VALUING CROWDING IN PUBLIC TRANSPORT: IMPLICATIONS FOR COST-BENEFITS ANALYSIS

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ABSTRACT

This paper investigates the valuation of crowding in public transport trips. We use a stated preference survey where crowding levels are represented by means of specially designed figures, and use this data to estimate progressively more flexible discrete choice models. We assume that the disutility associated with travelling under crowded conditions is proportional to travel time. Our results show that passenger density has a significant effect on the utility of travelling by public transport. In fact, the marginal disutility of travel time in a crowded vehicle (6 passengers/m^2) is two times higher than in a vehicle with a low crowding level (1 passenger/m^2). We also compare the effects of different policies for improving bus corridors, and the effect of adding crowding valuation in cost-benefit analysis. Our results indicate that important benefits may be accrued from policies reducing crowding; they also imply that ignoring crowding effects significantly overestimate the benefits associated with travel time reductions in cost-benefits analysis.

Keywords: crowding, cost-benefits analysis, public transportation

1. INTRODUCTION

Fast growing transport needs are a common concern for urban areas in both the developed and developing worlds. To address this issue, many cities have already implemented improved high-capacity transit systems (BRT, tramway or subway). However, quite often these systems are designed in the developing world using an engineering standard of six or more passengers/m^2. This design standard is used as an average across all buses of a service during the peak period, which means that it is very often exceeded in a significant fraction of buses since headways are far from homogeneous and therefore the load across buses is far from being even. The problem is that many individuals are not willing to use the system under such crowded conditions, and choose travelling by car or shift to a car as soon as it becomes available. This prevents public transport modal shares from growing, increasing congestion and emissions.

Such phenomenon is especially important in less developed countries, where motorization levels are rapidly increasing and car emissions tend to account for nearly half of all urban pollution. In addition, crowdedness is usually left aside in most public transport demand models used for planning. Thus, the need for a more detailed understanding of crowding on travel decisions and its impact on project evaluation or cost-benefits analysis (CBA) is becoming an urgent priority.

The actual mode-choice process is quite complex and considers many more variables than those usually included in traditional demand models, i.e., fare, in-vehicle travel time, and walking and waiting time (Ortúzar and Willumsen, 2011). In particular, it has been empirically demonstrated that the level of comfort of different alternatives may be a significant factor in explaining travel behaviour (Ben-Akiva *et al*., 2002; Cherchi and Ortúzar, 2002; Raveau *et al*., 2011; Tirachini et al., 2013). Crowding, which is obviously associated with comfort, can also imply a perceived lack of control, stimulus overload, amongst other stressors. Thus, travel decisions involving comfort and crowding are complex mental processes involving attitudes, psychological states, preferences and socioeconomic constraints. For that reason, two questions are relevant: (i) how to measure crowding and (ii) what would be the maximum acceptable level that would not decrease modal shifts.

Most work addressing the valuation of comfort in public transport systems use choice-based stated preference (SP) methods (e.g. Li and Hensher, 2011). But Guerra and Bocarejo (2013), and Haywood and Koning (2013), have also applied contingent valuation to find the willingness to pay (WTP) for reducing overcrowding in the Bogota bus system and in the Paris metro system, respectively. Li and Hensher (2011) reviewed public transport crowding valuation research, focusing on studies conducted in the UK, USA, Australia and Israel. Most studies used logit models with SP data covering commuters, and focused mainly on in-vehicle congestion costs. Nevertheless, Douglas and Karpouzis (2005) estimated crowding costs at the platform (related to waiting time) and in the access-way/entrance to train stations (related to walking time).

As the majority of studies used choice-based SP data the way crowding has been represented in such experiments is highly relevant. Whelan and Crocket (2009) conducted an SP experiment using the seat occupancy rate and the number of standing passengers as proxies for crowding. These parameters allowed them to calculate the load factor (number of passengers/number of seats) and passenger density (standing passengers/m^2), and to specify time multipliers according to each level. In this respect, Wardman and Whelan (2011) suggest that passenger density is a better indicator of in-vehicle congestion, given that a same load factor may have different levels of crowding across different types of vehicles/wagons with varying seat composition.

Besides the time multiplier approach, crowding cost can be obtained directly as a monetary value. Lu *et al*. (2008) conducted an SP experiment for train users in Greater Manchester in 2005, and estimated values for crowding costs that were more than twice as high as the value of in-vehicle time in a non-congested scenario. In their survey, crowding was represented as the combination of a probability of occurrence and a length of time (for instance, two out of five times someone stands for the whole journey of 30 min).

The general objective of this paper is to measure WTP for crowding reductions in existing transit systems. The study was carried out in Santiago, Chile. We focus on the estimation of crowding valuation in terms of travel time; we designed an SP survey – based on the actual trip reported by the respondent - wherein one of the attributes was related to crowding. Pictures depicting passenger densities on board of vehicles served to represent the level of crowding. Valuation was obtained by means of the estimation of utility parameters of discrete choice models.

In addition, this paper explores the effects of crowding valuation on the cost-benefit analysis of policies typically proposed for improving bus corridors, i.e., to increase bus frequency, to increase vehicle capacity, and to build exclusive bus lanes.

Section 2 presents the experimental design of the SP survey and the information collected in the survey. Section 3 discusses our discrete choice modelling approach and presents the main estimation results. Section 4 discusses the effect of including crowding on the cost-benefit analysis of three common measures to improve the performance of a bus corridor. Some final comments are given in Section 5.

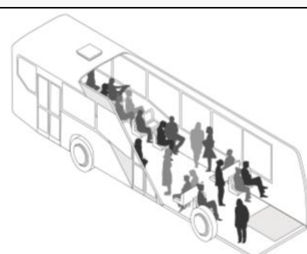
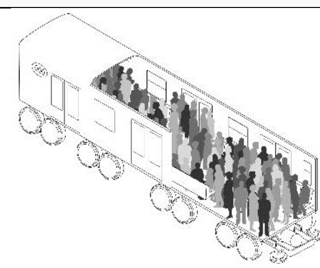
2. SURVEY DESIGN

Prior to the experimental design, we conducted focus groups that served to define which attributes would be most important to consider and which could be their levels of variation. Alternatives were finally described by six attributes: transport mode, travel time, travel cost, average waiting time, waiting time variability (coefficient of variation), and crowding level inside the vehicle (bus or train).

