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Financial sustainability of rail transit service: The effect of urban development pattern

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ABSTRACT

The positive correlation between urban population density and transit service patronage is well recognized, as was ascertained via statistical approaches in previous studies. In this study, we seek to derive some prescriptive results of the relationship between urban population density and the financial sustainability of rail transit service. We consider an idealized metropolitan region with a central business district (CBD) at its center, whose population is distributed according to a certain density gradient pattern. Trips generated from the region to the CBD are either served by the rail service supplemented with feeder buses, or by autos. We study the effect of urban development density on the financial sustainability of the rail service by examining the supply and demand patterns. The analysis result sheds light on the threshold urban density required to ensure financially sustainable rail transit service. The result also provides guidelines to policy makers for planning urban developments with financially sustainable rail services.

1. Introduction

Public transit services (PTS) are important assets to any major city. It is ideal if the PTS are financially sustainable[1] with affordable fares and expedient quality. The key lies in how the urban form and density are planned to ensure their sustainability. Indeed, the relationship between urban density and transport characteristics had been studied before (Cervero and Kockelman, 1997; Dunphy and Fisher, 1996); the results showed that urban density is positively correlated with PTS usage. Previous studies generally analyzed the problem descriptively based on statistical approaches. Newman and Kenworthy (1999), as well as Kenworthy and Laube (1999), collected data from 32 cities around the world and performed regression analyses between transport variables and urban density. Among the findings, they found that higher urban density is positively correlated with lower levels of car ownership and auto trips, and higher levels of transit trips. Sinha (2003) pointed to a similar conclusion, that the fundamental variable to increased transit usage and sustainability is urban population density or activity density. Along a similar thread, using Hong Kong as an example, Tong and Wong (1997) contended that the high density in Hong Kong was one major contributing factor to its commercially viable public transportation services.

According to the literature, there is no doubt that high urban density is positively correlated with high transit usage. The descriptive result is important and interesting. Yet they are not sufficiently refined to be adopted as policy guidelines. Basically, how high should the urban density be for the provision of financially sustainable PTS? A prescriptive answer provides guidelines for integrating the planning of urban development with financially sustainable PTS. Granted high density developments are not panacea for every region, the answer at least allows planners to understand the implications of PTS quality and financial sustainability in relation to a certain density development. Pushkarev and Zupan (1977), based on a statistical approach, developed a set of "land-use thresholds" that are necessary to justify financially different types of transit investments. However, few previous studies analyzed this problem based on analytical methods. This study aims to fill the literature gap by developing analytical models to investigate this question. Actually, the answer to this prescriptive question is specific to the type of PTS under consideration. It also requires a detailed transportation analysis. One must pay attention to the specific transportation characteristics under study, and the demand patterns in a defined geographical and network context. In modeling public transit service in multi-modal transport networks, some previous research works in the literature applied discrete modeling approach on multi-modal transport network. Bovy and Hoogendoorn-Lanser (2005) proposed modeling approach on route choice behavior in multi-modal transport networks. Lo et al. (2003) developed a state-augmented multi-modal (SAM) network approach

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[1] i.e., the fare revenue is sufficient to at least recover the cost.

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to model transfer and nonlinear fare structure in multi-modal transport network. Sumalee et al. (2011) developed a multi-modal transport network assignment model considering uncertainties in both demand and supply sides of the network. Li et al. (2013) constructed a train routing model combined with a train scheduling problem. Besides, researchers also use continuum modeling approach to model multi-modal network (e.g., Liu et al. (2009), Du and Wang (2014) and Wang and Du (2016)).

This study aims to develop analytical models to provide prescriptive answers to the following question: what kinds of urban development patterns, and their associated population density profiles, would provide favorable conditions for financially sustainable rail transit services. We recognize that there are sophisticated simulation software for evaluating the performance of specific transit system designs under specific application scenarios. Our focus here, on the other hand, is to explore the broader issue of the interactions between urban development patterns and rail services planning and their financial viability. To do so, we analyze the interactions between rail service demand and supply patterns via analytical models. Inevitably, some simplifying assumptions are needed to make the method tractable, so that the relationships between the urban development pattern and system design characteristics can be established, which would offer planners, both transit and land use, some guidelines for financially sustainable rail services. If one is interested in analyzing the performance for specific scenarios, the methodology developed in this study is still applicable, achieved by coding the specific scenario parameters in the model, as illustrated in the case study of the TKO new town in Hong Kong (Lo et al., 2008). To summarize, the primary objective of this study is to develop an analytical approach to investigate the relationship between urban density distribution and public transit service financial sustainability. By doing so, we can answer the prescriptive question that how high urban density is required to ensure a financially sustainable public transit service can be provided. In contrast, previous studies in the literature analyzed this question descriptively by using statistical approach. The developed analytical approach in this study is by no means a substitute for the statistical approach, but contributes to the literature by serving as a complement to the statistical approach to provide the policy makers guidelines on integrated urban planning and sustainable public transit service planning.

