Transportation Research Part C 49 (2014) 73–86

Contents lists available at ScienceDirect

Transportation Research Part C

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

Solving a discrete multimodal transportation network design problem

Lihui Zhang [a,*], Hai Yang [b], Di Wu [c], Dianhai Wang [a]

[a] Institute of Transportation Engineering, Zhejiang University, Hangzhou, Zhejiang 310058, China
[b] Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong 999077, China
[c] Department of Civil and Coastal Engineering, University of Florida, Gainesville, FL 32611, United States

ARTICLE INFO

Article history:
Received 21 November 2013
Received in revised form 23 October 2014
Accepted 23 October 2014
Available online 16 November 2014

Keywords:
Multimodal network design
Road capacity expansion
Bus route layout
Active-set algorithm
Multimodal user equilibrium

ABSTRACT

This paper investigates the multimodal network design problem (MMNDP) that optimizes the auto network expansion scheme and bus network design scheme in an integrated manner. The problem is formulated as a single-level mathematical program with complementarity constraints (MPCC). The decision variables, including the expanded capacity of auto links, the layout of bus routes, the fare levels and the route frequencies, are transformed into multiple sets of binary variables. The layout of transit routes is explicitly modeled using an alternative approach by introducing a set of complementarity constraints. The congestion interaction among different travel modes is captured by an asymmetric multimodal user equilibrium problem (MUE). An active-set algorithm is employed to deal with the MPCC, by sequentially solving a relaxed MMNDP and a scheme updating problem. Numerical tests on nine-node and Sioux Falls networks are performed to demonstrate the proposed model and algorithm.

1. Introduction

Multimodal approach is recognized as one of the major solutions to the spreading traffic congestion and sustainable mobility. The efficiency of the multimodal transportation system largely depends on a well-designed multimodal network. Most previous research deals with unimodal network design problems, i.e., the traditional network design problem (NDP) and the transit network design problem (TNDP). The NDP is to expand the current auto network by adding new roads or increasing the capacity of the existing roads thus to improve the system efficiency (Yang and Bell, 1998), while TNDP is mainly to optimize the layout of transit routes, the fare levels and service frequencies (Guihaire and Hao, 2008; Kepaptsoglou and Karlaftis, 2009; Nuzzolo et al., 2012; Parbo et al., 2014). Recognizing that the expansion of auto network will increase the feasible region for building the transit network, this paper investigates the multimodal network design problem to expand the current auto network, and meanwhile build transit network with appropriate frequency and fare settings to maximize the overall system performance, under some budget constraints.

Extensive research has been carried out in the literature that investigates unimodal network design problems. According to the type of capacity-related decision variables, the NDP can be classified into continuous NDP (CNDP) and discrete NDP (DNDP). Most studies formulated NDP into bi-level structure, and various techniques have been proposed to solve the two different NDPs, e.g., sensitivity based heuristic (Yang, 1997), augmented Lagrangian algorithm (Meng et al., 2001),

* Corresponding author. Tel.: +86 185 0581 1559.
E-mail address: lihuizhang@zju.edu.cn (L. Zhang).

http://dx.doi.org/10.1016/j.trc.2014.10.008
0968-090X/

linearization based method (Wang and Lo, 2010), penalty algorithm accompanied by multi-cutting plane algorithm (Li et al., 2012) and complementarity slackness–relaxation based algorithm (Wang et al., 2014) for CNDP, branch-and-bound technique (LeBlanc, 1975), support-function based method (Gao et al., 2005), active-set algorithm (Zhang et al., 2009), system optimal-relaxation based method and user equilibrium-reduction based method (Wang et al., 2013) for DNDP.

