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A new solution framework for the limited-stop bus service design problem

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ABSTRACT

Limited-stop services are a key element to the successful operation of bus rapid transit corridors. In this study, we present a framework for addressing the limited-stop service design problem over a corridor, and formally introduce a family of subproblems involved in its solution. Using a bi-level optimization approach, we introduce a method of designing these services while considering bus capacity, transfers, and two behavioral models for passengers: deterministic and stochastic. The algorithm and its variants were tested on nine scenarios with up to 80 stops. Working with deterministic passenger assignment, our model solved the problem in a small fraction of the time required by a benchmark algorithm. We use this algorithm to show that neglecting transfers can lead to suboptimal solutions. We finally show that although it makes the problem much harder, working with stochastic assignment leads to more realistic and robust solutions.

1. Introduction

Since their first implementation in 1974 in Curitiba, Brazil, bus rapid transit (BRT) systems have gained popularity, and this trend does not seem to decline. BRT systems are generally efficient, high-capacity systems that aim to provide services that combine the quality of rail transport with the flexibility and economy of buses. Some of the elements commonly associated with these systems are fare integration, prepaid boarding zones, segregated road lanes, and provision for limited-stop services.

Limited-stop services, which omit some stops from a corridor to provide a faster journey, can be beneficial to both operators and users when properly designed. From the operators' perspective, running services with shorter cycle times allows more rotation for their buses, increasing their capacity and efficiency of operation. Also, the cost per kilometer drops since buses reduce the time they need to accelerate, decelerate and open their doors. Limited-stop services are also attractive to users because they provide a faster trip for some origin-destination (O-D) pairs. However, limited-stop services can increase waiting times at bus stops that are omitted, and in some cases, they force riders to transfer in order to arrive at their destination; therefore, special consideration should be taken in the design of these systems, so that their benefits will not be outweighed by their costs.

The case of the Transmilenio BRT system in Bogota, Colombia illustrates the importance of the limited-stop service design problem (LSDP). The Transmilenio BRT corridor network is one of the largest in the world. It has more than 100 service lines, most of which are limited-stop services, and it also has the bus corridor with the largest volume of passengers transported

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per hour and direction worldwide (BRT Centre of Excellence, 2016). Since the implementation of the system, demand has steadily grown, reaching a point in which the level of service became severely damaged during peak periods. Users have expressed their dissatisfaction since buses operate at maximum capacity, there is overcrowding at bus stops, and travel condition density is high. Some scholars have even pinpointed the intricacy of the limited-stop service itineraries as a source of congestion in the system while still recognizing their value (Ramirez, 2012). This shows an urgent necessity for a reliable limited-stop service design tool to support the planning of a BRT system.

In this paper, we study the LSDP, with the objective of identifying the set of services that makes the operation of a certain bus corridor system most efficient for a given trip matrix. We provide a formal definition of the problem and propose a solution framework that breaks down the LSDP into two simpler subproblems: a limited-stop service generation problem (LSGP) and a capacitated frequency optimization and assignment problem (CFOAP). In the LSGP, the objective is to find the set of limited-stop services that should serve a given transit corridor. A series of heuristics is proposed and tested for this problem in Larrain et al. (2015) (although in that work the acronym was not yet introduced). The CFOAP, in turn, takes a set of proposed services and optimizes their frequencies. This optimization has consider a prediction of passenger behavior for a given transit system (i.e., the passenger assignment), and has to take into account that buses have a limited capacity. Based on this framework, we propose a bi-level optimization algorithm for the CFOAP that greatly outperforms our previous solution algorithm. In conjunction with the heuristics for the LSGP, this approach enables a faster solution of the LSDP.

In our experience, models and algorithms for designing limited-stop services have some limitations. First, and central to this study, is that most of these algorithms consider a single type of passenger behaving deterministically. This means that in a solution to the problem, every passenger traveling on an O-D pair will choose the same route. This leads to unrealistic solutions that can overestimate or underestimate the utilization of certain services. To tackle this issue, we explore the possibility of modeling passenger assignment (i.e., the way passengers choose their routes) as a stochastic process, thus spreading the trips among the alternatives and yielding solutions that are more robust.

This paper is organized as follows: In Section 2 we present a review of existing literature on the design of limited-stop services. In Section 3, we introduce a framework for the LSDP, which is divided into simpler subproblems: the LSGP and the CFOAP. In Section 4, we describe a bi-level algorithm for the solution to the CFOAP which allows to solve the LSDP. This algorithm works with both deterministic and stochastic passenger assignment, and allows us to include transfers. We also introduce a GRASP variant of the capacity algorithms from Leiva et al. (2010) and Larrain (2013). Subsequently, in Section 5, a series of experiments is presented to test the algorithm and its variants. In this section, we create scenarios consisting of 20, 40, and 80 bus stops based on three real-life corridors: two in Santiago, Chile and one in Bogota, Colombia. Finally, in Section 6, we present our main conclusions and propose possible avenues for future research.

2. Literature review

According to Desaulniers and Hickman (2007), the first work to address the design problem of a limited-stop service was that of Jordan and Turnquist (1979). This work solves the problem of service design and frequency optimization for corridors with a one-to-many demand structure (i.e., all trips originate from a single station). Furth (1986) expanded this work, generalizing it to both bidirectional and branched corridors, but maintaining a restricted demand structure. Furth and Day (1985) proposed a taxonomy of operating strategies for public transport corridors; this work introduced the concepts of short turning, deadheading, and limited-stops, which are widely used in BRT corridors today.

The worldwide boom of BRT systems has been accompanied by a renewed interest in the LSDP. Some case studies have shown the potential for this type of service (see, for example, Ercolano (1984), Silverman (1998), or Tétreault and El-Geneidy (2010)), while some other studies provide guidelines to assess the potential of a corridor to host these type of services (see Larrain and Muñoz (2016), Yi et al. (2016) and Hart (2016)). All these works agree in that limited-stop services perform better in a corridor where trips are longer and ideally concentrated in a few O-D pairs on the corridor.

Various recent studies have proposed mathematical formulations and solution methods for this design problem. Leiva et al. (2010) and Larrain (2013) propose design models that minimize the total costs of the system. These works model passenger assignment considering common lines (i.e., when users can wait for a set of services and take the first to arrive on a stop) and transfers, although in the solution of medium-sized corridors (20 stops per direction) transfers are ignored owing to computational limitations. Their solution approach, which inspire the framework that we propose in Section 3, is to split the LSDP into two smaller problems: a service generation problem where one defines a set of services to consider for optimization, and a capacitated frequency optimization and assignment problem (CFOAP) that finds the optimal frequencies and associated passenger assignment for a given set of services considering bus capacity constraints. The limited-stop service generation problem (LSGP) has been addressed directly by Larrain (2013) and Larrain et al. (2015).

To deal with bus capacity in their solution, Leiva et al. (2010) proposed a greedy heuristic that was later improved by Larrain (2013). These heuristics iteratively impose progressively higher lower bounds on the frequencies of critical services and solve the design problem until a valid solution is found. Note that although it makes the problem much easier to solve, it is not correct to directly model bus capacity as a constraint on a social cost optimization problem, because it leads to an "altruistic" assignment where passengers minimize social costs, rather than their own.

Following the line of research on design models for limited-stop services, Chen et al. (2012), Chiraphadhanakul and Barnhart (2013), and Sun et al. (2008) propose various models and algorithms to solve the LSDP. While these models si-