Transportation Research Part B 111 (2018) 203–226

Contents lists available at ScienceDirect

Transportation Research Part B

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

Optimal design of intersecting bimodal transit networks in a grid city

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ARTICLE INFO

Article history:
Received 7 December 2017
Revised 12 March 2018
Accepted 14 March 2018

Keywords:
Bimodal transit network
Continuum models
Optimal design
Transit route choice

ABSTRACT

The urban transit system in a real city usually has two major components: a sparse express (e.g. rail) network and a dense local (e.g. bus) network. The two networks intersect and interweave with each other throughout the city to furnish various route options for serving transit patrons with distinct ODs. The optimal design problem of this bimodal transit system, however, has not been well explored in the literature, partly due to the difficulty of modeling the patrons' complex route choice behavior in the bimodal networks. In light of this, we formulate parsimonious continuum models for minimizing the total cost of the patrons and the transit agency for an intersecting bimodal transit network in a grid city, where the perpendicular local and express lines intersect at transfer stops. Seven distinct route types are identified in this network, which represent realistic intra- and inter-modal route options. A lower-level assignment problem between these routes is embedded in the upper-level network design optimization problem. We develop an efficient method to find near-optimal designs of the intersecting network. Numerical results unveil a number of insightful findings, e.g., that sizable cost savings are observed for the intersecting bimodal design as compared to the single-mode designs for moderate to high demand levels, and that only moderate benefits are observed as compared to the trunk-feeder designs under certain operating conditions. We also show that the conventional practice of designing the local and express networks separately would greatly undermine the benefit of the bimodal system.

1. Introduction

An urban public transit system often consists of two overlapping and interweaving single-mode networks: a local bus network that features high line and stop densities but low speed and operating costs, and an express transit network that features high speed and capacity, but has to be sparsely spaced due to the high costs. The latter is often operated by Bus Rapid Transit (BRT) or rail. Cities having this kind of bimodal transit systems include Beijing, London, San Francisco (bus plus metro), and Bogota (bus plus BRT), among many others. The interweaving local and express networks furnish multiple route options, so that patrons with distinct OD can choose the routes that best suit their needs. For example, short-distance travelers whose origins and destinations are far from the express lines can choose to travel by local lines only, and long-distance travelers can take the local service as feeder to access the express lines. Survey data in real cities served by bimodal

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https://doi.org/10.1016/j.trb.2018.03.007

transit systems have confirmed that there are significant proportions of patrons who chose more than one route type. For example, it was reported for a number of major cities in the world that the percentage of transit trips involving intermodal transfers was among 25–30%, while the rest of the trips are local-only or express-only (Guo, 2008).

Despite the wide presence of bimodal transit systems, a fundamental question has yet to be answered: does this interweaving and redundant bimodal transit network, if optimally designed, perform better than other network designs (e.g. single-mode networks) under certain operating conditions? There seems to be a chance for the bimodal network to win, thanks to the potential patron benefits resulting from the multiple route options. Unfortunately, at present there is no study that examines how the patrons' benefits trade off optimally with the extra agency cost for providing the service redundancy, and how the optimal system design performs in various operating environments, as we shall see next.

1.1. Literature review and rundown of the paper

Studies on transit network optimization can be classified into two categories: those on discrete models and those on continuum models. Discrete models (see the detailed reviews by Kepaptsoglou and Karlaftis, 2009 and Ibarra-Rojas et al., 2015) are often built upon a well-defined graph with nodes and links representing the underlying street network, the discrete demand points, and candidate stops. These models are thus able to account for the specific OD and irregular street layouts in real cities. However, the resulting formulation (typically a vehicle routing problem) is usually NP-hard, and cannot be solved to global optimum by exact solution methods (e.g. branch-and-cut), save for a few networks of very small sizes (e.g. Guan et al., 2003; Wan and Lo, 2003). On the other hand, heuristic solution methods (e.g. genetic algorithm) were often used to provide reasonably good solutions to small-to-medium-scale problems with few dozens of nodes and links (Ceder and Wilson, 1986; Fan and Machemehl, 2004). For large-scale networks, especially those with multiple transit modes (e.g. Wan and Lo, 2009), the heuristic methods either cannot guarantee the solution quality (i.e. how close the heuristic solution is to the global optimum), or have intolerable computation times.