The choice experiments were based on *D-efficient designs* (Rose and Bliemer, 2009; Ortúzar and Willumsen, 2011, Ch. 3) using Ngene (http://choice-metrics.com/). A difficulty in finding efficient designs is that they require *a priori* values of the parameters to be estimated. Since these values are unknown at the beginning of the search for an efficient design, we use zero as prior values for the parameters. Based on this design, a preliminary survey was carried out in order to obtain initial parameter estimates. These values were then used as priors for obtaining a new design, which was used in the final survey. Therefore, the survey was designed and applied in two stages. In the first, the preliminary choice experiment was applied and some minor corrections to the survey instrument were carried out; as the survey was internet-based, it was possible to make changes quasi on-line. In the second stage, the final survey was designed and applied. In what follows, the variables (and its levels) used in the designs are discussed. Figure 1 shows an example of SP choice scenario.

The transport modes were presented based on their real availability in the reference trip reported by each individual. Therefore, if the respondent reported using public transport, the choice scenarios only included bus and Metro as alternatives. If respondents declared using car, they were asked whether they would be able to use public transport for the trip. If yes and if the respondent could use only bus, say, the choice scenarios included car and bus; otherwise, the choice scenarios included car, bus and Metro. Based on this "mode availability", three sets of choice experiments were built: one for individuals that could travel only by bus or Metro; another for individuals that could travel by car, bus or Metro; and another for individuals that could travel only by car or bus.

The levels of the attributes were determined according to the actual levels reported by the respondents for their reference trips. The levels for travel time were pivoted on the actual travel time of the longest leg of the reference trip and took the values 80%, 100%, 120% and 130% of the actual travel time. Notwithstanding, in the final experimental design the minimum pivotal travel time was set to 20 min to avoid some very small variations observed on the levels presented in the preliminary survey.

Attribute	Alternative A	Alternative B
Mode	Bus	Metro
Cost	Ch$ 590	Ch$ 650
In-vehicle travel time	25 min	15 min
Average waiting time	10 min	5 min
Waiting time range It is possible that the bus or Metro passes at any moment in this range	Between 0 and 29 min	Waiting time is fixed
Occupancy Figure represents how crowded the bus or the train will be when arriving at the stop or station.		

Which alternative would you choose to make your trip?

○ Alternative A ○ Alternative B ○ I would not travel

Figure 1. Example of SP choice scenario

The travel cost levels depended on the transport mode. For bus or Metro, the cost levels were Ch$ 590 or Ch$ 650[1], the modes' single fares at the time. In turn, if the alternative was car, the travel cost levels were set either at their current levels experienced by the individuals, or with a 10%

[1] At the time of the survey 1 US$ = 530 Ch$ (Chilean pesos).

increment. The cost of using a car includes expenditure in fuel, and was computed on the basis of travel time, average speed and average fuel consumption. In the final survey, if respondents paid for parking or for urban highway tolls in their reference trips, these values were added to the car travel cost.

The average waiting time levels were different for every mode: zero for car, 5 or 10 min for bus, and 3 or 5 min for Metro. Headway regularity had been classified as one of the most important attributes for participants of the focus groups; for this reason, we introduced waiting time variability in the experimental design (as a measure of regularity), even though it was not the focus of our study. Waiting time variability was presented in the survey as "the bus or Metro passes at any moment in this interval" (see Figure 1). Each interval was associated with a coefficient of variation, which was zero for car, and 0, 0.5, 0.7 and 1.0 for public transport[2].

Crowding for bus and Metro were presented using six levels of standing passenger density by means of specially designed figures (Table 1). Each figure was associated with a level of standing passenger density, starting in 0 and until 6 passengers/m^2. In the case of bus, the levels of passenger density were 0, 0.5, 1.0, 2.0, 3.5 and 6.0. In the case of Metro, the levels were 0, 0.5, 2.0, 3.5, 5.0 and 6.5. In the preliminary survey, we also included the crowding level uncertainty as an attribute, represented with three levels of passenger density with equal probability. However, respondents considered the experiment too complex, and for this reason we did not include crowding level uncertainty in the final design.

Finally, the SP experiment considered six choice scenarios with two alternatives each. Tables 2 to 4 summarize the final designs for the various mode availabilities.

The survey was implemented in laptops and applied face to face at the respondents' workplaces, because it took 15 to 20 min to complete. All choice scenarios included a "non-purchase option" (I would not travel), as recommended in the literature (Ortúzar y Willumsen, 2011). Figure 1 shows a choice scenario presented to the respondents.

The survey form also included questions designed to obtain information about the respondent's characteristics (gender, age, car ownership and income), a reference trip to work, and attitudes towards comfort in public transport. The information sought for the reference trip was travel time, frequency, number of legs of the trip, and for every leg, mode, in-vehicle travel time, waiting time, comfort level (sit, standing with room around, standing with little room, standing in a quite crowding vehicle), and parking and toll costs if the trip had been by car. This information was used for pivoting the attributes presented in the choice scenarios.

[2] In the preliminary survey the coefficients of variation varied between 0 and 1.5; but some possible waiting time intervals resulted too high in this case.

Table 1. Passenger density and figures used to represent level of crowding

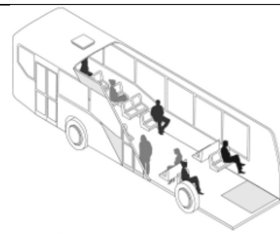
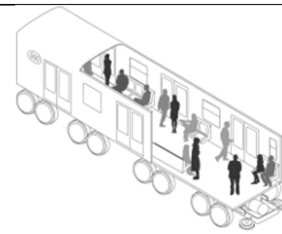
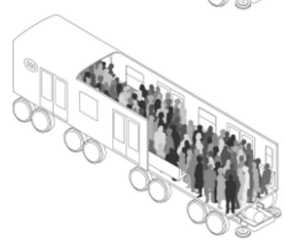
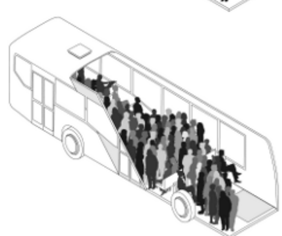
Level of passenger density	Bus	Train
1		
2		
3		
4		
5		
6		

