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Design of a rail transit line for profit maximization in a linear transportation corridor

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ABSTRACT

This paper addresses the design problem of a rail transit line located in a linear urban transportation corridor. The service variables designed are a combination of rail line length, number and locations of stations, headway and fare. Two profit maximization models, which account for the effects of different transit pricing structures (flat and distance-based fare regimes), are proposed. In the proposed models, the effects of passenger demand elasticity and population density along the urban corridor are explicitly considered. The solution properties of the proposed models are explored and compared analytically, and the indifference condition for the two fare regimes in terms of the operator's net profit is identified. A heuristic solution algorithm to solve the proposed models is presented. Numerical examples are provided to show the effects of the fare regimes, rail capital cost and urban configuration (in terms of urban population distribution and corridor length) on the design of the rail transit line and the profitability of the rail transit operations.

1. Introduction

1.1. Background and motivation

Over the past few decades, rapid urban expansion due to urbanization and economic growth in some large Asian cities, including Shanghai and Hong Kong, has drastically increased the size of these cities. Traffic congestion has worsened due to the shortage of space for road expansion projects to accommodate the growing traffic demand in urban areas. To address this problem, the local authorities of these cities have launched rail transit development projects, which include extension of existing rail transit lines and construction of new rail transit lines. For instance, the Shanghai municipal government is currently extending Rail Line 11 about 5.76 km westwards and creating four new stations on the line, while the Hong Kong government recently approved a proposal to build a new metro line to connect Shatin New Town to Central (i.e., the central business district (CBD) of Hong Kong), with a total length of 17 km and 10 stations. The construction of this new metro project is expected to start in 2011 and be completed in 2019.

In principle, the basic parameters to be determined in planning a rail transit line project include the rail line length, number and locations of stations, headway and fare (see, e.g. Vuchic, 2005; and the references shown in Table 1). The design of these parameters depends very much on the population density in the planning area. This is because the urban population

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Table 1
Some major analytical models for transit service design.

Citation	Decision variables	Objective function	Transit mode	Network geometry	Passenger demand
Vuchic and Newell (1968)	Station location and spacing	Min. total user travel time	Rail	Linear	Uniform, inelastic, many to one
Vuchic (1969)	Station location and spacing	Max. number of passengers	Rail	Linear	Uniform, inelastic, many to one
Hurdle (1973)	Route spacing and frequency (headway)	Min. operator and user cost	Feeder bus to rail	Rectangular grid	Piecewise uniform, inelastic, many to one
Hurdle and Wirasinghe (1980)	Station location or spacing	Min. operator and user cost	Rail	Rectangular grid	Uniform, inelastic, many to one
Wirasinghe and Ghoneim (1981)	Stop spacing	Min. operator and user cost	Bus	Linear	Piecewise uniform, inelastic, many to many
Kocur and Hendrickson (1982)	Route spacing, headway and fare	Max. operator profit, max. user benefit	Bus	Rectangular grid	Elastic, many to one
Wirasinghe and Seneviratne (1986)	Route length	Min. operator and user cost	Rail	Linear	Piecewise uniform, inelastic, many to one
Kuah and Perl (1988)	Route spacing, headway and stop spacing	Min. operator and user cost	Feeder bus to rail	Rectangular grid	Piecewise uniform, inelastic, many to one
Chang and Schonfeld (1993)	Zone size, route length, route spacing and headway	Min. operator and user cost	Bus	Rectangular grid	Uniform, inelastic, many to one
Spasovic et al. (1994)	Route spacing, length, headway and fare	Max. operator profit, max. social welfare	Bus	Rectangular grid	Uniform, elastic, many to one
Liu et al. (1996)	Rail line location and length	Min. operator and user cost	Feeder bus to rail	Linear	Piecewise uniform, inelastic, many to many
Chien and Schonfeld (1997)	Route spacing and headway	Min. operator and user cost	Bus	Rectangular grid	Uniform, inelastic, many to many
Furth and Rahbee (2000)	Stop spacing	Min. operator and user cost	Bus	Linear	Uniform, inelastic, many to one
Saka (2001)	Stop spacing	Min. bus fleet size	Bus	Linear	Inelastic, one to one
Wirasinghe et al. (2002)	Terminus location	Min. operator and user cost	Feeder bus to rail	Linear	Piecewise uniform, inelastic, many to many
Chien and Qin (2004)	Stop location	Min. operator and user cost	Bus	Linear	Discrete, inelastic, many to one

density directly influences the level of passenger demand. For instance, in a sparsely populated city (e.g. many Western cities), operators prefer to short rail transit lines in order to minimize their costs (Spasovic and Schonfeld, 1993; Spasovic et al., 1994). However, in a densely populated city, such as Hong Kong in which most people use transit services for their daily travel, a benefit-driven operator has an incentive to extend the rail transit line from the city's CBD area into its outer areas so as to procure more profit. It is, therefore, important to address the relationship between the design parameters of the rail transit line and the urban population density.

Obviously, there are various tradeoffs between the extension of a rail transit line and its associated costs. For instance, the length of a rail line is closely related to its service coverage and its capital and operating costs. A longer rail line provides greater service coverage but incurs higher capital and operating costs, whereas a shorter rail line has lower capital and operating costs but offers less service coverage. The station spacing along a rail line directly affects the train operating speed and train dwell time at stations, and thus passenger demand on that line. In general, shorter station spacing can decrease the average passenger access time to stations. However, it also increases the average passenger in-vehicle travel time and train operating costs because of higher acceleration and deceleration delays caused by frequent stops. Conversely, longer station spacing can increase the train operating speed and decrease the average passenger in-vehicle travel time, but also increases the average passenger access time to stations. Since these tradeoffs are directly related to the revenues and thus profits of the rail transit operations, all of these parameters – the rail line length, number and spacing of stations, headway and fare – should be carefully designed. The present study addresses this design problem for strategic planning purposes.

1.2. Literature review

Significant progress has been made in transit service design models since the pioneering work of Vuchic and Newell (1968) in developing an analytical continuum model to optimize rail station spacing. For the convenience of readers, we have summarized in Table 1 some principal contributions of various analytical models to transit service design, which include: decision variables, such as the location or spacing of transit routes and/or stations, headway, and fare; the objective function, which is typically the minimization of the total system cost (i.e., the sum of operator and user costs); the transit mode involved, such as rail, bus or feeder bus; the geometry of transit lines, such as a linear structure or rectangular grid; and demand characteristics, including fixed or elastic demand, uniform or non-uniform demand distribution, and one-to-one, many-to-one, or many-to-many travel patterns.