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A bi-level programming for bus lane network design

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ABSTRACT

This paper proposes a bi-level programming model to solve the design problem for bus lane distribution in multi-modal transport networks. The upper level model aims at minimizing the average travel time of travelers, as well as minimizing the difference of passengers' comfort among all the bus lines by optimizing bus frequencies. The lower level model is a multi-modal transport network equilibrium model for the joint modal split/traffic assignment problem. The column generation algorithm, the branch-and-bound algorithm and the method of successive averages are comprehensively applied in this paper for the solution of the bi-level model. A simple numerical test and an empirical test based on Dalian economic zone are employed to validate the proposed model. The results show that the bi-level model performs well with regard to the objective of reducing travel time costs for all travelers and balancing transit service level among all bus lines.

1. Introduction

With the economic boom and urbanized advancement in China, traffic problems in big cities are becoming more and more severe. To alleviate urban traffic congestion, many cities in China has adopted the policy of Transit Priority and constructed exclusive bus lanes on some road sections. Urban transport network is a large-scale complex system where link interactions cannot be ignored. Therefore, although buses on an exclusive bus lane can be ensured to operate smoothly even in cases of traffic congestion, delay incurred by private vehicles on corresponding links increases due to the reduction in passing opportunities.

For an urban transit system, the improvement of transit operation conditions cannot be achieved just by building one or two exclusive bus lanes. Only when the exclusive bus lane network takes shape can the transit service level be really lifted. However, as the coverage of transit network in a city is significantly huge, the paradox between maximizing transit service level and minimizing delay to private vehicles can be a big problem, when considering building up exclusive bus lanes. Therefore, the distribution of exclusive bus lanes is a complex optimization problem.

Transit problems had drawn the attention of transport sector as early as 1970s (Smith, 1967; Goodman, 1972). The first bus lane was set up in Curitiba, Brazil (Parasram, 2003). In 1974–1976, Kanazawa City opened up 19 bus lines in bid to alleviate the heavy traffic congestion in urban area (Katsuragi, 1999). With decades of development, there have been various bus lane systems and techniques applied in the real world. Levinson et al. (2003) introduced some guides and design features of bus lane planning in the Transit Cooperative Research Program report. In recent years, Transit Signal Priority (TSP) has

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attracted many researchers as it is an effective tool to ensure transit priority (Duerr, 2000; Janos and Furth, 2002; Lin, 2002; Yao et al., 2014). Therefore, some researchers attempted to combine TSP with bus lane deployment. Wu and Hounsell (1998) addressed the design, operation and optimization problem of pre-signals which provided buses with priority at or near the end of a bus lane. Xu and Zheng (2011) analyzed the varying influences of different bus lane locations on TSP. Intermittent Bus Lane (IBL) is another bus priority scheme proposed by Viegas and Lu (2001, 2004) and further developed by Eielller and Daganzo (2006) who set forth the concept of Bus Lane with Intermittent priority (BLIP) and analyzed the required conditions as well as the effectiveness of BLIP. Agrawal et al. (2013) reviewed different policies and strategies applied to manage shared-use bus lanes in 7 cities throughout the world. Li et al. (2009) found the total travel time of buses in a single-bus-lane configuration was quite close to that in a double-bus-lane configuration.

As early as 1970s, Amano et al. (1975) had started researches on the theory and application of bus lane planning in urban area. So far, there have been several approaches for the bus lane planning. Some researchers analyzed the bus lane planning in terms of benefit and cost (Jeason and Ferreira, 2000). Particularly, computer simulation techniques are employed by many researchers during their cost-effectiveness analysis of bus lane implementation (Shalaby, 1999; Arasan and Vedagiri, 2008, 2009). Based on field observed data and micro simulation technique, Arasan and Vedagiri (2010) also developed a heterogeneous traffic flow model which was then applied in different traffic volumes to study the impact of introduction of bus lanes on the delay of other modes. Zhu et al. (2012) simulated two deployment scenarios, i.e. the curbside bus lane and the median bus lane, and tested the different impacts on the expressway traffic in the two scenarios. Besides, Chen et al. (2013) presented a micro-simulation approach to identify the influence of bus lanes on the capacity of off-ramps and on-ramps of the urban expressway.

