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The economics and engineering of bus stops: Spacing, design and congestion

Alejandro Tirachini *

Transport Engineering Division, Civil Engineering Department, Universidad de Chile, Blanco Encalada 2002, Santiago, Chile

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ABSTRACT

This paper re-considers the problem of choosing the number of bus stops along urban routes, first by estimating the probability of stopping in low demand markets, and second by analysing the interplay between bus stop size, bus running speed, spacing and congestion in high demand markets. A comprehensive review of the theory and practice on the location and spacing of bus stops is presented. Using empirical data from Sydney, Australia, we show that the widely used Poisson model overestimates the probability of stopping in an on-call bus stopping regime, and consequently underestimates the optimal number of bus stops that should be designed. For fixed-stop services, we show that bus running speed, frequency and dwell time are crucial to determining the relationship between bus stop spacing and demand, with bus stop congestion in the form of queuing delays playing a key role. In particular, we find that bus stop spacing should be decreased if demand increases at a constant bus running speed; however, if both bus running speed and the speed of the passenger boarding process increase, then the distance between bus stops should be kept long even at high demand levels, a result that is consistent with the implementation of Bus Rapid Transit (BRT) systems that feature high bus running speeds and long distances between stops relative to conventional bus services.

1. Introduction

Bus stops and train stations provide accessibility to public transport services at the expense of slowing down vehicles and increasing riding time. This simple fact makes the decision of what number of stops to provide on a network far from trivial. The purpose of this paper is twofold: first, to review the theoretical approaches and common practices in bus stop location, spacing and design; and second, to provide an integrated approach for the analysis of bus stop placement in order to understand the relationships between bus stop spacing and demand, bus size, bus stop size, queuing delays, bus running speed and the probability of stopping. As argued by Wirasinghe and Ghoneim (1981), no optimisation is necessary to establish that bus stops should be located at hospitals, schools, universities, shopping centres and other points of high boarding and alighting demand, but because it is unclear where bus stops should be located in between major activity centres, an optimisation approach could be useful to gain an indication of the best average distance between stops.

Three typical stopping regimes are usually found in urban bus operations (Kikuchi and Vuchic, 1982): (i) demand stopping: buses stop at any location at which passengers wish to get on and off; (ii) on-call stopping: fixed stops are provided but buses stop only when required; (iii) fixed stopping: vehicles stop at all stops or stations. The implementation of one regime or the other is usually dictated by demand levels (Vuchic, 2005): when demand is very low it seems natural to provide demand-stopping, but as demand grows it eventually becomes more convenient to group passengers in a limited number of

* Tel.: +56 2 29784380.
E-mail address: alejandro.tirachini@ing.uchile.cl

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locations, providing on-call stops in close proximity to each other. Finally, when demand is high, it is more reasonable to locate stops further apart and stop at all of them.

This paper analyses on-call and fixed stopping patterns. From a modeller's perspective, the main difference between these two regimes is that in the former it is necessary to estimate the probability that a bus will stop, a problem that does not exist in the latter case. The only theoretical approach published for modelling the stopping probability in on-call regimes is the Poisson model proposed by Hauer (1971) and Mohring (1972) and subsequently applied by several authors (Wirasinghe and Ghoneim, 1981; Kikuchi and Vuchic, 1982; Kikuchi, 1985; Furth and Rahbee, 2000; Furth et al., 2007; Li and Bertini, 2009; Chien et al., 2010). Using empirical data collected in the outer suburbs of Sydney, Australia, we show that the Poisson model overestimates the number of stops actually made, and consequently underestimates the optimal number of bus stops that should be established.

On systems with a fixed stopping pattern, characteristic of high demand markets, we pay special attention to the relationship between bus stop spacing and demand. The existent literature is not conclusive in this regard, as some studies find that bus stop spacing should decrease with demand while others find that it should increase. The theoretical and numerical analyses presented in this paper demonstrate the conditions that lead to one result or the other. We highlight the importance of the bus operating speed and bus stop congestion in a total cost minimisation model that for the first time includes the choice of bus stop size as a decision variable.

The reminder of the paper is organised as follows: Section 2 presents an extensive review of the literature, including academic papers on the optimal spacing of bus stops and train stations (Section 2.1), guidelines and common practices (Section 2.2) and recommendations regarding the location of bus stops relative to intersections (Section 2.3). In Section 3 we provide a description of the Poisson model to estimate the probability of stopping at bus stops and empirically derive two alternative models using data from Sydney. Section 4 introduces a simple total cost minimisation model to analyse the relationship between bus stop spacing and demand. In Section 5 we estimate queuing delays at bus stops for different sizes of buses and bus stops. Optimal bus stop spacing and size are determined and discussed with an extended total cost model in Section 6 for the cases of fixed stopping (6.1) and on-call stopping (6.2). Section 7 summarises the findings of the paper.

2. The spacing and location of bus stops: theory and practice

2.1. Theoretical approaches and main results

The first studies that identify the trade-off between access and riding time that characterises the problem of locating boarding and alighting stations were published one hundred years ago, which makes this problem one of the oldest in the field of transport economics and engineering. Vuchic and Newell (1968) report that between 1913 and 1930 at least five studies on the subject were published by German authors, who were concerned with finding the optimal spacing of stations for urban and suburban railways, usually with the objective of minimising passengers' travel time, including both access and in-vehicle times. These studies assumed a uniform population distribution along the route and kept the interstation spacing constant. The next wave of works came in the 1960s when Vuchic and Newell (1968) and Vuchic (1969) analysed the problem of a population commuting to the Central Business District (CBD), and found that the station spacing is a function of the ratio between the number of passengers aboard a train and those waiting to board and alight; correspondingly, station spacing increases in the direction of passenger accumulation (towards the CBD during the morning peak).

After these early contributions, a large number of authors have worked on the analysis of stop location and spacing, either as a single decision variable or in combination with other factors such as network design, bus frequency, route density and bus size. The most common approach is the development of optimisation models for which several objective functions have been proposed and analysed, namely:

- Total cost (users plus operator) minimisation, e.g.: Mohring (1972), Wirasinghe and Ghoneim (1981), Kikuchi and Vuchic (1982), Kuah and Perl (1988), Chien and Qin (2004), dell'Olio et al. (2006), Ibeas et al. (2010), Tirachini and Hensher (2011).
- User cost minimisation subject to a supply-side constraint (frequency, fleet size or budget constraints): Vuchic and Newell (1968), Kikuchi (1985), Furth and Rahbee (2000), van Nes and Bovy (2001), Li and Bertini (2009), Chien et al. (2010).
- Social welfare maximisation: van Nes and Bovy (2001), Basso et al. (2011), Basso and Silva (2013).
- Private profit maximisation: van Nes and Bovy (2001).

Mohring (1972) proposed the first microeconomic model to jointly optimise bus frequency and stop spacing, which was later extended by Kuah and Perl (1988) and Chien and Schonfeld (1998) who added route density as a decision variable for the analysis of a rail line with a feeder bus network. In general, the number of buses required for a service depends on the product of the frequency and the number of bus stops, and this multiplicative term prevents the problem from having a closed form solution when both elements are variables (see discussion in Section 4). By ignoring this term, Kuah and Perl (1988) find a closed form for the optimal bus stop spacing (the total route length divided by the number of stops), namely a square root formula that increases with the average trip length, walking speed, the delay due to stopping and the value of in-vehicle time savings, and decreases with the value of access time savings.