Table 2. Final experimental design for individuals that can travel by bus or Metro

Block	Alternative A						Alternative B					
	Mode	Travel Time	Travel Cost	Waiting Time	W.T. Coef. Var.	Crowding Level	Mode	Travel Time	Travel Cost	Waiting Time	W.T. Coef. Var.	Crowding Level
1-1	Bus	100%	590	10	0	4	Bus	130%	590	5	0.5	2
1-2	Bus	100%	590	10	0.7	1	Bus	120%	590	5	0.7	4
1-3	Bus	100%	590	10	1	3	Metro	80%	650	5	0	4
1-4	Bus	100%	650	5	0.7	3	Bus	120%	590	10	1	6
1-5	Bus	100%	590	5	0.5	6	Metro	130%	590	3	0	3
1-6	Bus	100%	650	5	0.7	2	Bus	80%	650	10	0.5	3
2-1	Bus	100%	590	5	0.5	5	Bus	100%	590	5	1	1
2-2	Bus	100%	590	10	0	2	Bus	100%	590	5	0	6
2-3	Bus	100%	650	5	0	1	Metro	120%	650	10	0.7	5
2-4	Bus	100%	650	10	1	5	Metro	130%	590	5	0.5	1
2-5	Bus	100%	590	10	1	6	Metro	80%	650	3	0.5	2
2-6	Bus	100%	650	5	0.5	4	Bus	100%	650	10	0	5

Table 3. Final experimental design for individuals that can travel by car, bus or Metro

Block	Alternative A						Alternative B					
	Mode	Travel Time	Travel Cost	Waiting Time	W.T. Coef. Var.	Crowding Level	Mode	Travel Time	Travel Cost	Waiting Time	W.T. Coef. Var.	Crowding Level
1-1	Car	100%	1.0*C	0	0	1	Metro	130%	650	5	0	1
1-2	Car	100%	1.0*C	0	0	1	Bus	80%	650	10	0	3
1-3	Car	100%	1.0*C	0	0	1	Bus	100%	590	10	0.5	5
1-4	Car	100%	1.1*C	0	0	1	Metro	120%	590	3	0.5	4
1-5	Car	100%	1.1*C	0	0	1	Bus	120%	650	5	1	1
1-6	Car	100%	1.1*C	0	0	1	Bus	100%	590	5	0.5	6
2-1	Car	100%	1.1*C	0	0	1	Metro	100%	590	3	0	5
2-2	Car	100%	1.0*C	0	0	1	Metro	80%	650	5	0.5	2
2-3	Car	100%	1.1*C	0	0	1	Bus	80%	590	10	0.7	4
2-4	Car	100%	1.0*C	0	0	1	Bus	130%	650	5	0	2
2-5	Car	100%	1.0*C	0	0	1	Bus	120%	650	10	1	6
2-6	Car	100%	1.1*C	0	0	1	Bus	130%	590	5	0.7	3

Table 4. Final experimental design for individuals that can travel by car or bus

Block	Alternative A						Alternative B					
	Mode	Travel Time	Travel Cost	Waiting Time	W.T. Coef. Var.	Crowding Level	Mode	Travel Time	Travel Cost	Waiting Time	W.T. Coef. Var.	Crowding Level
1-1	Car	100%	1.1*C	0	0	1	Bus	80%	590	10	0.5	4
1-2	Car	100%	1.0*C	0	0	1	Bus	120%	650	5	0.7	2
1-3	Car	100%	1.0*C	0	0	1	Bus	120%	650	10	1	5
1-4	Car	100%	1.1*C	0	0	1	Bus	130%	590	10	0.7	1
1-5	Car	100%	1.0*C	0	0	1	Bus	130%	650	5	0	4
1-6	Car	100%	1.1*C	0	0	1	Bus	100%	590	5	0.5	5
2-1	Car	100%	1.1*C	0	0	1	Bus	80%	590	10	0.7	3
2-2	Car	100%	1.0*C	0	0	1	Bus	100%	650	10	0	2
2-3	Car	100%	1.0*C	0	0	1	Bus	130%	650	5	0.5	3
2-4	Car	100%	1.1*C	0	0	1	Bus	80%	590	5	1	1
2-5	Car	100%	1.0*C	0	0	1	Bus	120%	650	10	1	6
2-6	Car	100%	1.1*C	0	0	1	Bus	100%	590	5	0	6

3. MODELLING AND ESTIMATION

3.1 Model specification

The framework for our model specification is random utility theory. In the context of the choice of transport mode, the theory can be summarized in the following assumptions about individual's behaviour.

- There is a (finite) set of transport alternatives, mutually exclusive, for the individual's trip.
- Individual preferences for the alternatives can be represented by a utility function that depends on attributes of the alternatives and individual's characteristics.
- The mode that generates the highest utility among all available alternatives in the individual's choice set is selected.
- In the individual's utility function, there are variables that the modeller does not observe. This way, two individuals with the same choice set and the same observable characteristics may choose different transport modes.
- It is assumed that the unobservable individual utility components are randomly distributed in the population.

In practical terms, the theory of random utility involves defining a utility function for each mode, which depends on specific modal attributes, the individual characteristics and a random component with a certain distribution over the population. Analytically, the random utility of alternative *m* for individual *i* is written as $U(x_m, z_i, e_{mi})$, where x_m is a vector with observable attributes of mode *m* (travel time, cost, etc.), z_i is a vector with characteristics of the individual *i* (age, sex, driver's license, etc.), and e_{mi} is the random component.

As we assume that individuals choose the alternative that maximizes utility, then mode *m* is chosen if $U(x_m, z_i, e_{mi}) \geq U(x_k, z_i, e_{ki})$ for all modes *k* in the set of available modes of individual *i*. Since *U* is a random variable, we can write the probability that individual *i* chooses alternative *m* as Prob (*i* chooses *m*) = Prob ($U(x_m, z_i, e_{mi}) \geq U(x_k, z_i, e_{ki})$, for all *k*), and different models can be obtained according to assumptions made about the functional form of the utility and the probability distribution of the random component. In particular, the MNL model is obtained assuming that the random component is additively separable in the utility function, and identically and independently distributed Extreme Value type I (McFadden, 1974). The panel mixed logit (ML) model is obtained by adding a random component that varies across individuals but does not vary across choice scenarios faced by each respondent (Revelt and Train, 1998).

