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Transit network design based on travel time reliability

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ABSTRACT

This paper presents a transit network optimization method, in which travel time reliability on road is considered. A robust optimization model, taking into account the stochastic travel time, is formulated to satisfy the demand of passengers and provide reliable transit service. The optimization model aims to maximize the efficiency of passenger trips in the optimized transit network. Tabu search algorithm is defined and implemented to solve the problem. Then, transit network optimization method proposed in this paper is tested with two numerical examples: a simple route and a medium-size network. The results show the proposed method can effectively improve the reliability of a transit network and reduce the travel time of passengers in general.

1. Introduction

Traffic congestion is a growing problem in almost every metropolis or major city in the world. In China, traffic congestions and delays are becoming more and more frequent and severe as rapid increase of automobile ownership. Authorities have recognized the congestion problem and the induced other problems including air pollution and energy consumption, etc. Due to limited urban land resources, the mode of expanding the street and road systems is not a sustainable development choice for the existing traffic problems. Therefore public transportation is considered as one of the best ways, through which our major urban centers can fight congestion. In most cities in China, the developments of public transportation systems are given priority to relieve congestion.

Transit route network is the "infrastructure" of transit system, and determines the efficiency as well as service level of public transportation. From 1960s, the transit network optimization has attracted many attentions from researchers from all over the world (Dubois et al., 1979; Ceder and Wilson, 1986; Hasselström, 1981; Baaj and Mahmassani, 1995; Guan et al., 2004; Sonntag, 1979; Wang and Yang, 2001).

In most previous studies, most transit network optimization models were based on the lengths or the averages of travel times of links. Some researchers hold that transfer optimization attempts to minimize the overall inconvenience, which is in terms of the travel time and transfers, to passengers who must transfer between lines in a transit network (Bookbinder and Desilets, 1992; Dessouky et al., 1999). And in order to provide an effective computational tool for the optimization of a large-scale transit route network. Some studies aim to minimize transfers and optimize route directness while maximizing service coverage (Zhao and Gan, 2003). In the above literatures, the solution algorithms are mainly based on classical dynamic programming approaches (e.g. Dijkstra's algorithm). However, bus operations are under a complex and uncertain traffic conditions. It is obvious that the lengths and the mean travel times cannot reflect the detailed status of the travel times that may be varied greatly from day to day due to network uncertainty.

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Although average travel times of some links maybe equal, big variance of the travel times could lead to poor transit reliability. The reliability of transit routes is very important for bus passengers, especially when commuters (e.g., workers and students) have to consider the travel time variations if they want to arrival on time. For the unreliable transit service, commuters need to accommodate some extra time in their schedule to ensure to arrive on time. Large extra time will cause inconvenience and dissatisfaction to bus passengers. Therefore, designing reliable and efficient transit network is the key part in transit planning and operation.

The designed transit network, by introducing the reliability of travel time of road links rather than the average travel time, is better for practical use. Recently, the uncertainty of transport networks has been applied for transportation network design (Lo and Tung, 2003; Sumalee et al., 2006). Furthermore, some researchers presented several methods to measure the reliability of travel time of transportation network (Park et al., 2007; Lyman and Bertini, 2008; Shao et al., 2006). And there are several studies on the reliability evaluation of transit routes or network (Chen et al., 2009; Sorratini et al., 2008; van Oort and van Nes, 2009; Casello et al., 2009; Yu et al., 2012, Yan et al., 2013). However, link travel time in reliable shortest path problem is non-additive (Chen et al., 2012, 2013a,b,c). While Bellman's Principle of Optimality (Bellman, 1958), states that a sub-path between any pair of nodes on the shortest path is the shortest path itself. So for solving reliable shortest path problem (RSPP) advanced methods such as multi-criteria label-setting algorithm and a multi-criteria A^* algorithm should be adopted (Chen et al., 2013a).

Passenger transportation in most cities of China mainly relies on efficient public transportation systems. Convenient transit service is considered as an effective way to attract travelers away from private car trips toward transit service in congested metropolitan areas. Therefore, an efficient transit network should maximize bus service coverage, i.e., the transit network should provide service for most, if not all, of the transit demand. And in China, the operating and constructing of public transportation are mostly based on government grants, so local transit agencies take more priorities on the benefit of passengers than the benefit of themselves. As the above mentioned, the designed transit network based on the average travel times cannot provide reliability transit service in practice. Therefore, the objective of this paper is to optimize transit network based on travel time reliability of transportation network. The optimized transit network considering the uncertain traffic conditions can provide passengers reliable transit service.

In this paper, the contributions with respect to the current literature are the following: the paper presents a robust optimization model considering travel time uncertainty to satisfy the demand of passengers and provide reliable transit service. The paper aims to design transit route network based on the travel time reliability. The remainder of the paper is organized as follows. The assessment of the travel time reliability is given in Section 2. In Section 3, a heuristic algorithm based on Tabu search is presented. In Section 4, some computational results are discussed. And lastly, the conclusions are discussed in Section 5.

2. Optimization model

In China, bus system is not only the most important component of public transportation system, but also one of the most effective strategies that supporting by government to alleviate traffic congestion and pollution in urban areas. In order to attract more passengers, passengers' benefit should be taken a daily priority by transit agencies. And most bus passengers prefer rapid, convenient and reliable transit service. Therefore, the efficient design of transit network based on travel time reliability should look at the benefits of passengers first. In this study, the objective is to maximize the efficiency and reliability of the optimized transit network considering the benefits of passengers.

Transit journey travel time is one of the primary concerns of passengers. In this study, the minimum average passenger journey travel time of the whole network is used to denote the passenger benefits. Firstly, the transportation system can be described in terms of nodes (N) and links (L) which connect pairs of nodes. Then, a connected road network with a directed graph $G = \{N, L\}$ is the base of the transit network design. A binary variable Δ_{ij} represents whether the nodes i and j are adjacent. If the nodes i and j are adjacent, i.e., $l_{ij} \in L$, $\Delta_{ij} = 1$, otherwise $\Delta_{ij} = 0$.

Consider a transit network with a set of S stops, A segments between pairs of stops and R routes to be served. In this study, the stop set is the subset of the node set, i.e., $S \subseteq N$. And each segment may contain one or several links. The binary decision variable x_{ij}^r equal to 1 if and only if the link l_{ij} on the designed route $r \in R$, otherwise $x_{ij}^r = 0$.

Assume Q represents the total bus passenger demands of the transit network and q_{od} represents the bus passenger demand between the nodes o and d ($o, d \in N$). A binary variable y_{odij}^r denotes whether the bus passenger demand q_{od} between the nodes o and d uses the link l_{ij} on the route r.

$$\Delta_{ij} = \begin{cases} 1 & \text{if the nodes } i \text{ and } j \text{ are adjacent } (l_{ij} \in L) \\ 0 & \text{otherwise} \end{cases} \tag{1}$$

$$x_{ij}^r = \begin{cases} 1 & \text{if the link } l_{ij} \text{ on the route } r \\ 0 & \text{otherwise} \end{cases} \tag{2}$$

$$y_{odij}^r = \begin{cases} 1 & \text{if the passenger uses the link } l_{ij} \text{ on the route } r \\ 0 & \text{otherwise} \end{cases} \tag{3}$$