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Multimodal pricing and optimal design of urban public transport: The interplay between traffic congestion and bus crowding

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ABSTRACT

The interplay between congestion and crowding externalities in the design of urban bus systems is identified and analysed. A multimodal social welfare maximisation model with spatially disaggregated demand is developed, in which users choose between travelling by bus, car or walking in a transport corridor. Optimisation variables are bus fare, congestion toll, bus frequency, bus size, fare collection system, bus boarding policy and the number of seats inside buses. We find that optimal bus frequency results from a trade-off between the level of *congestion inside buses*, i.e., passengers' crowding, and the level of *congestion outside buses*, i.e., the effect of frequency on slowing down both buses and cars in mixed-traffic roads. A numerical application shows that optimal frequency is quite sensitive to the assumptions on crowding costs, impact of buses on traffic congestion, and overall congestion level. If crowding matters to users, buses should have as many seats as possible, up to a minimum area that must be left free of seats. If for any other reason planners decide to have buses with fewer seats than optimal (e.g., to increase bus capacity), frequency should be increased to compensate for the discomfort imposed on public transport users. Finally, the consideration of crowding externalities (on both seating and standing) imposes a sizeable increase in the optimal bus fare, and consequently, a reduction of the optimal bus subsidy.

1. Introduction

When deciding whether or not to undertake a trip by public transport, travellers are influenced by a number of characteristics or attributes of the public transport mode, including accessibility, waiting time, travel time, price, reliability, comfort and safety. Demand is sensitive to the overall quality of service, which in turn depends on the design of the system; hence understanding the economic nature of urban public transport operations is crucial as a means to ensure the efficiency of a public transport network and, ultimately, the sustainability of the entire transport system. From a transport planner's perspective, the challenge associated with the design of public transport services lays in the myriad number of trade-offs that need to be considered at once, in order to establish an *optimal* service design. For example: increasing bus frequency reduces waiting time for users but increases the cost of operation; increasing the number of bus stops reduces users' access

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time but increases bus riding time for all-stop services; and investing in a quicker fare collection technology and dedicated road infrastructure for buses reduces bus travel time (and consequently may reduce operating cost) but increases capital cost. In this paper we introduce two trade-offs within the microeconomic modelling framework of optimal supply levels and pricing of an urban bus route, that are crucial to the level of service offered to public transport users: (i) the interaction between road congestion and passenger crowding externalities when setting supply levels of public transport, and (ii) the decision on the number of seats that public transport vehicles should have.

First, the influences of congestion and crowding on optimal bus service frequency have been treated independently in the literature. On the one hand, Jara-Díaz and Gschwender (2003) show that passenger crowding externalities push optimal public transport frequency up, with a total cost minimisation model without road congestion. On the other hand, Tirachini and Hensher (2011) find that the existence of bus congestion in the form of queuing delays at bus stops pushes optimal frequency down, with a total cost minimisation model that ignores crowding externalities. Moreover, buses may also slow cars down in shared roads. Therefore, there are possible counter-effects of congestion and crowding on optimal frequency that need to be addressed simultaneously. In this paper we propose a multimodal social welfare maximisation model that includes both passenger crowding and mixed-traffic congestion externalities, and find that optimal bus frequency is the result of crowding and congestion acting as colliding forces.

Second, going beyond microeconomic models that optimise public transport frequency and/or vehicle size to set supply levels (e.g., Mohring, 1972; Jansson, 1980; Oldfield and Bly, 1988; Chang and Schonfeld, 1991), we look at the internal design of vehicles by including the number of bus seats as a decision variable that influences both comfort and capacity. Different configurations of vehicles regarding number of seats and space for standees are relevant for the level of crowding and standing externalities in public transport (Whelan and Crockett, 2009). This is a key insight from the estimation of crowding and standing disutilities that has not been given attention in the literature on the design and optimisation of public transport systems. Microeconomic models that have included the level of crowding as an influence on the value of in-vehicle time savings do not distinguish between passengers sitting and standing (Jara-Díaz and Gschwender, 2003; Tirachini et al., 2010); whereas Kraus (1991) applies a premium on the value of travel time savings for passengers standing, but his research is concerned with the marginal cost and pricing of services considering the discomfort of standing, rather than with the design of vehicles. Thus, even though crowding and discomfort externalities have been analysed in the literature, previous studies always assumed a given internal design or layout of the vehicles involved, i.e., a given bus or train capacity. In short, it is assumed that size implies capacity. However, reducing the number of seats increases bus capacity by allowing more standees; thus a seat implies a trade-off between comfort and capacity that is allowed for in our model.

The analytical approach consists of a social welfare maximisation model with disaggregated origin and destination demand, and multiple travel alternatives. The model is applied to a single transport corridor in Sydney, Australia, which allows us to obtain detailed measures of crowding levels section by section. In contrast to other social welfare maximisation models (e.g., De Borger et al., 1996; Proost and Van Dender, 2004; Wichiensin et al., 2007; Ahn, 2009; Parry and Small, 2009; Jansson, 2010; Basso et al., 2011), our approach provides a more comprehensive modelling of the bus mode, including bus frequency, bus size, fare collection system, bus boarding policy, number of bus seats and fare level as decision variables. We also show that the inclusion of a non-motorised mode (walking) as an alternative to choosing bus and car for short trips may have a significant role when the transport system is optimised in highly congested scenarios.[2] Results are discussed for several scenarios with different demand levels and modelling assumptions.

We show that optimal bus frequency is quite sensitive to the assumptions regarding crowding costs, impact of buses on traffic congestion and the overall congestion level. In particular, if the planner takes into account that crowding matters to users, our numerical application shows that bus frequency should increase (for a given bus size) with demand even under heavy congestion, however that might not be the case if the crowding externality is not accounted for, in which case an increase of total demand might be met by a decrease of both frequency and number of seats per bus, at the expense of crowding passengers inside buses and making more passengers stand while travelling. Likewise, we find that buses should be designed with as many passenger seats as possible (up to a minimum area that must be left free of seats for an aisle, next to the driver and doors, for a wheelchair and other possible uses). If for any other reason planners decide to have buses with fewer seats than optimal (e.g., to increase bus capacity), frequency should be increased to compensate for the discomfort imposed on public transport users.

The remainder of the paper is organised as follows. The theoretical model is developed in Section 2, including assumptions and definitions (Section 2.1), demand and crowding modelling (Section 2.2), travel time and congestion (Section 2.3), internal bus layout (Section 2.4), and operator cost items (Section 2.5); the section concludes with the formulation of the social welfare maximisation problem. Section 3 presents the numerical application of the model to Sydney and discussion of results in several scenarios. Conclusions are provided in Section 4.

[2] Excluding non-motorised alternatives, the properties of the bimodal car-bus competition for user equilibrium and/or system optimum solutions are analysed in a number of contributions, e.g., Ahn (2009), Li et al. (2012), and Gonzales and Daganzo (2012, 2013). The influence of an un-congestible non-motorised alternative on the optimal public transport fare is analytically studied by Tirachini and Hensher (2012) with a three-mode model.