao et al. (2012) further analyzed the combinatorial optimization of EBLs and bus frequencies. Yu et al. (2015) proposed a bi-level programming model to optimize the distribution of exclusive bus lanes and simultaneously balance the transit service levels among all bus lines by rearranging buses over the transit network. Ma et al. (2014) proposed a person-capacity-based optimization method for the integrated design of lane markings, exclusive bus lanes and passive bus priority signal settings for isolated intersections.

At the same time, the uncertainty of transportation demand and supply, which is caused by parked vehicle violations, traffic accidents, disasters and weather, has a significant effect on travel choice behavior and urban traffic flow redistribution. Traditionally, a traffic network equilibrium with uncertainty supply and/or demand has been developed for auto-only networks (Du and Nicholson, 1997; Nicholson and Du, 1997; Lo and Tung, 2003; Sumalee and Watling, 2003; Clark and Watling, 2005; Lo et al., 2006; Siu and Lo, 2008; Lam et al., 2008; Chen and Zhou, 2010; Nie, 2011; Sun et al., 2014; Xu et al., 2014; Yan et al., 2015). For multi-modal cases, Chang (2010) analyzed travel time perturbations of cars, buses and trains and how they affect the travel choice behavior of travelers without considering the network equilibrium analytically. Yao et al. (2011) analyzed the uncertainty of cars and the metro and proposed a multi-modal and multi-class user equilibrium model in a multi-modal degradable network. Sumalee et al. (2011) proposed a multi-modal transport network assignment model considering uncertainties caused by adverse weather conditions for both the demand and supply sides of the network. Meng et al. (2014) proposed a multimodal network equilibrium model incorporating cars, the subway and park and ride (P&R) trips. Based on the above studies, the uncertainty of transportation demand and supply could have significant effects on the flow distribution of the whole transportation network. Thus, it could be helpful to get more appropriate evaluations of EBLs setting scheme after incorporating the uncertainty of transportation demand and supply.

In this paper, EBLs setting is evaluated in a stochastic degradable network, which is considered as the uncertainty of transportation supply. Firstly, the link and route travel costs for car and bus transit modes with EBLs and without EBLs are modeled in a stochastic degradable road network. Because of travel time uncertainty led by road stochastic degradation, a user equilibrium model that considers travelers' risk adverse behavior is proposed to evaluate the configuration of exclusive bus lanes in a bi-modal traffic network where travelers by car only consider uncertainty in terms of link travel time and travelers by bus consider uncertainty simultaneously in terms of both of link travel time and waiting time at a bus stop. The uncertainty of the bus waiting time is considered to be especially relevant to the degradation of the front links of a bus line. A seven-link road network example is used to illustrate how the road degradation level, travelers' risk aversion level and the front link correlation level with uncertainty of the bus waiting time at a bus stop affect equilibrium status and system efficiency with and without EBLs. This allows comparison of EBLs' effect on a degradable road transportation network. How the road degradation level affects the optimal EBLs setting scheme is also evaluated by a nineteen-link road network. A paradox of EBLs setting is illustrated where adding one exclusive bus lane may decrease share of bus.

The remainder of the paper is organized as follows. In the next section, the transportation network equilibrium with and without EBLs is formulated in the bi-model degradable road network. Section 3 introduces the objective functions of the EBLs setting in the degradable road network. Section 4 demonstrates how related parameters affect the evaluation results of EBLs and a paradox of EBLs setting by two numerical examples. Finally, some conclusions and future research are discussed in Section 5.

2. Degradable transportation network equilibrium with and without EBLs

2.1. Description of the bi-modal degradable road network

In the degradable road network (V, A) with car and bus modes, V and A denote the sets of nodes and links respectively. Link $a \in A$ consists of n_a lanes, and the capacity of each lane is C_a. The degradable road network considers the stochastic degradation of road link capacity C_a caused by parked vehicle violations, traffic accidents and weather disasters (Lo and Tung, 2003; Lo et al., 2006; Siu and Lo, 2008). This is different from the general road network where road link capacity C_a is assumed to be constant. Traffic demand Q_{rs} is assumed to be fixed for each origin–destination pair $rs \in RS \subset V \times V$. To facilitate analysis, assume one person per car and all buses to be of the same type. Bus capacity can accommodate B passengers. Let the traffic flow for each bus be equivalent to K cars.

Let G denote the set of bus lines. F_g denotes the frequencies of bus line $g \in G$. Let the bus transfer path $(r, g_1, v_1, g_2, v_2, \ldots, v_{m-1}, g_m, s)$ denote the bus travel scheme from origin r to destination s, where (g_i, v_i, g_{i+1}) indicates traveler transfer from bus line g_i to bus line g_{i+1} at bus station v_i, and (v_i, g_{i+1}, v_{i+1}) indicates travelers who take bus line g_{i+1} from bus station v_i to bus station v_{i+1}. Bus transfer paths can uniquely determine a traveler's travel path by bus. The fees of transfer and walking can be obtained previously for each bus transfer path.

Let Q_{rs} denote the total travel demand, q^c_{rs} denote the travel demand by car and q^b_{rs} denote the travel demand by bus for $rs \in RS$.

For the travel demand by car q^c_{rs}, $rs \in RS$, let P^c_{rs} denote the path set of travelers by car, f^c_p denote the path flow for $p \in P^c_{rs}$ and x^c_a denote traveler flow by car for $a \in A$. Thus, traveler flow by car x^c_a can be written as: