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Demand-responsive transit circulator service network design

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A B S T R A C T

Commuter rail systems are being introduced into many urban areas as an alternative mode to automobiles for commuting trips. It is anticipated that the shift from the auto mode to rail mode can greatly help alleviate traffic congestion in urban road networks. However, the right-of-way of many existing commuter rail systems is usually not ideally located. Since the locations of rail systems were typically chosen long ago to serve the needs of freight customers, the majority of current commuter rail passengers have to take a non-walkable connecting trip to reach their final destinations after departing the most conveniently located rail stations. To make rail a more viable commuting option and thus more competitive to the auto mode, a bus feeder or circulator system is proposed for transporting passengers from their departing rail stations to final work destinations in a seamless transfer manner. The key research question with operating such a bus circulator system is how to optimally determine a bus route and stopping sequence for each circulating tour by using the real-time demand information. In this paper, we name this joint routing and stopping optimization problem the circulator service network design problem, the objective of which is to minimize the total tour cost incurred to bus passengers and operators with respect to minimizing the walk time of each individual bus passenger. A bi-level nonlinear mixed integer programming model is constructed and a tabu search method with different local search strategies and neighborhood evaluation methods is then developed for tackling the circulator service network design problem.

1. Introduction

Traffic congestion in urban road networks has been a long lasting phenomenon that causes a variety of political, economic, and environmental problems to our society. Considering all the practical constraints for roadway capacity expansions, many urban areas prefer to implement commuter rail systems as a strategic transportation solution to alleviate traffic congestion. Currently, commuter rail development and expansion programs are found at a number of locations in the United States and worldwide. Most of these programs use existing rail lines or available rights-of-way as they minimize land takings and relocation effects and save various costs associated with creating an all-new right-of-way through dense metropolitan

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areas (Zullig and Phraner, 2014). In fact, the availability of existing rail right-of-way has long been a major factor in evaluating relevant urban transportation development plans.

In many cases, however, using existing rail alignments poses critical accessibility issues (Grava, 2003). Because those rail systems were built at a previous time, often to serve freight traffic in a rather different city layout, they do not necessarily facilitate the use incurred by current residential and commercial activities. Distances from potential rail stations to commuters' workplace destinations are often greater than their walkable ranges. For a typical passenger who intends to take the commuter rail and accordingly chooses to drive his own car from home to a home-end rail station and then get aboard the rail, the likelihood is very low for him to have another car ready to use for finishing the remaining distance from a work-end station to his workplace. In this case, the most viable transportation option for the passenger may be to take another transit mode connecting the rail station and his workplace, given that walk is just not feasible. If he chooses an existing bus line, he will typically need to walk to the bus stop, wait for the bus to come, ride the bus to the closest stop to his destination, and most probably walk from the bus stop to the destination. If we consider the total time spent on driving, train riding, transferring, bus riding and walking to the destination, the commuter rail may lose its attractiveness or even its viability as an alternative mode to driving for the entire commuting trip.

In this regard, minimizing the transfer time from work-end rail stations and workplace destinations turns out to be very critical to the efficiency of those commuting trip chains described above. For this purpose, we introduce in the paper a recently proposed bus feeder or circulator system, which operates buses that will pick up passengers when a train arrives at the rail station, drop them off in turn at selected points along a selected route, and then return to the station for the next train. Obviously, the purpose of the above operation is to distribute passengers from the rail station to workplace destinations for home-to-workplace commuting trips (during the morning peak period), of which the spatial and temporal pattern of passenger demands is different from that of the collective operation between the rail station and workplace origins for workplace-to-home trips (during the afternoon peak period). This paper focuses on the development of modeling and solution methods for a distributive type of transit circulator systems operated in the destination end of home-to-workplace trips.

The success of operating such a bus circulator system depends on two important factors. First, a seamless transfer promise is the key to achieve the functionality and attractiveness of the bus circulator system. By seamless transfer, we mean that when a train arrives at the station, there should be always a bus ready to take passengers to their final destinations. If the seamless transfer is successfully implemented, we are able to eliminate to a large extent both the waiting time and the possible anxiety incurred to passengers at the transfer point. Second, making the optimal routing and stopping decisions on the operational level poses a data requirement on acquiring real-time destination information. Such real-time information can be readily collected by an onboard or roadside ticketing system or passengers' personal handheld devices (such as mobile phones) when they request or use the bus service (either before or immediately after they get aboard). Passengers are allowed to indicate their destinations among all demand zones served by the circulator bus. Based on the real-time information, the bus operator can use an onboard computer to dynamically identify an optimal route for each circulating tour. (In contrast, the previous common practice is to merely design a bus circulating route based upon static average demand estimates in a typical day and to operate the buses on a fixed route.) It is possible that, of course, some passengers might reluctantly provide their destination information, especially in the initial stage of system implementation. Incomplete information input certainly worsens the operational efficiency, as we will see from the sensitivity analysis in a later part of this paper. However, we believe that passengers who are not able or willing to provide information can still benefit from the suggested routing and stopping results based on other passengers' input; as they see the advantage of feeding information, they might start doing so for their own sakes.

From the perspective of commuter rail operators, such a bus circulator system is a cost-effective means to connect rail stations to final destinations, supporting a more competitive multi-modal transportation solution and potentially increasing the rail ridership. From the perspective of commuter rail passengers, this bus circulator system allows them to take advantage of the efficiency and rapidness of commuter rails while minimizing the transfer gap and anxiety between commuter rails and final destinations.

In the context of the bus circulator system described above, we name this joint routing and stopping optimization problem the *circulator service network design problem*, following the naming convention in the previous literature. The goal of the problem is to determine an optimal set of routing and stopping decisions for each group of passengers who arrive at a commuter rail station simultaneously and take a bus ride in a shared circulating tour. It should be noted that this network design problem does not involve any physical network construction or expansion; instead, all its decision makings are to be made on the operational level and the resulting operational procedure should be implemented in real time, given that a demand-responsive service is desirable.

Such a bus circulator system at least includes two types of decision makers on two levels: A decision maker on the leading level, i.e., the bus operator, who aims at minimizing the total system cost imposed on both the bus operator and passengers, including the vehicle operation cost, the in-vehicle travel time of all passengers, and (possibly) the out-of-vehicle travel time of all passengers, by choosing where to make stops and which route to take to cover all these stops; a group of decision makers on the following level, i.e., all individual passengers, any one of whom determines where to alight the vehicle in terms of the route and stop scheme (given by the bus operator) to minimize his or her walk time between their stop points and final destinations. Obviously, the decisions of these two levels are mutually dependent.

From the perspective of game theory, the interactions between the bus operator and passengers form a typical leader–follower game, or Stackelberg game (Gibbons, 1992). In this game, the bus operator first makes routing and stopping