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Optimal bus service design with limited stop services in a travel corridor

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ABSTRACT

This paper seeks to answer questions from the combined bus operator's and users' perspective on how to design limited stop service operation strategies when they are offered along with the normal bus services. The passengers' service choice is determined by the common line calculation. The problem is formulated as a Mixed Integer Nonlinear Program (MINLP) with equilibrium constraints. Thereafter, a global optimal solution method applying various linearization and convexification techniques is proposed. Numerical studies are then performed to evaluate the model validity and solution efficiency followed by concluding remarks.

1. Introduction

Public transit services are lifelines for daily commute in many major cities in the world. In order to increase the service quality, constant improvement in operation and design is of paramount importance. In the presence of increasing daily travel demand, public transit service operators now seek to improve their service quality to efficiently satisfy the travel demand while maintaining operation in a financially sustainable manner. In many cities, bus transit services have become more convenient with the inclusion of differential services such as normal, express, and limited stop services which are operated to cater to various demand patterns. While a normal service serves all the bus stops/nodes on a route, an express service travels end to end without or with very few intermediate stoppages. A limited stop service serving a selected subset of nodes in a corridor provides another alternative and helps transit operators in reducing overall passenger travel time. Hence, a limited stop service is of reasonable financial and social importance to bus transit operation and due academic attention needs to be given to developing methodologies for bus operators to design their operation strategies.

In the literature, transit corridor design problems have attracted much research attention. Ceder and Wilson (1986) discussed the bus route planning problem that minimizes total system operation cost while also addressing the scheduling problem. Since then, a vast body of literature on transit corridor design has emerged which involves optimal decisions of routing and scheduling, service frequency design, inter-node spacing, fleet size design, etc. Curtin and Biba (2011) proposed a mathematical model that maximizes the service value of a route, rather than minimizing its cost, and the cost (distance) is considered as a budget constraint on the extent of the route.

Wang and Lo (2008) presented a related work on a multi-fleet ferry routing and scheduling problem that considered ferry services with different operational characteristics. Cortés et al. (2011) presented a methodology to optimise costs while integrating two kinds of services in the transit network with deadheading and short turning services. Yadan et al. (2012) proposed a robust optimization model for the bus route schedule design problem by taking into account the bus travel time uncertainty and the bus drivers' schedule

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recovery efforts. A few studies discussed the bus dwelling time which is critical towards determining the total travel time of passengers (e.g., Meng and Qu, 2013; Sun et al., 2013). Bus transit generally operates under different market regimes and a few studies in the literature have also contributed towards this aspect (e.g., Li et al., 2010, 2008). Liu and Meng (2014) modelled the network flow equilibrium problem on a multimodal transport network with a bus-based park-and-ride system and congestion pricing charges. Li et al. (2011) addressed the design problem of a rail transit line located in a linear urban transportation corridor where the service variables include a combination of rail line length, number and locations of stations, headway, and fare. In addition to the above mentioned studies, there exist many other published works on transit service design; but unfortunately, few studies focus on the methodological design of a limited stop service in bus transit.

Limited stop services have been operating in cities like Bogota, Chicago, Montreal, New York City, Santiago. Afanasiev and Liberman (1983) described a limited stop service as a service with stops at intervals of about 0.8 km. Silverman (1998) proposed a few important considerations while designing a limited stop service: wider roadways, not too close to rapid transit corridors, operationally more successful over long distances. Conlon et al. (2001) noted that implementing a limited stop service parallel to a normal bus service drew appreciation from users in Chicago where user satisfaction for both the services increased after the inclusion of the former. El-Geneidy and Surprenant-Legault (2010) observed that a limited stop service is the most preferred choice of passengers as they tend to overestimate their time savings while using this service. Tétreault and El-Geneidy (2010) proposed a stop selection methodology for limited stop services based on archived Automatic Vehicle Location (AVL) and Automatic Vehicle Classification (AVC) data obtained from a travel behaviour survey in Montreal, Canada. This included different scenarios wherein stops were selected based on passenger activity and transfers. As it can be concluded, studies mentioned above mainly focused on the operational aspect of limited stop services which is data-driven and descriptive while no analytical approach was proposed for the service design.

In designing a limited stop service, bus stop selection is the prime decision variable, i.e., to determine which stops the bus service should stop or skip in the transit corridor. In addition, other operation strategies like optimal fleet size, service frequency and bus capacity should be determined with consideration of the passengers' service choices. Some research studies have been conducted to develop methodological frameworks to prescribe guidelines for their operation in terms of optimal service design. Larrain et al. (2010) proposed the methodology to select optimal express services for a bus corridor with capacity constraints considering various demand criteria, whereas, Larrain et al. (2015) designed zonal bus services which skip all intermediate nodes over a segment of the transit route while serving all nodes in the initial and final segment. Ulusoy et al. (2010) presented a methodology to optimise the operation of integrated normal, short turn, and express services. Leiva et al. (2010) presented an optimization approach to design a limited stop service with capacity constraints. However, in this work, the selection of bus stops for the limited stop service is given in priori, and the service frequency of limited stop services lines is the only operation strategy determined by the model, despite the fact that they discard some of the services assigning zero frequency. Using only several given subsets of bus stops as the candidate service design plan for the limited stop service, one cannot obtain the truly "best" bus service design for limited stop services. Chiraphadanakul and Barnhart (2013) proposed a design of the limited stop service by optimally reassigning certain bus trips rather than providing additional trips. However, this work does not consider transfers or multiple lines operating over common route corridors where passengers could make a choice. Besides, it allows only one limited stop service to be operated over the transit network and the frequency of the limited stop service is not taken into account for passenger assignment on the respective services. Recently, Larrain and Muñoz (2016) proposed a design algorithm for limited stop services in a corridor to optimise a number of services and then calibrated a regression model to estimate the benefits. Hart (2016) developed a methodology for transit agencies to evaluate the potential for limited stop service along existing bus routes where net benefits of travel time savings would outweigh the net costs as a result of implementation of limited stop service. Zhang et al. (2016) proposed a methodology to determine frequencies and skip-stop strategy; however, genetic algorithm was used to develop the model. A detailed comparison between some of the above mentioned studies on limited stop services which are closer to the contribution in this study is illustrated in Table 1.

In this paper, we present a mathematical model formulation to explicitly design a limited stop service with optimal decisions on bus line configurations (the set of bus stops served by the limited stop service) along with other operation strategies including operating frequencies and the optimal fleet size assignment. The model developed primarily considers the perspective of operators. Basically, given a fixed bus fleet size, the bus operators who decide to offer a limited stop service other than the normal bus service need to determine optimal operation strategies pertaining to service fleet size, line setting for limited stop services, and the service frequencies so as to minimize the total operation cost. At the same time, due consideration must be given to the service performance from the perspective of passengers as poor service performance may lead to a drop in demand or the possibility of losing the franchise of operating the routes altogether. Therefore, the objective function also incorporates passengers' travel and waiting time as important factors which are to be adjusted by appropriate weights. Although this study assumes that the bus services are operated in a monopolistic market with fixed total demand, it should be noted that the model framework (which focuses on how to model and solve the optimal operation strategies for limited stop services) can be easily extended to consider elastic demand or competition with existing alternative bus services.

In designing the transit corridor with the normal service and limited stop service, one intrinsic issue to be considered is the travellers' choice behaviour between different services. In this study, such passenger choices are described by the classical common line problem. Specifically, it is assumed that the travellers choose a subset of bus services that minimizes the expected total travel time which was defined as the common line problem in Chriqui and Robillard (1975). The common line problem has been investigated in many other research works in the literature such as Spiess and Florian (1989), De Cea and Fernandez (1993), and Cepeda et al. (2006).

In this study, the model is formulated into a MINLP. One may consider this bus service design problem with limited stop services