Moreover, it is generally assumed that the observable part of the utility function (V_{im}) is linear in the modal attributes. Thus, if the utility function includes time and cost, say, the parameters associated with them represent the marginal utilities of those variables. For example, if $V_{im} = a_m + bC_m + cT_m$, where C_m is travel cost and T_m is travel time, then $-b$ is the marginal utility of income and $-c$ is the marginal utility of time (in simplified terms).

The marginal rate of substitution between money and time is defined as the subjective value of time (VT). Therefore, this value can be calculated as the ratio between the parameters of time and cost (c/b) in linear utility functions (Gaudry *et al.*, 1989). In this study, we postulate that the marginal utility of travel time depends linearly on the level of crowding in the vehicle (bus and train). This is consistent with the time multipliers' approach adopted in similar studies reviewed by Li and Hensher (2011)[3]. Following Haywood and Koning (2013), we can write c as a linear function of in-vehicle passenger density d as follows:

$$c(d) = c_0 + c_1 d$$

This specification captures the increasing discomfort for travelling in crowded conditions, and also implies that the total discomfort is proportional to travel time. For consistency, both c_0 and c_1 must be negative.

The variables used in the utility specification include only those presented in the experimental design, i.e., travel cost, in-vehicle travel time, average waiting time, range of waiting time, and level of crowding measured in passenger density. The utility specification for the model is as follows:

$$V_{im} = \alpha_m + \beta C_m + (\gamma_0 + \gamma_1 D_m) T_m + \delta W_m + \varepsilon R_m \qquad (1)$$

where C_m is the cost of mode m, T_m is travel time, D_m is standing-passenger density, W_m is waiting time, and R_m is the coefficient of the waiting time variation. One important assumption of this utility specification is that the comfort level for a car trip is the same as that for a bus or train trip when the passenger density is equal to zero passenger/m^2.

Then, the value of time as a function of passenger density (D) is given by:

$$VT(D) = \frac{(\gamma_0 + \gamma_1 D)}{\beta} \qquad (2)$$

The next section presents our model estimation results. In addition to the model of Equation (1), we estimated a (miss-specified) model without the effect of passenger density in the utility function. This model is used in Section 4 to analyze the bias introduced by the miss-specification in the rest of the parameters and the implications on cost-benefits analysis.

3.2 Estimation results

The estimation sample was composed of 3,380 pseudo-individuals corresponding to 580 respondents of our SP survey. This sample comprises the individuals surveyed using both the preliminary and final experimental designs (which had three different versions depending on mode

[3] Batarce et al. (2015) find a nonlinear effect of passenger density on travel time using mixed SP/RP data. The utility function is specified with dummy variables to represent three levels (or ranges) of passenger density, because the RP data uses an approximated measure for it. In this paper, we use a linear utility specification of the passenger density effect, because the model is used for prediction and the equilibrium computation needs a continuous utility function in passenger density. In addition, estimation of a quadratic effect of passenger density on travel time resulted on non-significant parameters.

availability, as shown above). The differences in design suggest that model estimation should consider treating the different data sources as in the case of mixed datasets (Ben-Akiva and Morikawa, 1990). Thus, to estimate the panel ML models we introduced different scale factors and considered four datasets: preliminary design with and without car available, and final design with and without car available. For identification purposes we normalized the scale factor of the sample from the preliminary design without car to one.

Table 5 summarizes our estimation results for the panel ML models with the utility functions presented in equation (1). The miss-specified model, estimated without passenger density effects, is also presented in Table 5 to compare the results of omitting this variable on the rest of the parameters. The likelihood ratio test allows to reject the hypothesis of null passenger-density effect on travel time (H_0: $\gamma_1 = 0$, LRT=21.22, p-value = 0.00). The most significant change in the parameters is the cost parameter increasing (in absolute value) by 40%, which leads to a significant decrease in the estimated subjective value of time. The mode specific constants also change significantly, making the model less sensitive to changes in the level of service variables.

Table 5. Model estimation results and implied subjective values of travel time

Parameters	Miss-specified panel ML		Panel ML (Eqs. 1 & 2)	
	Estimates	t-test[a]	Estimates	t-test[a]
Bus constant (reference)	-	-	-	-
Metro constant (α_{metro})	-0.4770	-4.70	-0.8440	-5.93
Car constant (α_{car})	2.1900	1.36	1.2900	1.53
Travel cost (β)	-0.0014	-1.85	-0.0010	-2.32
Travel time (γ_0)	-0.0293	-4.35	-0.0276	-3.97
Waiting time (δ)	-0.1510	-12.11	-0.1540	-12.33
Coefficient of variation of waiting time (ε)	-0.9150	-15.37	-0.8840	-14.86
Crowding level (passenger density) (γ_1)			-0.0070	-3.82
St. dev. panel error component Metro	1.0600	5.57	1.2200	6.16
St. dev. panel error component Car	2.8500	2.52	2.3600	3.73
Scale factor dataset 1 (fixed)	1	-	1	-
Scale factor dataset 2	1.0600	0.13	1.3300	0.83
Scale factor dataset 3	0.9860	-0.10	0.8590	-1.06
Scale factor dataset 4	0.8290	-0.50	0.9690	-0.10
Log-likelihood	-1885		-1875	
Subjective value of travel time (US$/hr)				
0 standing-passenger/m^2	2.40		3.15	
1 standing-passenger/m^2	2.40		3.94	
2 standing-passenger/m^2	2.40		4.74	
3 standing-passenger/m^2	2.40		5.53	
4 standing-passenger/m^2	2.40		6.33	
5 standing-passenger/m^2	2.40		7.13	
6 standing-passenger/m^2	2.40		7.92	

[a] In the case of the scale factors, the test-t is for the hypothesis that the parameter is equal to one.

The results indicate that crowding produces a significant increase in disutility. The marginal disutility increases 25% for an increase of 1 standing-passenger/m^2. A minute of travelling in the highest density condition (6 passengers/m^2) produces a discomfort that is two and on half times greater than that obtained at the lowest density condition.

