Economics of Crowding in Public Transport

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Abstract

Many public transport systems are crowded at peak times. This paper proposes a structural model in which public transport users face a trade-off between crowding and schedule delay costs and choose when to travel. We derive the individual cost functions for a uniform fare regime. We then consider several alternative fare regimes and optimal service. We focus on the economic insights of crowding in public transport and differences from the bottleneck model of automobile travel.

1 Research questions

Many transport policies are designed to shift travel from private road vehicles to public transport and other more environmentally friendly modes. Yet most of these policies do not consider crowding on public transport, although it is a fundamental feature of urban mass transit. On the one hand it degrades in-vehicle comfort and the users' satisfaction, and on the other hand, it increases the dwell time, which makes the travel time longer and less reliable. Therefore ignoring the crowding effect in public transport limits the effectiveness of mode-shifting policies. Prud'homme et al. (2012) have shown that the 8% increase in densities in the Paris subway over the 2002-2007 period implies a a welfare loss of at least 75 M€/year.

To analyze the welfare effects of public transit crowding, and policies to alleviate it, in a conceptually consistent way it is necessary to use a structural model that incorporates trip scheduling decisions, an empirically plausible crowding cost function, and alternative pricing (i.e., fare) regimes. Several papers in the transport economics literature have laid much of the groundwork for such a model. Vickrey's (1969) bottleneck congestion model is the seminal work on scheduling of automobile trips. Arnott et al. (1990, 1993) extended it to time-varying tolling schemes and capacity investment decisions. Tabuchi (1993) added public transit by considering a setting in which travelers can choose between driving and taking a rail service with scale economies and no crowding. Danielis and Marcucci (2002) and Mirabel and Reymond (2011) have studied various pricing regimes in the two-mode-bottleneck model. Huang (2000) introduced a linear crowding cost function, but his model excludes scheduling decisions because only one train or bus is assumed to be available.

The traditional framework to study pricing and optimal service in public transport is from Mohring (1972). In this model, the users arrival rate at the origin station is uniform during the peak period.

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Kraus and Yoshida (2002) consider that there is an unique preferred arrival time at destination, that waiting time at the station is possible and that the number of users in a train cannot exceed a strict capacity . They derive both optimal pricing and service and they disconfirm Mohring's finding which states that the optimal service frequency increases with the square root of the raise in patronage. The decentralized optimum is highlighted but the equilibrium user cost function has not received so much attention.

We build on this corpus of work a structural model of public transportation with crowding. The public transport commodity considered here is a "mass transit" service. It is headway-based service: the service is continuous and the headway between two trains is fixed. We derive equilibrium for various pricing/fare regimes and alternative assumptions about users' trip-timing and crowding preferences.

2 Methodology

We develop a structural model of a public transit system featuring a fixed number of users, N, and a continuous headway-based service. In-vehicle travel time is assumed to be independent of both vehicle occupancy and departure time, and without loss of generality it is normalized to zero. Commuters therefore arrive at the destination as soon as they depart, and departure time and arrival time can be considered synonymous. In the base-case regime the fare is assumed to be independent of time of day, and it is normalized to zero. Users incur three types of cost: a linear waiting time cost at the platform, a piecewise-linear schedule delay cost that is incurred if they arrive before their preferred arrival time (late arrivals are impossible i.e. γ approaches infinity), and an increasing crowding cost that depends on the number of users entering the train at the same time.

Each commuter chooses when to arrive at the train station by trading off schedule delay costs and crowding costs. Equilibrium obtains when no commuter can decrease his journey cost by changing his departure time, taking all other commuters' departure times as fixed. Thus, as in the Vickrey (1969) model the equilibrium is a pure-strategy Nash equilibrium with departure times as the decision variables. The social optimum is reached when the marginal social cost of a trip is the same in any train during the peak hour

3 Results

We derive the individual cost functions for a uniform (flat) fare regime and we prove that if the crowding cost function is strictly increasing, the individual cost at equilibrium is a continuous piecewise linear concave function of N. This property of the model differs from the bottleneck model where the equilibrium cost is a linear function of N.

Next, we derive the socially optimal departure rate that minimizes total user costs. We show that the social optimum can be decentralized using a continuously time-varying toll. Tolling reduces the deadweight loss of crowding, and generates fare revenue that could be used to expand public transit service. However, unlike in the bottleneck model the social optimum lasts longer than the flat-fare equilibrium (the number of trains used at optimum is around $\sqrt{2}$ times higher than the number of trains used at equilibrium) and users incur a higher cost than they do in the flat-fare equilibrium. Optimal transit pricing is less effective than tolling in the bottleneck model because the crowding cost function is assumed to be smooth whereas the bottleneck queuing delay function features a strict capacity constraint such that queuing can be completely eliminated with no reduction in throughput. Some crowding of transit is therefore efficient even in the social optimum.

In the last section, the number of operated trains is endogenous i.e. the transit authority chooses how many trains run, without restriction. The optimal number of operated trains increases with the square root of the increase in the number of users. This is reminiscent of the Mohring "square root principle".

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