A Mathematical Optimization Model for Solving the Intercity Transit Network Design Problem

Andisheh Ranjbari · Mark Hickman · Yi-Chang Chiu

Abstract This study presents a network design problem formulation and solution procedure for an intercity transit service that has multiple routes and serves multiple terminals in the origin and destination cities. The proposed solution procedure consists of three steps, combining local knowledge and policy decisions with a mathematical optimization model. The proposed methodology was implemented for a newly conceived transit service between Tucson and Phoenix in Arizona, USA, and the sensitivity analysis results along with the final routes found by the model are presented.

Keywords: Transit Network Design · Intercity Transit Service · Mathematical Optimization Model

1 Introduction

Intercity travel is a growing problem in major corridors around the world. While highways and freeways face large capacity challenges in many corridors, the intercity bus industry has been on the rise over the past decade. The growing demand for intercity bus services intensifies the need for an efficient network design and service schedule to provide a competitive public transportation service for travelers and to minimize operator costs.
In the past, there have been many studies devoted to solving the Transit Network Design Problem (TNDP), and some reviews of these studies can be found in Desaulniers and Hickman (2007), Guihaire and Hao (2008), Kepaptsoglou and Karlaftis (2009), Farahani et al. (2013), and Ibarra-Rojas et al. (2015). However, these studies occur in the context of urban transit. While intercity and typical urban bus services share a number of similarities, the TNDP in an intercity context has significant differences with the urban TNDP, and there are certain considerations that need to be taken into account. To the best of our knowledge, there is no previous study dealing with network design for intercity bus services, wherein a transit service has multiple routes and serves multiple terminals in the origin and destination cities.

In this study, a mathematical optimization model and a solution procedure is presented for designing the transit routes and their frequencies for an intercity transit service. Moreover, the developed model considers almost all the important parameters for the Transit Network Design and Frequency Setting Problems (TNDFSP) that have been considered in previous studies.

2 Solution Methodology

Our proposed approach assumes that we have the street network graph and the origin-destination (OD) demand matrix. The origins and destinations are aggregated into traffic analysis zones (TAZs), creating the matrix of demand between cities. With this as input, the proposed network design procedure consists of three steps. First, a set of candidate terminals are selected in each city. The candidate terminals should include major trip production and attraction points in these cities and may include other locations to which the operator wishes to provide service. Assuming that passengers will choose the terminal closest to their trip origin, once the candidate terminals are selected, demand from nearby nodes of the network which are not candidate terminals will be assigned to those candidate terminal nodes. In the second step, candidate routes are generated between those terminals using a k-shortest path (KSP) algorithm. The third step of the proposed solution procedure is a mixed-integer optimization model that finds the optimal terminal locations, transit routes and corresponding frequencies, the required number of vehicles, and the start/end depot locations for the intercity service. The model’s objective function minimizes a weighted sum of total passenger travel time (user costs) and vehicle deadheading time (excess operator costs).

Constraints on the optimization model include a requirement to satisfy a minimum fraction of the total intercity travel demand (a so-called “minimum demand satisfaction ratio”), minimum and maximum route frequencies, and a certain capital budget (or alternatively a maximum number of terminals and fleet size). The use of
the minimum demand satisfaction ratio ensures that a sufficient number of trips across all OD pairs is served by the intercity service. Also, for each city, only one depot is permitted, which supports all terminals in that city.

3 Results

The proposed TNDP solution procedure was implemented for a newly conceived intercity transit service between the metropolitan areas of Tucson and Phoenix in Arizona, USA. The studied service is an innovative flexible and express transit service proposed by the authors, called Flexpress (Ranjbari et al., 2016). Flexpress has multiple terminals in both urban areas, travels at a high speed on a dedicated guideway on freeways between the two cities, and returns to a regular speed in urban areas to provide access to selected terminal locations.

The statewide network and intercity demand matrices were provided by the Arizona Department of Transportation and were simplified and reformatted to fit the data standards developed for the optimization model. Overall, 51 locations were selected for candidate terminals in the greater Tucson and Phoenix areas. Using a KSP algorithm based on Dijkstra’s algorithm and considering k=2, a total of 1,276 candidate routes were generated.

The solution procedure was implemented for the AM Peak period demand. The total travel demand between Tucson and Phoenix for the AM peak period is 124,571 person-trips. The total intercity transit demand is assumed to be 5% of the total travel demand for each origin-destination pair, equalling 6,228 person-trips. Vehicle capacity is assumed to be 30 persons, and the upper and lower bounds of route frequency are set to 60 and 4 (veh/hr), respectively.

The optimization model was coded and run in the GLPK open-source optimization solver (GLPK, 2017). The model was run for different values of the minimum demand satisfaction ratio (m), the maximum number of routes (N), the maximum number of terminals (T), and the maximum fleet size (F) constraints. The results showed that demand satisfaction is a binding constraint for all cases; in addition, the number of routes is also commonly a critical (binding) constraint. The maximum fleet size and the maximum number of terminals seemed not to have much influence on the solution, and changing the values in these two constraints did not change the objective function value significantly, or in some cases even at all.

The sensitivity of the objective function to the changes in these constraints is exhibited in Figure 1. Considering values of m={0.5, 0.6, 0.7}, N={20, 30, 40}, T={20, 25, 30} and F={400, 500, 600}, a baseline scenario was created by the combination of mean values for each parameter (m=0.6, N=30, T=25, F=500).
Other scenarios were built by varying one parameter at a time (±16.67% for m, ±20% for T and F, ±33.33 for N), while other parameters were held constant at their baseline values. Figure 1 shows that the objective function is most sensitive (the biggest slope) to changes in the demand satisfaction ratio, and then to the number of routes and fleet size, and is not affected nearly as much by changes in the number of terminals. It also shows that the demand satisfaction ratio has a direct influence on the objective function (positive slope), while the other three inversely affect the objective function (negative slope); i.e. loosening the number of routes, the number of terminals and fleet size constraints (increasing their upper bounds) will decrease the objective function value.

The final routes found by the model also looked reasonable, serving the most important trip production and attraction locations in Tucson and Phoenix. Figure 2 shows the final routes found for the baseline scenario. Most of these routes had a frequency of 4-10 buses per hour (6-15 min headways), and there were only one or two routes which were required to operate at frequencies of at least 20 per hour (headways of 3 min or less).
4 Conclusion

The proposed solution methodology combines local knowledge and policy decisions with a mathematical optimization model that leads to reasonable results, and it was shown that the solution procedure could successfully be implemented on a real-life large-scale network.

However, there are certain options for improving and extending this research, such as including the revenues in the optimization model and modifying the objective function to maximize revenues; considering the access to transit more explicitly (currently, it is assumed that passengers will choose the terminal closest to their trip origin); and considering the freeway capacity and thus controlling the combined frequency over the intercity section of the trip.
References