To see the impact of changes of passenger density on the demand for public transport and car, Table 6 shows the own and cross passenger-density elasticities for both modes. In the estimated models, the passenger-density elasticity depends on the specific travel times that are being experienced; therefore, the results are presented for the average in-vehicle travel time (28 min) in Santiago. In addition, since elasticity depends on the modal share, we used the actual bus shares in Santiago (41%).

As expected, elasticity increases with the crowding level. Although both the bus and car demands are relatively inelastic to passenger density in public transport, the demand for bus becomes significantly more elastic for high levels of crowding.

Table 6. Own passenger-density elasticity of demand for public transport and cross passenger-density elasticity of demand for car

Passenger density (passengers/m^2)	Bus own passenger-density elasticity	Car cross passenger-density elasticity
1	-0.12	0.08
2	-0.23	0.16
3	-0.35	0.24
4	-0.46	0.32
5	-0.58	0.40
6	-0.69	0.48

4. IMPLICATIONS FOR COST-BENEFIT ANALYSIS

In this section the impact of including the effect of overcrowding in the cost-benefit analysis of a project to improve public transport analysis is discussed. For this, a bus corridor operated by a bus line is considered. Initially, buses operate on a street with mixed traffic (cars and buses), can accommodate 100 passengers and have a frequency of 15 buses/hr. Total demand in the corridor is 5,000 passengers/hr, and the travel alternatives are bus and car. The analyzed measures for improving the quality of public transport service are: (i) increasing the frequency to 20 bus/hr, (ii) increasing capacity to 140 passengers/bus, and (iii) increasing operational speed by building a segregated busway.

Bus demand is estimated using the mode choice models from the previous section, that is, both the model that includes passenger-density effect and the miss-specified model. Thus, it is possible to analyze the impact of using the wrong model in estimating demand and benefits.

In addition, a simple model was developed to estimate the costs and benefits of changes in some operational features in the bus corridor given total travel demand. This simplified model simulates the operation of the system according to several variables related with the capacity supplied. In this way, it is possible to model different technologies (conventional bus, BRT, Metro) just by changing certain operating variables such as speed, capacity, frequency or the coefficient of variation of the headway. A more complex model was developed by Tirachini *et al.* (2014) to define optimal policies, such as optimal frequency, taking into consideration crowding effect. Our focus is on the crowding effects on cost-benefits analysis. In particular, we use Chilean data to estimate costs and other relevant parameters for the analysis. It is worth noticing that in our cost-benefit analysis we only compare annual cost and benefits, and do not compute the present value of the net benefits in the time horizon of the project.

4.1 Operational model, cost and benefit measures

We assume a corridor of length L where the average distance travelled by the passengers is l. The service frequency is f (buses/hr) with a coefficient of variation of bus headways of c_f. The average vehicle capacity is k (passengers/bus), which implies that the average supplied capacity of the system is given by:

$$Q = \frac{L}{l} \cdot k \cdot f \quad \text{(passengers/hr)}$$

The operational speed in the corridor depends on the type of infrastructure (e.g. mixed traffic vs. segregated bus lanes). We can specify that a fraction of the corridor (a) operates with one type of infrastructure (e.g. mixed traffic), and a fraction ($1-a$) operates with another one (e.g. segregated lanes). The average speed in corridor, s, is the weighted average of the speed in each type of infrastructure. The dwell time due to passengers boarding and alighting is included in the operational speed. The circuit time of the vehicles includes a fixed time due to operations at the extremes of the route.

The required fleet is determined by the operating frequency, the circuit time and the fraction of the fleet in operation. Likewise, the total distance driven by the bus results from the frequency and length of the corridor. The fleet and run distance are relevant to compute the cost of the system.

Demand is estimated with the binary logit models presented in previous section. The relevant variables are fare, travel and waiting time, coefficient of variation of headways, and crowding level. Travel time is obtained from the operating speed, thus includes the boarding and alighting times at stops. Even though boarding/alighting time depends on the demand of the bus service, this effect is not considered because it requires additional assumptions: the number of stops, the distance between them, and the passenger distribution across stops. As the focus of this paper is on the implications of crowding on cost-benefit analysis, the model disregards the effect of boarding/alighting passengers on the operating speed. In addition, if travel time depends on the demand for the buses, this introduces another equilibrium condition in the model, which increases its complexity beyond the scope of this research.

The waiting time is determined by the frequency and the coefficient of variation of headway. The expression for the average waiting time is:

$$t_w = \frac{1}{2f}(1 + c_f^2)$$

This expression assumes that all passengers can board the first bus arriving at a stop. To consider the effect of insufficient bus capacity on waiting time it would be necessary to introduce another equilibrium condition in the model. Therefore, to keep tractability of model, this passenger congestion effect is also disregarded. Additionally, we assume that passengers do not need to transfer across bus services in the corridor to reach their destinations.

The average passenger density (passengers/m^2) is determined by the ratio of the total demand to the supplied capacity multiplied by the maximum passenger density acceptable for the vehicle under consideration. In turn, the maximum passenger density depends on the specified vehicle capacity, and both variables must be consistent. The crowding level is also the result of an equilibrium condition, because the demand depends on the passenger density, which, in turn, depends on the demand. The simulation model solves the equilibrium condition to estimate consistently the demand for bus taking into account the passenger-density effect.

To evaluate the policies, the model computes the total driven kilometres and operating costs for the estimated fleet. These include operating costs/km and capital costs (depreciation). Information on bus costs is obtained from Batarce and Galilea (2013) and SECTRA (2003), and car-operating costs are estimated using data from MDS (2014). The external costs of bus and car are also included in the analysis (Rizzi and de la Maza, 2014) and comprise accidents, air pollution and noise. A summary of the bus operating variables and costs used for the computations is presented in Table 7. The car travel cost and times are US$ 3.21 and 27 min respectively[4] for an average trip length of 10 km. The results of one hour of operation are expanded to annual benefits using the values in Table 7.

The benefits of the various policies are estimated using the compensating variation (*CV*). In the case of logit demand models, Small and Rosen (1981) derived an exact analytical expression for the *CV*. For changes in level of service that imply changes in the utility from V^0 to V^1, the expression for the *CV* is:

$$CV = \frac{N}{\lambda}\left[\ln \sum_{i=1}^{M} \exp(V_i)\right]_{V^0}^{V^1}$$

The term inside the brackets is the logsum or expected maximum utility; λ is the marginal utility of income, which equals the absolute value of the cost coefficient in the estimated discrete choice models, and N is the total number of travellers.

