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Transit route and frequency design: Bi-level modeling and hybrid artificial bee colony algorithm approach

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ABSTRACT

This paper proposes a bi-level transit network design problem where the transit routes and frequency settings are determined simultaneously. The upper-level problem is formulated as a mixed integer non-linear program with the objective of minimizing the number of passenger transfers, and the lower-level problem is the transit assignment problem with capacity constraints. A hybrid artificial bee colony (ABC) algorithm is developed to solve the bi-level problem. This algorithm relies on the ABC algorithm to design route structures and a proposed descent direction search method to determine an optimal frequency setting for a given route structure. The descent direction search method is developed by analyzing the optimality conditions of the lower-level problem and using the relationship between the lower- and upper-level objective functions. The step size for updating the frequency setting is determined by solving a linear integer program. To efficiently repair route structures, a node insertion and deletion strategy is proposed based on the average passenger demand for the direct services concerned. To increase the computation speed, a lower bound of the objective value for each route design solution is derived and used in the fitness evaluation of the proposed algorithm. Various experiments are set up to demonstrate the performance of our proposed algorithm and the properties of the problem.

1. Introduction

Transit network design has received considerable attention over the last two decades due to its practical importance. For example, in Hong Kong, over 90% of the 11 million daily trips that people make involve public transport. Hence, a well-designed transit network is important for meeting passenger demand. Guihaire and Hao (2008) and Kepaptsoglou and Karlaftis (2009) provided comprehensive reviews in this area. Previous works on this topic focus on route design (e.g., Mandl, 1980; Murray, 2003; Wan and Lo, 2003; Li et al., 2011, 2012), frequency setting (e.g., Furth and Wilson, 1982; LeBlanc, 1988; Hadas and Shnaiderman, 2012), timetabling (e.g., Wong et al., 2008; Fleurent et al., 2004), vehicle scheduling (e.g., Bunte et al., 2006), crew scheduling (e.g., Wren and Rousseau, 1993), fare structure (e.g., Li et al., 2009), fleet size determination (e.g., Li et al., 2008), and a combination of the above (e.g., Ceder and Wilson, 1986; Lee and Vuchic, 2005; Szeto and Wu, 2010).

The majority of previous studies have considered the optimization of transit route structures and service frequencies separately. For example, Fernandez and Marcotte (1992), Constantin and Florian (1995), Zubieta (1998), Gao et al. (2004), Uchida et al. (2005, 2007), and Leiva et al. (2010) proposed models for optimizing frequencies to achieve different objectives

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within an existing transit network, whereas Laporte et al. (2010) and Yu et al. (2012) focused exclusively on designing route structures. Both transit route structure and frequency setting determine the level of service (e.g., in terms of in-vehicle congestion and waiting time at bus stops); more importantly they determine whether the service has sufficient capacity to meet passenger demand. Therefore, it is important to simultaneously optimize the transit route structure and the frequency setting.

In transit network design, it is essential to consider the in-vehicle congestion issue. In-vehicle congestion leads to increased waiting and travel times, along with the comfort problem prompted by a lack of seats for passengers. This comfort problem can be particularly serious if the trip time is long or demand is high. Generally, there are two approaches to addressing the congestion issue: capacity constraint and the congestion cost function. The capacity constraint approach (e.g., Kurauchi et al., 2003; Lei and Chen, 2004; Lam et al., 1999, 2002; Cepeda et al., 2006; Sumalee et al., 2009, 2011; Schmöcker et al., 2008, 2011; Szeto et al., 2013; Cortés et al., 2013) incorporates capacity constraints in transit assignment models that disallow flows on transit vehicles to be greater than the corresponding capacity. The congestion cost function approach (e.g., Spiess and Florian, 1989; de Cea and Fernández, 1993; Lo et al., 2003; Li et al., 2008, 2009, 2011; Sun and Gao, 2007; Teklu, 2008; Szeto et al., 2011a; Szeto and Jiang, 2014) adopts an unbounded increasing convex function to model the effect of in-vehicle congestion on waiting time. Although both approaches have been used in the literature, practically speaking, the former is more realistic because the latter can result in an unacceptable line flow that is far greater than the corresponding capacity.