On the other hand, mathematical programming has also been applied in bus lane planning. Dafermos (1982) and Smith (1983) proposed variational inequality (VI) models for solving the asymmetric traffic equilibrium problem. In the years that followed, modeling techniques and algorithms for traffic assignment were further developed by Dial (1996) and Huang and Lam (1992), as well as Yang and Huang (2004). Moreover, Williams et al. (1991) developed a Nest Logit Model for the multi-modal traffic equilibrium problem. Considering the main factors that influenced traffic choice of traveler, Si et al. (2008) proposed a combined model incorporating modal split and traffic assignment. Based on an integrated VI formulation, Li and Ju (2009) developed a multi-mode dynamic traffic assignment model to investigate the influence of bus lanes on travelers' mode choices, path choices, as well as the average travel time of cars and buses.

As the objective of bus lane planning is to make an optimal decision in order to minimize the total travel cost in the transport network, bus lane planning could be viewed as the network design problem (NDP). The fundamental work on NDP was done by Leblanc (1975) who built a mixed inter programming model to address the problem of determining which links could be improved so as to alleviate the congestion in the transport network. Chen and Alfa (1991) used the stochastic incremental assignment method to select routes for the discrete NDP. In Yang and Bell (1998)'s study, they optimized the NDP incorporating elastic travel demand, and introduced the mixed network design problem in which simultaneous choice of link addition and capacity improvement were involved.

The application of bi-level programming further boosted the study on bus lane planning and optimization. The original concepts of bi-level programming were put forward by Bracken and McGill (1973). Kim and Suh (1988) formulated a bi-level transportation planning model in which the interest conflict between public and private parties was represented and they also attempted some algorithmic procedures for solution. Gao et al. (2005) designed a new algorithm based on the support function concept to solve the bi-level programming for the discrete transportation network planning. Based on the logit stochastic user equilibrium assignment, Huang et al. (2001) developed a bi-level model which formulated the interactions of elastic demand and link capacity improvements, with the objective of maximizing network economic benefit. To solve the network design problem, Chiou (2005) and Wang et al. (2013) respectively used a bi-level programming, of which the upper level aimed at minimizing the total travel time and investment costs for link expansion and the lower level was a traffic assignment based on user equilibrium. Jia et al. (2012) established a bi-level programming model to optimize the joint utilization of exclusive bus lane and bus frequencies, with the aim of minimizing the total cost of travelers and transit operators.

With the increase of income, automobile becomes affordable to more Chinese people. Private car holdings in China are rapidly rising. As a result, daily trips by car are also going up. Despite of the severe traffic congestion in many cities, residents are still keen on automobile trip. Except the megacities, e.g. Beijing, Shanghai and Shenzhen where the metro networks have been well-developed, on-land transport is still the major part of transit systems in many other cities in China. Buses in such cities are very crowded and uncomfortable in the morning peak and will also be trapped in congestion. That is why people would rather drive a car and be stuck in traffic jam than stay on a crowded bus. Such psychological preference is called "to trip with dignity" by them. Urban rail transit can be a rival of private cars because it is hardly affected by congestion, but buses could never be, unless they get exclusive priorities on roads. Therefore, in this paper, the effect of exclusive bus lanes on transport mode choice is considered when designing the exclusive bus lane network. That is to say, motorist will forgo car trips and take buses instead due to the decreased travel time costs by bus, thus bus passengers between any origin–destination (O–D) pair is assumed to be determined by a logit split function.

Because the exclusive bus lane could reduce the bus turnaround time, fewer buses are required to operate on the transit lines that traverse exclusive bus lanes. The "redundant buses" can be put on other lines without exclusive bus lanes. Therefore, by optimizing bus frequencies among transit lines, the transit service levels can be improved over the whole