The compensating variation is independent of the order of the introduced changes in the corridor. For instance, increasing frequency has two effects: to reduce waiting time and crowding. The benefits due to increasing frequency may be decomposed in the compensating variation for reducing the waiting time plus that for reducing crowding, given the new waiting times. Hence, to isolate the benefits due to changes on crowding conditions, the compensating variation is computed using this decomposition (see Table 8).

[4] To obtain this we assume that the fuel consumption is 10 km/lt, the fuel price is 0.76 US$/lt, and there exists a parking cost of 0.53 US$. We also assume the average car speed in peak-hour is 22 km/hr.

Table 7. Operational variables of the simulation model

Bus operation variables	
Corridor total demand (passengers)	5,000
Bus corridor length (km)	20
Average trip length (km)	10
Operating speed in mixed traffic (km/h)	16
Operating speed in exclusive bus lanes (km/h)	22
Operation time at terminals (min)	30
Frequency (buses/hr)	15
Coefficient of variation of headway	1.2
Operating costs	
Average bus operating costs	
12-meter-length bus (capacity 100 passengers/bus) (US$/km)	2.83
18-meter-length bus (capacity 140 passengers/bus) (US$/km)	3.54
Cost of buses	
12-meter-length bus (capacity 100 passengers/bus) (US$/bus)	180,000
18-meter-length bus (capacity 140 passengers/bus) (US$/bus)	240,000
Residual value of buses	20%
Lifetime of buses (years)	7
Car operating costs (US$/km)	0.15
External costs	
Bus	
12-meter-length bus (capacity 100 passengers/bus) (US$/km)	0.79
18-meter-length bus (capacity 140 passengers/bus) (US$/km)	0.90
Car (US$/km)	0.12
Infrastructure costs	
Investment costs of bus corridor (MUS$/km)	9.43
Annual capital cost of investment on infrastructure (MUS$/km)	1.01
Annual depreciation of investment on infrastructure (MUS$/km)	0.19
Parameters for expansion to annual costs and benefits	
Days per year	250
Length of demand peak (hours/day)	3
Length of operation peak (hours/day)	4

4.2 Increasing capacity policies

We evaluated two policies for improving the bus capacity of the corridor: to increase the average bus capacity and to increase the bus frequency. The policy of increasing bus capacity, from 100 to 140 passengers/bus, produces significant user benefits (measured as compensating variation), which are higher than the costs (see Table 8). Thus, cost-benefit analysis suggests that the policy should be implemented. The demand for bus increases by 10%, which is consistent with a policy for reducing car usage. This analysis also considers the positive effects on congestion and pollution due to a reduction in the car share. Indeed, the car driven kilometres drop, while the bus driven kilometres keep constant. If the occupancy rate is 1 passenger/car, this leads to a saving of around 2.5 million car kilometres per year, which corresponds to benefits of US$ 240,000 due to reductions of external cost (accidents, air pollution and noise). It is worth noticing that the increasing bus capacity has no effect on waiting times, because the operation model does not consider the effect of congestion on boarding the buses. The only effect of this policy is to reduce crowding in the buses. Thus, according to the miss-specified model, the policy of increasing bus capacity does not produce any benefit for the users. Consequently, the CBA based on the miss-specified model would reject the implementation of this policy.

Table 8. Costs and benefits of policies for improving a bus corridor in Santiago: increase of bus capacity and increase of bus frequency

<table>
<tr><th rowspan="2"></th><th rowspan="2">Baseline case</th><th rowspan="2">Capacity increase</th><th colspan="2">Frequency increase</th><th rowspan="2">Frequency increase miss-specified model</th></tr>
<tr><th>Waiting-time effect</th><th>Passenger-density effect</th></tr>
<tr><td>Operating variables</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Fare (US$)</td><td>1.1</td><td>1.1</td><td colspan="2">1.1</td><td>1.1</td></tr>
<tr><td>Frequency (buses/hr)</td><td>15</td><td>15</td><td colspan="2">20</td><td>20</td></tr>
<tr><td>Bus capacity (passengers)</td><td>100</td><td>140</td><td colspan="2">100</td><td>100</td></tr>
<tr><td>Passenger density (pass./m^2)</td><td>5.9</td><td>4.7</td><td>5.9</td><td>5.0</td><td></td></tr>
<tr><td>Waiting time (min)</td><td>4.9</td><td>4.9</td><td colspan="2">3.7</td><td>3.7</td></tr>
<tr><td>Bus travel time (min)</td><td>37.5</td><td>37.5</td><td colspan="2">37.5</td><td>37.5</td></tr>
<tr><td>Car travel time (min)</td><td>27.3</td><td>27.3</td><td colspan="2">27.3</td><td>27.3</td></tr>
<tr><td>Required bus fleet</td><td>46</td><td>46</td><td colspan="2">61</td><td>61</td></tr>
<tr><td>Bus driven kilometres</td><td>600</td><td>600</td><td colspan="2">800</td><td>800</td></tr>
<tr><td>Car driven kilometres</td><td>20,689</td><td>17,314</td><td>19,442</td><td>16,845</td><td>19,467</td></tr>
<tr><td>Bus share</td><td>59%</td><td>65%</td><td>61%</td><td>66%</td><td>61%</td></tr>
<tr><td>Annual costs and benefits</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Users’ benefits (MUS$)[a]</td><td>-33.27</td><td>-32.00</td><td>-32.83</td><td>-31.81</td><td>-12.98</td></tr>
<tr><td>Bus operation costs (MUS$)</td><td>1.70</td><td>2.12</td><td colspan="2">2.26</td><td>2.26</td></tr>
<tr><td>Capital cost of buses (MUS$)</td><td>0.95</td><td>1.26</td><td colspan="2">1.25</td><td>1.25</td></tr>
<tr><td>Bus external costs (MUS$)</td><td>0.47</td><td>0.54</td><td colspan="2">0.63</td><td>-0.63</td></tr>
<tr><td>Car operating costs (MUS$)</td><td>2.39</td><td>2.00</td><td>2.25</td><td>1.95</td><td>-2.25</td></tr>
<tr><td>Car external costs (MUS$)</td><td>1.87</td><td>1.57</td><td>1.76</td><td>1.53</td><td>-1.76</td></tr>
<tr><td>Net benefits</td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Compensating variation (MUS$)</td><td></td><td>1,27</td><td>0.44</td><td>1.02</td><td>0.31</td></tr>
<tr><td>Cost difference (MUS$)</td><td></td><td>-0.11</td><td>-0.78</td><td>0.54</td><td>-0.78</td></tr>
<tr><td>Total net benefits (MUS$)</td><td></td><td>1.16</td><td colspan="2">1.22</td><td>-0.47</td></tr>
</table>

[a] Benefits are measured as the maximum expected utility divided by the marginal utility of income. The difference of these measures of benefits equals the compensating variation. User benefits are negative as they represent the disutility of travelling. In the case of the CBA with the miss-specified model, users’ benefits must be compared with the users’ benefits of the baseline case computed with the same model; these benefits are MUS$ -13.29.