In addition to the congestion issue, it is important to consider passenger transfers between transit vehicles, as they can generate passenger inconvenience. The number of passenger transfers is an important network performance indicator, especially in Hong Kong, for the following reasons. First, the total number of passenger transfers reflects the number of passengers without direct services to their destinations, which can indicate inconvenience. Second, passengers always complain when there are no direct services to their destinations (Szeto and Jiang, 2012). The total number of passenger transfers also indirectly reflects the number of complaints regarding lack of direct services. Optimizing the number of passenger transfers can reduce the number of complaints implicitly. However, very few studies have considered this number. Baaj and Mahmassani (1990) embedded the transfer concept into their route generation procedures, such that a route with more than two transfers was abandoned. Similarly, the number of passenger transfers was modeled implicitly in Zhao et al. (2005). The travel cost calculated in the objective function excluded the travel costs of routes with more than two transfers, yet they did not optimize the total number of passengers needing to transfer between transit vehicles. Guan et al. (2006) used the total number of passenger transfers as a surrogate of transfer and waiting times in passenger line assignment, which is the lower level problem of their transit network design problem. Jara-Díaz et al. (2012) considered the total number of passenger transfers to investigate the condition under which a transit network design with transfers is preferable. Most of the existing studies have used the total passenger travel time as the objective function. However, there is no guarantee that minimizing the total number of passenger transfers also minimizes the total passenger travel time. In some cases, there can be a tradeoff between the total number of passenger transfers and total passenger travel time (Szeto and Wu, 2010). It is essential to explicitly capture the total number of passenger transfers in the objective function.

This paper proposes a bi-level model for designing transit routes and their frequencies that explicitly minimizes the total number of passenger transfers in the objective function of the upper-level problem and incorporates strict capacity constraints to address the in-vehicle congestion in the lower-level problem. This bi-level model is formulated as a mixed integer non-linear program that is NP-hard and considers the route choice behavior of passengers through the lower-level user-equilibrium problem. The model also considers the stop location choice of each route within each zone of the study area. This model differs from the bi-level models proposed by Constantin and Florian (1995), Gao et al. (2004) and Uchida et al. (2005, 2007) in the sense that they only considered frequency setting, whereas our model further considers route design and stop location choice.

To solve transit network design problems, exact methods (e.g., Wan and Lo, 2003) and metaheuristics such as genetic algorithms (GAs) (e.g., van Nes et al., 1988; Bielli et al., 2002; Chakroborty and Dwivedi, 2002; Tom and Mohan, 2003; Ngamchai and Lovell, 2003; Shih et al., 1998; Fan and Machemehl, 2006a; Mazloumi et al., 2012) and simulated annealing (e.g., Fan and Machemehl, 2006b; Zhao and Zeng, 2006) have been used. A hybrid artificial bee colony (ABC) algorithm—a matheuristic that combines a metaheuristic and an exact algorithm—is developed for the transit network design problem as an improvement to the original ABC algorithm, a metaheuristic proposed by Karaboga (2005) and motivated by the foraging behavior of honey bees.

Compared with existing evolutionary algorithms such as GAs, the ABC algorithm has a better local search mechanism that improves the solution quality. More recently, the ABC algorithm has been applied to solve complex engineering optimization problems. For example, Kang et al. (2009) successfully applied an ABC algorithm to the parameter identification of concrete dam-foundation systems. Karaboga (2009) proposed an ABC algorithm to solve a digital filter design problem and obtained good results. Karaboga and Ozturk (2009) used an ABC algorithm to train neural networks for pattern classification, and their results on benchmark instances showed that such use was efficient. Szeto et al. (2011b) improved the ABC algorithm to solve a capacitated vehicle routing problem. Szeto and Jiang (2012) enhanced the ABC algorithm to solve a single-level transit network design problem without considering the in-vehicle congestion effect. Long et al. (2014) improved the ABC algorithm to solve a turn restriction design problem. Szeto and Jiang (2012) and Long et al. (2014) showed that their proposed ABC algorithms are better than the GA for solving their problems, but it has not yet been improved to solve bi-level transit network design problems that consider in-vehicle congestion. This study enhances the ABC algorithm to solve this problem.

The proposed algorithm relies on the ABC algorithm to design route structures and a proposed descent direction search method to determine an optimal frequency setting for a given route structure. A node insertion and deletion strategy for