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Long-term planning for ring-radial urban rail transit networks

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A B S T R A C T

Extensive work exists on regular rail network planning. However, few studies exist on the planning and design of ring-radial rail transit systems. With more ring transit lines being planned and built in Asia, Europe and the America's, a detailed study on ring transit lines is timely. An analytical model to find the optimal number of radial lines in a city for any demand distribution is first introduced. Secondly, passenger route choice for different rail networks is analyzed, for a many-to-many Origin-Destination (OD) demand distribution, based on a total travel time cost per passenger basis. The routes considered are: (1) radial lines only; (2) ring line only or radial lines and ring line combined; or (3) direct access to a destination without using the rail system. Mathematica and Matlab are used to code the route choice model. A cost-benefit optimization model to identify the feasibility and optimality of a ring line is proposed. Unlike simulations and agent-based models, this model is shown to be easily transferable to many ring-radial transit networks. The City of Calgary is used as an example to illustrate the applicability of each model. The existing urban rail network and trip distribution are major influencing factors in judging the feasibility and optimal location of the ring line. This study shows the potential net benefit of introducing a ring line by assessing changes in passengers' costs. The changes in passenger cost parameters, such as ride cost and access cost, are shown to greatly influence the feasibility of a ring line.

1. Introduction

In a purely radial rail network, trips with destinations away from the city center have to be made along the radial lines passing through the center. For cross-town trips, this can cause unnecessary passenger loads on some corridors, high transfer loads in the city center, and additional passenger travel distances, travel times, and transfers. A ring line provides better connectivity and decreases a network's vulnerability, since there are alternative routes to reach each destination. Laporte et al. (1994), Kennedy and Derrible (2009), and Yi and Chao (2010) showed that a ring or circumferential transit line can greatly improve network connectivity, directness, and operational efficiency of the network.

Ring transit lines are laid out around a city center, intersecting radial lines, creating transfers and, thus, making an integrated multipath network. They can be a closed loop with no terminus or only part of a ring. They are found less in North American cities than in European and Asian cities. The reason for this may be due to the separation of land uses of North American cities, which are typically characterized by highly concentrated commercial/business activities in a central

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business district (CBD) and surrounded by more distant residential neighborhoods; whereas, European and Asian cities are mostly characterized by larger centers that have greater mixed land use and are surrounded by several cross-town activity centers (Vuchic, 2005).

In addition to the possible savings in transit riders' travel and waiting times, increased transit network connectivity, reliability and the reduction of the transit load in the downtown core, the presence of ring lines plays an important role in increasing accessibility to suburban areas and, thus, the development of new satellite centers, which are often associated with smart growth plans. While an auto ring road usually encourages development to take place on the outskirts of a city beyond the ring (Miller, 2012), a transit ring line can encourage higher density, mixed-use development along an inner city ring corridor. A ring transit line is also important for public transit users, in terms of trip directness, mobility, and accessibility. The average circumference of existing ring lines is 28.18 km with a standard deviation of 11.59 km, ranging from as short as 10 km (Glasgow) to 57 km (Beijing) (Saidi et al., 2014). Within big cities, most ring lines orbit a city center, connecting peripheral rail stations.

Saidi, et al. (2014) performed a regression analysis to review rail transit networks around the world and found relationships between transit ridership and city parameters, such as population, city area, and population density. They also reviewed cities with rail ring transit lines, such as London, Moscow, Berlin, Beijing, Tokyo, and Shanghai. They suggested that a feasible ring line should connect a band of higher density areas possibly with satellite centers. Many cities, such as Paris (Leasia, 2013), Chicago (Warade, 2007), Washington, DC (Reed, 2013), Bangkok (Urbanalyse, 2012), and Moscow (Panin, 2014) are considering a new ring line.

There is intensive literature on rail transit planning (e.g., Baaj and Mahmassani, 1995; Wirasinghe and Vandebona, 1999; Lee and Vuchic, 2005; Marín and García-Ródenas, 2009; Chen et al. 2015). These models except for Chen (2015) are not directly applicable to ring lines. There is a gap in the transit literature on examining whether and when a ring line is feasible in a given city and, if it is feasible, how to obtain its optimal alignment. With the increasing interest to build ring transit lines in Asia, Europe and the America's, a more detailed research study on ring transit planning is needed, and this paper takes several steps in this direction.

In order to determine the feasibility of a ring line for a city, a detailed economic study is required based on population and job distribution in the city, transit mode share, value of ride time, wait time for the passengers, and unit values of operations and capital cost of the rail transit line. Such variables, in particular current and future trip distribution in a city and the current configuration of the radial rail transit system, would greatly impact the feasibility and optimal layout of a ring line.

This paper considers an urban transit network with radial lines and a ring rail for a long range planning horizon. Since many cities have a CBD at the center and radial lines that connect the suburban areas to the center, initially we identify the optimal number of rail transit lines for a city. We first develop a mathematical model for the optimal number of radial lines and then extend the analysis to find the optimal radius and feasibly of a ring line. This research combines mathematical models which will be applicable to most cities with realistic assumptions of trip patterns by using actual or forecasted origin destination (OD) travel demands, as opposed to approaches that assume theoretical demand densities that are either uniform or exponential (Badia et al., 2014; Tsekeris and Geroliminis, 2013; Li et al., 2012; Tirachini et al., 2010).

1.2. Rail transit planning – a review of the literature

Approximately 90 years of transit network research started with attempts at a solution to a line planning problem by Patz (1925). Transit network design has been used for various modes, such as bus (Newell, 1979; Wirasinghe and Ghoneim, 1981; Wirasinghe and Vandebona, 2011; Cipriani et al., 2012; Szeto et al., 2012), light rail (Liu et al., 1996; Shin et al., 2004; Samanta et al., 2011), heavy rail (Wirasinghe and Vandebona, 1999; Laporte, 2011), and mode combinations (Wirasinghe, 1980; Uchida et al., 2005; Wan and Lo, 2009; Mohaymany and Gholami, 2010) to produce an optimal transit network configuration.

Depending on the ownership of the urban transit system (i.e., private or public), the objective function might be formulated differently. Some consider user travel time minimization as the objective and the transit agency's cost and revenue as the constraints. For a private transit agency, profit maximization is the main objective and user travel time might be considered as the constraint. For social benefit maximization, a bi-objective optimization framework can be adopted, in which optimizing users' and agency's cost is considered simultaneously (Lee and Vuchic, 2005).

Few studies exist on the specific planning and design of ring transit lines (Saidi et al., 2014). There is a similar issue in the design of ring roads. Zitron (1974) proposed a continuous model of optimal cost of roads in a circular city. An Euler–Lagrange equation was derived for the general radial symmetric case for position-dependent cost. The analysis determined the minimal cost routes between two diametrically opposite points at the city limits. Tan (1966) estimated the average trip length for different road networks (e.g., direct, ring, rectangular, radial, and arc-radial) in a circular city. He found the average area of road space required and average travel time for each configuration. Additionally, Li et al. (2014) presented an analytical model to optimize circular cordon toll locations in a monocentric city. It was shown that population distribution has a significant effect on the optimal location of cordon radius and social efficiency of the urban system.

Continuum Approximation methods have been used by several researchers (Newell 1973; Wirasinghe and Ghoneim 1981; Wiraisnghe and Ho 1982; Vaughan 1986; Daganzo 1984; Chen e. al. 2015) using "slowly varying" continuous variables instead of discrete variables for mathematical modeling and optimization. Parameters such as station spacing, line spacing,