The policy of increasing bus frequency from, 15 to 20 buses/hr, also produces significant benefits, which counterbalance the associated cost. The compensating variation is decomposed into the effect of waiting time reductions due to frequency increases and the effect of crowding reductions due to average capacity increases (because of the higher frequency); the former effect is around one third of the latter. This points out to the relevance of crowding on user benefits. In fact, the policy is not socially worthy when considering only waiting time benefits because of the high cost associated with incrementing the frequency of the bus system. The crowding effect produces not only more user benefits, but also cost reductions. The reduction of car share (from 39% to 34%) implies reduction of car driven kilometres, which is the source of savings in operating and external costs for the car. These savings compensate the increase in operating and external costs of the buses.

The CBA carried out with the miss-specified mode choice model also rejects this policy of increasing bus frequency as not socially worthy. The cost of increasing the frequency is not counterbalanced by the users' benefits and the reduction of car costs. Indeed, the only source of benefits is the reduction of waiting time, as the model is insensitive to changes on passenger density. If we compare the waiting-time benefits obtained with both models, we see that the miss-specified model leads to lower benefits than the well-specified one. This is due to the bias of the cost parameter, which reduces the monetary value of the benefits (and the value of waiting time).

Comparing both policies, our results suggest that increasing bus capacity is preferable to increasing frequency in this case. This is quite remarkable because standard cost-benefit analyses cannot capture the direct benefits of operating a fleet with larger buses. Complex transport models capture this type of benefits by modelling waiting time as a function of bus capacity (e.g. De Cea and Fernandez, 1993). Reductions on waiting time occur because larger buses increase the probability of boarding the first arriving bus. However, explicit inclusion of crowding in the utility function (or in the modal shares model) allows us to measure the real impact of crowding on users' welfare with simple models using average busloads. In addition, the impact of crowding seems to be more significant than the impact of waiting time reductions.

4.2 Increasing bus speed

Another common policy used to improve the quality of public transport is to build bus corridors with exclusive lanes and, often, with stations with pre-boarding payment. These are the key features of the Bus Rapid Transit (BRT) corridors that are being implemented in several cities worldwide (BRT Centre of Excellence et al, 2015). The goal of building bus lanes is to improve operating speeds and reduce travel times. We assume the project is a bus corridor with exclusive lanes and 10 kilometres length, located in the middle of the 20 km bus route. This increases bus speed from 16 km/hr in mixed traffic to 22 km/hr in the exclusive bus lanes (see Table 7). These speeds are valid for Santiago de Chile and estimated with data from Muñoz *et al*. (2013). The infrastructure costs are estimated from a recent study of a bus corridor in Santiago (SECTRA, 2011).

We compare demand forecasts and user benefits obtained with the models that consider passenger-density on the travel time valuation and the model that does not. In the case of the model with passenger/density effect, the demand is estimated in two steps. In the first one, the passenger-density is kept constant and equal to the level before the speed is increased. Therefore, the estimated demand and the user benefits will be wrong in this step. In the second step, the demand is estimated with the passenger-density of the equilibrium. This results are compared with those obtained by the miss-specified model producing an incorrect demand forecast due to biased parameters.

We also compare the user benefits computed by standard cost-benefit analysis (CBA) with benefits measured using the compensating variation. The standard CBA consists of computing total time savings and valuing the benefits by multiplying the time savings by the value of time. The foundation for this procedure is to assume that time is a valuable resource for society. The value of time is usually fixed by some authority being responsible for transport planning or public project appraisal and is often called the *social value of time* (*SVT*). For instance, in the case of Chile, the value of time is fixed in 2.68 US$/hr by the Ministry of Social Development (MDS, 2014). Generally, this approach does not consider any effects of crowding on the value of time; therefore, the benefits associated with reducing crowding are not included in project appraisal. Thus, the proposed comparison should shed some light on the benefit losses due to a constant value of time, independent of passenger density.

To be consistent with the estimated model, we assume that the value of time increases linearly with passenger density. Therefore, it increases by 0.80 US$/hr when passenger density increases by 1 passenger/m^2. To compute the net benefits of travel time savings considering the crowding effect, we assume that the total travel time spent in mode m is T_{0m} before the project and T_{1m} after the project implementation. Then, the net time benefits for bus users, ΔB_b, is given by:

$$\begin{aligned}\Delta B_b = B_{0b} - B_{1b} &= T_{1b}(VT + \gamma H_1) - T_{0b}(VT + \gamma H_0) \\ &= VT \cdot \Delta T_b + \gamma(T_{1b}H_1 - T_{0b}H_0)\end{aligned}$$

In this expression γ is the increment in the value of time associated with an increment in crowding, *VT* can be associated to the value of time for a car user (or for a bus user in a bus with passenger density equal to zero), hereafter the base level of value of time, while H_0 and H_1 are the bus passenger densities before and after project implementation respectively. Analogously, the net benefit for car users is:

$$\begin{aligned}\Delta B_c = B_{0c} - B_{1c} &= T_{1c} \cdot VT - T_{0c} \cdot VT \\ &= VT \cdot \Delta T_c\end{aligned}$$

