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Models for technology choice in a transit corridor with elastic demand

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ABSTRACT

We present two optimization models for a transit line under the assumption that the demand is elastic and can be approximated by a linear function of fare and passenger travel time components. These models can be used to strategically evaluate technology choices. We study the effect of demand elasticity on the technology choice by analytic and numerical comparison with some fixed demand models. We assume a range of objective functions having as two extrema the maximization of operator's profit and the maximization of social welfare. We show both analytically and numerically that accounting for demand elasticity does not change the conclusions that can be derived by an equivalent fixed demand model. This invariance holds for a broad range of objective functions in the elastic case. The significant difference between the two objective function extrema lies in the proportions of captured demand.

1. Introduction

The research question considered in this paper is the effect of demand elasticity on the technology choice for a transit line. We extend the transit technology choice models of Moccia and Laporte (2016) by assuming an elastic demand which depends linearly on the fare and passenger travel time components. We posit a general setting where passenger travel time components depend non-linearly on the demand level or other operating variables. For example, we incorporate in the in-vehicle time a crowding penalty which is a function of the vehicle load ratio. We assume a range of objective functions having as two extrema the maximization of operator's profit and the maximization of social welfare. Our contribution is the demonstration of an equivalence scheme between fixed and elastic demand optimization models. Its significance is twofold. First, the equivalence scheme is instrumental to an effective solution method for the elastic demand optimization model. A bounding procedure and a decomposition scheme are presented. Second, we show both analytically and numerically that accounting for demand elasticity does not change the conclusions that can be derived by an equivalent fixed demand model. For a given level of captured demand, the optimal configuration and the operating policies are invariant with respect to the assumptions on the demand model, fixed or elastic. This invariance holds for a broad range of objective functions in the elastic case. The break-even points between technologies do not change when demand elasticity is considered. The approximated proportion of captured demand under profit maximization is circa half of that under social welfare maximization.

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These results do not rely on a specific assumption on the fare elasticity parameter. When the fare elasticity is very small the proportion of captured demand tends to the derived upper bound.

1.1. Literature review

The literature on structural transit analysis was initiated by Byrne (1975) for radial lines, by Newell (1979) for a hub-and-spoke network, by Vaughan (1986) for ring and radial routes, and by Chien and Schonfeld (1998) for a rail trunk line with a feeder bus service. In recent years several continuous approximation-based studies have addressed the strategic evaluation of transit technologies (Daganzo, 2010; Estrada et al., 2011; Badia et al., 2014; Sivakumaran et al., 2014). The main research question that we are dealing with is the effect of demand elasticity on the optimal configuration of a transit line, and hence in Section 1.1.1 we limit our review to some studies that compare fixed and elastic demand models. Another literature thread of concern, the assessment of passenger in-vehicle crowding, is briefly discussed in Section 1.1.2.

1.1.1. Comparison of fixed and elastic demand models

Kocur and Hendrickson (1982) studied the design of a local bus service under linear elastic demand and where the optimized variables are line spacing, headway and fare. Three objective functions were analyzed, namely profit maximization, maximization of a combination of consumer surplus and operator profit, and maximization of consumer surplus subject to a budget constraint. The derived closed form solutions are such that there is a proportionality between headway and line spacing for all the elastic demand objective functions. The authors noted that the same result was obtained by Hurdle (1973) adopting a fixed demand model. Moreover, the authors observed that there is little variation in the optimal values of line spacing and headway from the user's perspective across the range of objective function studied, and they defined this finding as “surprising”.

Chang and Schonfeld (1991) studied single- and multi-period bus networks where there are both a line haul section and a local service area. These authors presented fixed and elastic demand models and compared total cost minimization, and profit and social welfare maximizations. Some of their findings are commented in Appendix A.1.

Tirachini et al. (2010) compared transit technologies for a single line under fixed and elastic demand models and where the optimized variable is the frequency. One of their results relevant to our paper is that the optimal frequency under social welfare maximization is approximately $\sqrt{2}$ times larger than under profit maximization. This finding is commented in Appendix A.2.

Daganzo (2012), under very general assumptions valid not only for transportation but for public services at large, established conditions for the decomposition between system design and control, and demand forecasting and pricing. In the case of consumer surplus as a metric for the net user benefit, the studied objective of an endogenous demand model is the maximization of the sum of the consumer surplus and of the net benefit to the rest of society (the operator profit plus the balance of the externalities). The optimality conditions for the system design and control variables of the former model are proved to be equivalent to those of the generalized system cost minimization at the optimal demand level. In the case of a for-profit operator, the socially optimal design and operating scheme can be induced by a specific payment formula set by a public agency.

A related topic is the optimal transit service supply under fixed and elastic demand models. Van Reeven (2008) questioned the rationale for fare subsidization by presenting a model with endogenous demand where the optimal frequency of a for-profit operator is the same as that of a public agency that maximizes social welfare. This result contradicts the fixed demand model of Mohring (1972) where economies of scale on the passenger waiting cost were found to motivate fare subsidization. Basso and Jara-Díaz (2010), and Savage and Small (2010) reassessed in an elastic demand framework the rationale for transit fare subsidization. Savage and Small (2010) noted that the result of Van Reeven (2008) critically depends on a strong reduction of the effect of fare on demand. Basso and Jara-Díaz (2010) derived optimal frequencies for profit and social welfare maximizations such that the latter is always larger than the former.

1.1.2. Passenger in-vehicle crowding

Wardman and Whelan (2010) reviewed studies on rail crowding in Great Britain. Crowding conditions, in the form of load factor or standing passengers per unit of area, influence the value of time of both seated and standing passengers. Crowding appears to affect the value of time of seated passengers as soon as 50% of the seats are occupied, albeit the worsening is minor at this load factor and occurs only for leisure trips. The most recent and comprehensive studies reviewed by Wardman and Whelan (2010) indicate that the crowding multiplier of the base in-vehicle time with respect to the load factor is well approximated by a piecewise linear function which is equal to one up to the load factor corresponding to the seated capacity, and then starts to increase linearly. More recently, Hörcher et al. (2017) used large scale automated demand and train location data to estimate the user cost of crowding in a revealed preference route choice framework. A linear crowding multiplier model was validated, and this study found that at six passengers per square meter and no chance to find a seat, the value of time *circa* doubles. The authors observed that these new travel time multipliers were comparable in magnitude but somewhat lower than earlier stated preference results.