Transportation Research Part E 110 (2018) 71–89

Contents lists available at ScienceDirect

Transportation Research Part E

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

Optimal design of demand adaptive paired-line hybrid transit: Case of radial route structure

Peng (Will) Chen, Yu (Marco) Nie*

Department of Civil and Environmental Engineering, Northwestern University, 2145 Sheridan Road, Evanston, IL 60208, USA

ARTICLE INFO

Keywords:
Hybrid transit
Demand adaptive service
Continuous approximation
Radial network
Discrete-event simulation

ABSTRACT

This paper studies the design problem of a demand adaptive paired-line hybrid transit system with a radial network structure. Depending on whether the demand adaptive service is operated along circular or radial transit lines, two variants of such systems are considered: a Circular Model (or C-Model) and a Radial Model (or R-Model). A continuous approximation approach is employed to develop the optimal design problem, which is formulated as a mixed integer program. A comprehensive numerical experiment is performed to compare various cost components corresponding to the optimal design of the two systems, and a discrete-event simulation is developed to validate the analysis. Numerical and simulation results suggest that the radial route network outperforms the grid route network, which was analyzed previously in the literature, with a significant margin, while the C-Model and R-Model offer similar performance.

1. Introduction

1.1. Background

This paper is concerned with the design of a new hybrid transit system that aims to marry the flexibility of a demand responsive service with the efficiency of a traditional fixed-route service. This kind hybrid system has received limited attention in the past. Notable examples include the "fixed-route + dial-a-ride" system of Stein (1978) and Aldaihani et al. (2004), the demand adaptive system (DAS) of Malucelli et al. (1999) and Crainic et al. (2001), and the high-coverage point-to-point transit system (HCPPT) of Cortés and Jayakrishnan (2002). Recent advances in information technology, especially ubiquitous mobile computing, has stimulated a new wave of interest in such systems. On one hand, technologies have enabled transit service providers to track their fleet, make short-term projections, and most important, interact with passengers and cater to their needs in real time and enroute. On the other hand, the rise of Transportation Network Companies (TNC) such as Uber and Didi Chuxing offers a viable demand responsive service ready to be integrated with existing transit services. Major TNCs are actively pursuing such a strategy,[1] having realized the efficiency of fixed-route transit is the key to scaling up to a mass personal transport platform.

A couple of strategic questions must be addressed before a hybrid transit system envisioned above can be configured with greater details. The first is how to spatially couple the two services, referred to in this paper as relative spatial position (RSP). There are two typical RSP designs: a zone-based design (Stein, 1978; Aldaihani et al., 2004) in which demand responsive services are assigned into relatively small zones centering around a given transit stop of the fixed-route service, and a line-based design (Chen and Nie, 2017a),

---

* Corresponding author.
E-mail address: y-nie@northwestern.edu (Y.M. Nie).

[1] For recent developments in this area, see https://nextcity.org/daily/entry/lyft-transit-agency-partnership-first-mile-last-mile-goals and http://transloc.com/transloc-and-uber-partner-to-pioneer-a-new-standard-in-public-transit.

https://doi.org/10.1016/j.tre.2017.12.006
Received 9 May 2017; Received in revised form 22 November 2017; Accepted 15 December 2017
1366-5545/

in which the demand responsive service is operated with a stable headway to cover all stops along a paired fixed-route line. The other question is related to the choice of the route structure for the fixed-route service, which is the focus of the present study.

1.2. Relevant studies

Various models have been developed for the transit network design problem. Among these models, the majority tackle the problem by choosing a system of fixed routes and the corresponding frequencies to serve a given demand pattern (Ceder and Wilson, 1986). The mathematical problems that arise are often nonlinear, non-convex and they are solved by different combinatorial optimization methods. Consequently, developing heuristics for solving problems of realistic size has been a recurring theme in this area (see e.g. Rea, 1972; Mandl, 1980; Ceder and Wilson, 1986; Baaj and Mahmassani, 1991, 1995; Zhao, 2006; Zhao and Zeng, 2008; Guihaire and Hao, 2008; Szeto and Wu, 2011).

