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Improved models for technology choice in a transit corridor with fixed demand

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ABSTRACT

We present three extensions to a base optimization model for a transit line which can be used to strategically evaluate technology choices. We add to the base model optimal stop spacing and train length, a crowding penalty, and a multi-period generalization. These extensions are analytically solvable by simple approximations and lead to meaningful insights. Their significance is illustrated by means of an example in which two road modes and two rail modes are defined by a set of techno-economical parameters. These parameters loaded in the base model yield dominance of road modes for all but the largest demand levels. We consistently keep this set of parameters for all models, and show how the break-even points between road and rail modes progressively recede toward lower demand levels when model refinements – not parameter changes – are applied. Scenario analyses of plausible parameter sets highlight the model's versatility, and caution on general conclusions regarding technology dominance.

1. Introduction

Rapid transit provides a key tool for sharply reducing the negative environmental externalities of transport in urban areas, and for improving access to employment and services to lower income groups (Fulton and Replogle, 2014). Rapid transit consists of bus rapid transit (BRT), light rail transit (LRT), metro, and commuter rail. In recent years, several models have been put forward for the strategic choice of transit technology (see e.g. Daganzo, 2010; Estrada et al., 2011; Sivakumaran et al., 2014; Tirachini et al., 2010b). Here we extend in several directions the model of Tirachini et al. (2010b) which is used as our base model. In it the optimized variable is the frequency, the objective function is the minimization of the sum of passenger and operator costs, and the demand is assumed to be fixed in a single period. This model can be solved analytically. We first extend the base model to account for optimal stop spacing. We then introduce optimal train length and a crowding penalty. Finally, we consider a two-period case and a multi-period generalization. In spite of some notational complexity, the proposed extensions can be solved by simple approximation schemes which provide some analytical insights into the structure of optimal solutions. In particular, we find that the ratio of optimal stop spacings among different modes follows a square root formula. A crowding penalty moves away the optimal frequency from the minimal values induced by the critical capacity. Road and rail modes handle crowding in different ways. Road modes aim to offer a higher frequency, whereas rail modes provide leverage on both frequency and train lengths. The multi-period model further increases the model realism when comparing different technologies.

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The remainder of this paper is organized as follows. Section 2 contains the literature review which motivates our work. Section 3 presents mathematical models and approximation schemes. Section 4 provides numerical analyses of a base parameter set, and Section 5 discusses plausible scenarios. Some conclusions are reported in Section 6.

2. Literature review

We first review the relevant literature on microeconomic models of transit systems in Section 2.1, and then the analytical models for transit network design in Section 2.2. Finally, we present our approach in Section 2.3.

2.1. Microeconomic models

Jara-Díaz and Gschwender (2003) review microeconomic models for the operation of public transport, propose extensions, and compare models' results. The authors extend the model of Jansson (1980), where demand is fixed, by including the effect of vehicle size on operating costs and the influence of crowding on the value of in-vehicle time. The authors show how a better characterization of user cost significantly increases optimal frequencies, and alters key design variables of a transit system. Bruun (2005) introduces a parametric cost model for BRT and LRT in order to compare these two technologies for base and peak service hours in trunk lines. Both the demand level and the shape of the demand profile determine operating costs. The author observes that rail technology can accommodate demand variations through the addition and removal of carriages from trains. According to cost parameters representative of transit agencies in the United States, the model finds LRT to be increasingly attractive when demand is above 2000 spaces per hour. In recent years, the effect of crowding on passengers' value of time started to attract some attention. Tirachini et al. (2013) review different literature threads related to crowding in public transport such as psychometric methods, engineering, economics, etc. Additional references are found in Qin and Jia (2012), Qin (2014), and De Palma et al. (2015).

2.2. Analytical models for transit network design

The literature on structural transit analysis was initiated by Byrne (1975) for radial lines, Newell (1979) for a hub-and-spoke network, Vaughan (1986) for ring and radial routes, and Chien and Schonfeld (1998) for a rail trunk line with a bus service as a feeder. In recent years the continuous approximation literature has addressed the strategic evaluation of transit technologies. Daganzo (2010) studies structural characteristics of a transit system for a square shaped urban area. The main assumption is that the origin-destination flows are uniformly and independently distributed over the square. The author acknowledges that this assumption penalizes the transit system with respect to private car, but justifies this assumption since it sets a higher bar for transit success. The objective function minimizes the sum of user and agency costs under a fixed demand. The user cost is the sum of access, waiting, transfer, riding, and egress times for an average trip. The agency cost is the sum of fixed and variable costs of the transit system normalized per trip. The non-linear model can be easily solved by a grid search on the domains of the variables. The author compares road and rail rapid transit systems and concludes that BRT dominates LRT and metro. This result is not surprising given the uniform demand assumption. In fact, the formula derived for the critical load results in relatively low values of transit occupancy, i.e. trains are not filled up. Estrada et al. (2011) extend the model of Daganzo (2010), and present a case study. Badia et al. (2014) further extend the model of Daganzo (2010) to cities with a radial street pattern. Sivakumaran et al. (2014) consider a hierarchical transit systems in which rail transit is the backbone of a bus feeder network.

Tirachini et al. (2010b) present models for a single transit line of fixed length where the number of stops is given. Under fixed demand, the goal of social welfare maximization is equivalent to the minimization of total user and operator cost. Under elastic demand, two goals are modeled: the maximization of the operator's profit and the maximization of social welfare. A distinctive characteristic of this model is that the critical load is defined by a specific parameter. Hence, this approach can synthetically model every type of demand distribution, centripetal or uniform. Passenger costs related to access, waiting, and in-vehicle times are finely represented. The authors also provide an extension to numerically account for crowding costs. This analysis is further expanded in Tirachini et al. (2010a) to a multi-period radial network in a circular service area.

2.3. Proposed approach

This literature review highlights the relevance of several issues. User values of time must be finely characterised (Jara-Díaz and Gschwender (2003), Tirachini et al. (2010b)), in particular crowding (De Palma et al., 2015; Qin, 2014; Qin and Jia, 2012; Tirachini et al., 2013, and references therein). The cost structure of different technologies is paramount (Bruun, 2005). Assumptions on demand distribution are crucial since rail transit systems arise when peak hour capacity is an issue (see e.g. Vuchic (2005), Vuchic et al. (2013)). Simple analytical models show broader applicability than numerical approaches (Daganzo (2010), Estrada et al. (2011)). Analytical models can be also useful to environmental assessments (Griswold et al. (2013), Griswold et al. (2014)). For these reasons, we extend the transit line model of Tirachini et al. (2010b) which can easily accommodate different assumptions on demand distribution and already provides a refined characterization of user costs. The extensions proposed in the following section show how a transit line model can be made more realistic without sacrificing analytic tractability, by resorting to approximations.