On the other hand, continuum models (e.g. Wirasinghe, 1980; Daganzo, 2010a; Chen et al., 2015; Gu et al., 2016) are often built upon idealized network forms (e.g. grid, radial, ring-radial) and demand patterns (e.g. uniformly or concentrically distributed demand). Despite the idealization, the continuum models are parsimonious and can usually be solved to global optimality or near optimality via computationally efficient numerical methods. Therefore, the continuum models are often used to examine the optimal network designs for a wide range of operating conditions, and to explore general insights into the cause-and-effect relations between key parameters and the optimal design. Thus, this approach is ideal for examining the fundamental question described above.

Regrettably, most studies on continuum models of transit system design are focused on single-mode networks (Newell, 1973; 1979; Holryod, 1967; Vuchic and Newell, 1968; Byrne, 1975; Wirasinghe and Ghoneim, 1981; Chien and Scholfeld, 1997; Wirasinghe, 2003; Daganzo 2010a, b; Estrada et al., 2011; Badia et al., 2014; Ouyang et al., 2014). Some works examined local-and-express systems (Gu et al., 2016; Fan et al., 2017) or other systems with differentiated transit services (Chang and Schonfeld, 1993; Li and Quadrifoglio, 2011; Freyss et al., 2013; Gu et al., 2016). In the above-cited works, however, the differentiated services were still operated by a single transit mode, and they were designed to serve a corridor only.

To our best knowledge, the only type of multimodal transit systems that has been studied in the literature of continuum models is the trunk-feeder system, where buses serve as feeders to carry patrons to or from the trunk (e.g. rail) lines. Among the limited number of works on this topic, however, most are about corridor service designs (Wirasinghe et al., 1977; 1980; Hurdle and Wirasinghe, 1980; Chien and Schonfeld, 1998; Sivakumaran et al., 2012; Fan and Mei, 2018), while Sivakumaran et al., (2014) seems to be the only one that modeled a city-wide trunk-feeder network.[1] This reference compared optimal trunk-feeder networks (bus feeding BRT and bus feeding rail) against the optimal single-mode networks (bus-only, BRT-only, and rail-only), and found the former triumphed over the latter in a wide range of operating conditions. However, in this trunk-feeder network each patron has to transfer three times in any trip, which greatly undermines the practicality of this system. Note in real urban transit systems that the average number of transfers per trip is only around 1.5 (APTA, 2007). The network structure in Sivakumaran et al., (2014) also penalizes short trips: they still have to transfer three times between the feeder buses and trunk lines since no direct local route is offered.

Also note that most studies on continuum modeling of transit networks (including the studies on multimodal systems; e.g. Sivakumaran et al., 2014) have assumed that each patron has only one route option. This simplification of patrons' route choice might be necessary for reducing the complexity of the modeling work, however it is unrealistic since most trips in a real bimodal urban transit system are offered multiple route options (APTA, 2007). The only exception seems to be Saidi et al., (2016), which modeled a relatively simple, single-mode transit network (consisting of one ring line and multiple radial lines). The route choice model is still too simple to represent patrons' realistic route choice behavior in a more complex bimodal network.

In light of the above, we formulate continuum models for optimizing a specific type of bimodal transit network atop a generic city with grid street pattern. We term this network as the "intersecting bimodal network", in which express and local lines intersect each other at the transfer stops (see Fig. 1). Although being special and idealized, this network furnishes

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[1] Here our discussion is limited to the networks with *fixed-route* feeder lines. Trunk-feeder networks with flex-route feeders (e.g. Chen and Nie, 2017a, b, 2018) are out of our scope.