Another popular methodology, adopted in our study, is to develop analytical models under idealized conditions. The focus of this approach is to produce “sketch” designs that rely on a small set of parameters (e.g. line density, headway) to provide a blueprint design, along with useful insights. The existing models may be classified based on route structure, which includes (1) linear corridors that connect residential areas to a business district (CBD) (Wirasinghe and Seneviratne, 1986; Jehiel, 1993; Li et al., 2012); (2) parallel corridors with perpendicular feeder lines (Byrne and Vuchic, 1972; Hurdle, 1973; Byrne, 1976; Wirasinghe, 1980; Chang and Schonfeld, 1991a,b); (3) rectangular grid (Holroyd, 1967; Wirasinghe and Ghoneim, 1981; Kocur and Hendrickson, 1982; Daganzo, 2010a); (4) radial network with CBD at the center (Vuchic and Newell, 1968; Byrne, 1975; Wirasinghe et al., 1977; Spasovic and Schonfeld, 1993; Badia et al., 2014; Chen et al., 2015); (5) hub-and-spoke networks where the hub is a large street (Newell, 1979; Daganzo, 2010a).

The impact of route structure on the performance of a transit system has been closely examined in the literature. Daganzo (2010b) proposed a mixed grid/hub-and-spoke structure for a square service region. The design model, constructed using the continuous approximation approach (Newell, 1973), estimates user and agency costs based on a small number of decision variables. It can be solved efficiently by commercially available meta-heuristics thanks to its simplicity. Estrada et al. (2011) generalized Daganzo’s model to a rectangular area. Stops with single coverage, i.e., those only served by one line, are introduced in the central area to improve spatial accessibility without significantly increasing the agency cost. Badia et al. (2014) reformulated and adapted the model to a radial street layout. In their model, a circular service region composed of a radial/circular structure in the central area and a hub-and-spoke network in the periphery. They compared the radial design model with the grid design model of Badia et al. (2014) and found similar total costs in various scenarios, with discrepancies less than 3%. Chen et al. (2015) further extended the model to allow spatially varying headway and line spacing for both grid and radial transit network designs. They showed that the cost differences between the two designs are typically 9% and 13%, but can be as large as 21.5%.

1.3. Overview

The objective of the present study is to compare the relative performance of two widely studied route structures in transit design, namely grid and radial, in a hybrid transit system. To the best of our knowledge, existing hybrid transit systems either only consider general and unstructured routes (Malucelli et al., 1999; Crainic et al., 2001; Cortés and Jayakrishnan, 2002), or focus on grid routes structure (Aldaihani et al., 2004; Chen and Nie, 2017a). Given the differences revealed in fixed-route transit systems, it is intriguing to examine whether and how the route structure would impact the performance of hybrid transit systems. Answering these questions is also critical to inform the strategic design of hybrid transit systems, as the choice of the route structure affects almost all other design parameters.

A continuous approximation approach will be adopted in this study, following the line of work initiated by Daganzo (2010b). In particular, we will adopt the line-based RSP design first proposed by Chen and Nie (2017a), which will hereafter be referred to as the demand adaptive paired-line hybrid transit (or DAPL-HT). We focus on the line-based RSP in this study because a recent study by Chen and Nie (2017b) compares zone-based and line-based RSP designs in grid networks, and concludes that the line-based design is generally comparable and in many cases outperform the zone-based design.

For the remainder, Section 2 presents the DAPL-HT system in a radial transit network. The optimal design problem for the proposed transit system is investigated in Section 3. Section 4 conducts numerical experiments to compare the proposed transit system against its counterpart in a grid network. Then, in Section 5, simulation results are presented to confirm the correctness of the analytical models developed for the proposed DAPL-HT system in radial transit network. Section 6 concludes the paper.

2. Hybrid transit system with a radial route structure

Consider a circular service area of radius R, in which the streets form a radial network. The service area generates λ passenger trips per hour per unit area, and the origins and destinations of these trips are uniformly and independently distributed in the service area.

The demand adaptive paired-line hybrid transit (DAPL-HT) system in a radial network consists of both fixed-route and demand-adaptive services. As depicted in Fig. 1, the fixed-route service has two types of transit lines: radial lines (boundary-center-boundary) and circular lines (concentric to the center with different radius). Note that the demand-adaptive service can cover the entire service area by operating along either the circular transit lines or the radial transit lines. Since it is not obvious which option is better, both are considered in this study. For narrative convenience, The DAPL-HT system with circular demand adaptive service is called the