On the other hand, designing transit network attracts even more researchers, whose main difficulty lies in determining the layout of transit routes. Most of the route generation algorithms reported in the literature are based on shortest path, e.g., Fan and Machemehl (2006) used Dijkstra's algorithm and modified k-shortest path algorithm to generate all feasible candidate routes under some pre-specified constraints, and then applied simulated annealing to select an optimal subset among all. Baaj and Mahmassani (1991) and Mauttone and Urquhart (2009) first generated shortest paths as transit routes to cover travel demand, and then improved these routes via single-node insertion and pair-node insertion. Zhao and Zeng (2008) built local node spaces around the stop nodes of a master path, and candidate transit routes were constructed by joining the piecewise shortest paths between node pairs from two successive local node spaces. Bagloee and Ceder (2011) also relied on shortest paths to build their hierarchical transit network. Nayeem et al. (2014) first constructed initial population of transit routes with shortest paths between selected terminals, and then applied genetic algorithm to find the final optimal design scheme. Some other studies proposed models and methods to directly generate transit routes, e.g., Wan and Lo (2003) developed a mixed-integer linear program to optimize multiple routes simultaneously, which are all acyclic. Borndörfer et al. (2007) formulated the 'line-planning problem' as a mixed-integer linear program, and proposed a column-generation approach to dynamically generate transit lines. Yang et al. (2007) and Yu et al. (2012) applied ant colony optimization that mimics the behavior of ants seeking food, and directly generated bus routes similar to the paths of foregoing ants in the real world. Yao et al. (2014) constructed candidate bus routes by performing deletion and alteration operations on some existing routes, and then applied tabu search to determine the optimal route set. In this paper, we propose another alternative approach to design all bus routes simultaneously, which is flexible to generate various forms of route layout.

Though some researchers have investigated various transportation problems or issues in the context of multimodal transportation (e.g., Bellei et al., 2002; Gentile et al., 2005; Munizaga and Palma, 2012; Artigues et al., 2013; Bouhana et al., 2013), not much attention has been paid to the design of multimodal transportation networks. Fletterman (2008) and Cipriani et al. (2012) both optimized the networks consisting of different transit modes, and considered no congestion interaction among different travel modes. Their solution methods were similar, starting with an initial large set of feasible routes, and then applying meta-heuristic algorithms to find the optimal subset. Wu et al. (2005) proposed a bi-level model to select the optimal locations of pedestrian-only streets, where the lower-level MUE problem explicitly considered the congestion interaction among different travel modes. The equilibrium problem was written in form of a variational inequality (VI), and solved using the methods of successive averages (MSA) combined with the Block Gauss–Seidel decomposition method. Uchida et al. (2007) optimized the frequency of transit service in multimodal network, and users' travel behavior was captured using a stochastic multimodal user equilibrium problem, which was solved using a sensitivity-analysis based method. Wan and Lo (2009) proposed a two-phase procedure to optimize multimodal transit networks, considering the inter-route and inter-modal transfers. The users' travel behavior was also represented by stochastic multimodal user equilibrium, and solved by a MSA with asymmetric path utility functions embedded. The transit routes were generated using the same model developed by Wan and Lo (2003). Gallo et al. (2010) tried to optimize auto and transit networks simultaneously, where the decision variables were the capacity to be added to each existing road and the hourly frequency of each transit route, while the network topologies remained unchanged. Their bi-level discrete formulation was solved via a meta-heuristic called scatter search, accompanied by a fixed-point method to deal with the lower-level multimodal equilibrium problem.

As can be observed from the above analysis, the research on the network design problem in multimodal context is limited, and most of them only deal with the transit network design with consideration of inter-modal congestion interaction. The only study trying to design both the auto and transit networks does not optimize the layout of transit routes, and does not consider the case of new link additions. This paper tries to propose an integrated model to optimize the auto and transit networks simultaneously. The interaction among different travel modes brings another dimension of complexity, as compared to the single-mode network design problems. The users' travel behavior is described with asymmetric multimodal user equilibrium, while users in the same travel mode still follow Wardropian user equilibrium. The asymmetric multimodal user equilibrium will be transformed into a nonlinear system based on strong duality theory, so that the final model can be formulated into a single level problem. An alternative approach will be provided to explicitly model the layout of transit routes with a set of mixed-integer constraints, which is flexible to represent different layout patterns. The final model obtained is a MPCC problem with multiple binary variables. The active-set algorithm proposed by Zhang et al. (2009) will be modified to solve the large-scale problem. The rest of paper is organized as follows: Section 2 proposes the detailed formulation for MMNDP considering asymmetric MUE, which is a MPCC with a lot of binary variables. Section 3 develops a dual-based active-set technique that incorporates commercial nonlinear solvers to solve the MMDNP, followed by various numerical tests in Section 4 to validate the model and solution approach. Concluding remarks are presented in the last section.

2. Formulating the multimodal network design problem

Three travel modes are considered throughout the paper: single occupancy vehicle (SOV), high-occupancy vehicle (HOV) and bus. The road network is assumed to contain no exclusive bus lanes, so vehicles of the three modes need to share the