In this study, for exposition purposes, we analyze the scenario of providing rail transit service in an idealized metropolitan region. We consider an idealized mono-centric metropolitan region with a central business district (CBD) at its center, whose land use development is described according to the density gradient model, with the urban population density expressed as the negative exponential function. That is, the population density at the CBD is the highest, which gradually tapers outward from the CBD. The basic equation $d_x = d_0 e^{-bx}$ is used to express the density–distance relationship (Clark, 1951), where d_x represents the density at distance x from the CBD; d_0 the density at the CBD; b the rate or gradient of decline of density. The combination of the density gradient factor b and the central density d_0 decides the spread of urban density within the idealized metropolitan region. In this study, we analyze the combinations and ranges of d_0 and b that can allow for financially sustainable rail services.

In the formulation, each trip generated in the metropolitan region is served either by the rail service together with a feeder bus, or by autos, as determined by the generalized travel costs of these two competing modes. The objective of this study is to minimize the total costs of providing the rail service from the perspective of the rail service operator, including amortized construction costs, operation costs, and the total fare revenue (expressed in negative terms to offset the costs); or in other words, we assume that transit operators' primary objective is profit maximization. The model takes into account the decision variables of the operator, including inter-station spacing, number of rail stations, and service headway, as they impact both the costs as well as the patronage and hence the fare revenue. To find the minimum urban density for breakeven operations (i.e., the revenue can fully recover the costs), we optimize the rail service operation, such as inter-station spacing, headway, etc., and then study the sensitivity of the urban density on the total costs. The results show that many different patterns of urban density spread, as represented by different combinations of d_0 and b, can allow for financially sustainable rail services. Through this modeling effort, the surprising result is that other than compact urban developments with high density, which are widely recognized to be imperative for PTS financial sustainability, urban developments with uniform but lower population density may also achieve the same outcome. This study also compares these viable cases to illustrate how the different urban density distribution patterns affect the financial sustainability of rail services, as well as their operations and designs.

This paper is organized as follows. Section 2 formulates the model to estimate the total costs under various urban density forms as a simple bi-level program. Section 3 describes the solution method. Section 4 contains a numerical example to illustrate the formulation. Finally, Section 5 provides some concluding remarks.

2. Model formulation

We consider an idealized metropolitan region with a CBD at its center. The physical layout of the region and public transport network are schematically illustrated in Fig. 1. It is assumed that the urban population is continuously distributed across the circular region, with urban density declining from the city center (CBD) towards the boundary. The region is assumed to have a closed urban form, while the urban boundary is determined by the total population and the population density distribution pattern. The dashed radial lines in Fig. 1 are used to divide the metropolitan region into even sub-regions or sectors. Several radial rail lines are designed to serve the commute traffic to the CBD, each for one sub-region or sector of the city. It is assumed that each sub-region or sector is sufficiently large (i.e., the angle

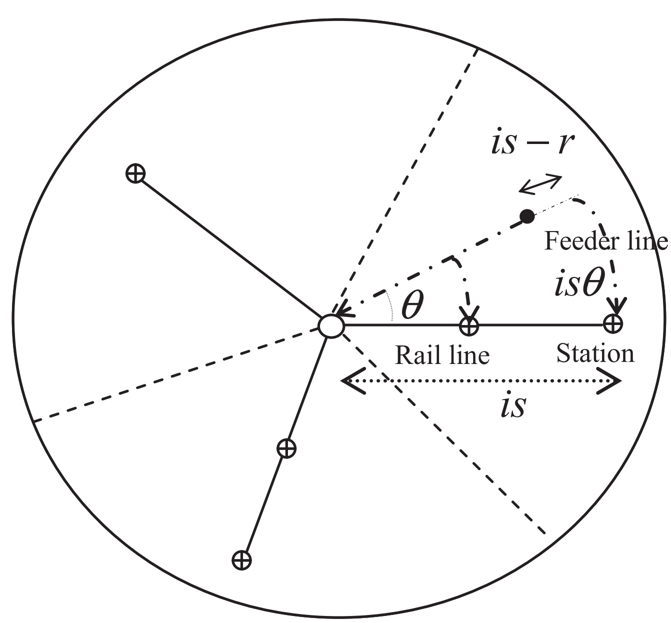

Fig. 1. The idealized metropolitan region.