As the net time benefits depend on the base level of the value of time, *VT*, we assume that the value of time used in the CBA without crowding is the weighted average of the value of time for car and bus users just before the implementation of the project. Thus we define $SVT = s_{car}\ VT + s_{bus}\ VT\ (1+\gamma H_0)$, where s_{car} and s_{bus} are the bus and car modal shares in the city (normalized to add one), and H_0 is the average bus crowding level in the baseline case. In the case of Santiago, this approach leads to a *VST* equal to 5.9 (US$/hr) in the case of the model with passenger-density effect, and of 2.4 (US$/hr) in the case of the miss-specified model. Finally, our assumptions imply that the time benefits for the standard CBA are given by:

$$\Delta B_{CBA} = SVT(\Delta T_b + \Delta T_c)$$

It is worth to note that, in Chile, the *SVT* is not determined on the basis of WTP for travel time reductions, but corresponds to a weighted average of the value of work time (measured as the average wage rate) and the value of leisure (measured as a fraction of the value of work). This approach is valid under some specific assumptions on user behaviour (for instance, DeSerpa, 1971). In addition, the composition of the social value of time is an open question needing more empirical analysis (Mackie *et al*., 2001). Hence, there is no direct way to find equivalence between *VT* and *SVT*.

Returning to demand modelling, our results show that in the first step of using the well-specified model (travel-time effect), the demand is overestimated since it assumes that crowdedness is kept constant (64% versus 62%; see Table 9, under column Travel time effect). The procedure should be similar to modelling the demand without estimating the crowding effect. In our case, bus demand estimated with the miss-specified model is slightly lower than the final demand estimated with the model with passenger-density effect (61% versus 62%; see Table 9, last column). This result is due to the low sensitivity of the miss-specified model to travel time (and the remaining level of service variables). Therefore, on the one hand, if the analyst estimates a discrete choice model considering the effect of crowding in the bus utility function, but s/he does not take into account this effect when using the model for demand forecasting, s/he will overestimate the bus demand. In this case, the bus share becomes 64%. On the other hand, if the analyst estimates a discrete choice model without taking into account the passenger-density effect, the demand forecasts could be close to those obtained with the correct model[5], but with a biased parameters leading to a wrong valuation of travel time.

Regarding the composition of the benefits using the well-specified model, the travel time effect (the first step) leads to overestimation of both user benefits and cost savings. This is because of the bus demand overestimation. Indeed, the reduction in car driven kilometres is overestimated and, as a consequence, the benefits due to the reduction of operating and external costs are overestimated too. The compensating variation is overestimated because the bus users travel faster and with the same level of passenger density. Thus, they get only benefits. However, when considering the passenger-density effect with respect to the situation with travel time reduction, the benefits are negative. The cost savings are negative because users change from bus to car due to the high level of crowding after the equilibrium is reached. The compensating variation is also negative, because bus users experiment more crowding, therefore higher disutility for travelling, even if they go faster. As a result, the total user benefits are about two thirds of the benefits due only to the reduction of travel time.

Using the miss-specified model, both user benefits and costs savings are underestimated as they depends on the predicted modal share, which underestimates the user change from car to bus.

Regarding the alternative measures of user benefits, when using the well-specified model, if travel time-savings are valued with constant *SVT,* user benefits are overestimated (see Table 9). The benefits due to the passenger-density effect are 4% of the travel time benefits. In fact, the change in bus demand due to crowding is in the opposite direction to that due to travel time reductions. This fall in bus demand is achieved when the equilibrium passenger-density is reached from the demand level estimated with only travel time changes (from 6.5 to 6.2 passengers/m^2). Thus, less users travel by bus, which produces a net time saving because car is faster than bus. Thus, using a constant *SVT* to value travel time leads to an overestimation of user benefits.

If the social value of time considers the effect of crowding, the time-savings benefits are consistent with the benefits measured using the compensating variation; however they are underestimated. In

[5] As the change in the level of service gets smaller, the difference between predictions decreases. Thus the forecasting accuracy of the miss-specified model depends on the size of the changes in the level of service.

this case the loss of benefits due to the crowding effect represents a 21% of the travel time-savings benefits.

Table 9. Costs and benefits of improving speed in a bus corridor in Santiago. Comparison of benefits with and without crowding effect

	Baseline Case	Speed increase		Speed increase miss-specified model
		Travel-time effect	Crowding effect	
Operating variables				
Fare (US$)	1.1	1.1		1.1
Frequency (buses/hr)	15	20		20
Bus capacity (passengers)	100	100		100
Passenger density (pass./m^2)	5.9	5.9	6.2	
Waiting time (min)	4.9	4.9		4.9
Bus travel time (min)	37.5	32.4		32.4
Car travel time(min)	27.3	27.3		27.3
Required bus fleet	46	40		40
Bus driven kilometres	600	600		600
Car driven kilometres	20,689	17,817	18,767	19,701
Bus share	59%	64%	62%	61%
Annual costs and benefits				
Users' benefits (MUS$)	-33.27	-29.36	-29.73	-13.04
Bus operation costs (MUS$)	1.70	1.70		1.70
Capital cost of buses (MUS$)	0.95	0.82		0.82
Bus external costs (MUS$)	0.47	0.47		0.47
Bus consumed travel time (hr)	1,373,941	1,302,851	1,264,400	1,226,583
Car operation costs (MUS$)	2.39	2.06	2.17	2.28
Car external costs (MUS$)	1.87	1.61	1.70	1.78
Car consumed travel time (hr)	705,316	607,408	639,788	671,634
Capital cost of infrastructure (MUS$)		7.47		7.47
Net benefits				
Compensating variation (MUS$)		1.21	-0.43	0.25
Operation and external cost savings (MUS$)		0.79	-0.22	0.33
Total net benefits (MUS$)[a]			1.34	0.58
Alternative measures of user benefits				
Time benefits with constant *SVT* (MUS$)		0.99	0.04	0.44
Time benefits *SVT* with crowding effect (MUS$)		0.86	-0.18	0.44

[a] Net benefits correspond to user benefits measured with the compensating variation plus operational and external cost savings. The annual capital cost of infrastructure is not included.

Summarizing, the standard CBA with constant *VST* results in an overestimation of benefits (1.03 MUS$), while the other two approaches (the compensating variation and the *VST* with crowding) give similar, but lower, results (0.78 MUS$ and 0.68 MUS$, respectively). Thus, if the compensating variation is the theoretically correct measure, valuing time savings taking into account crowding in the value of time is more accurate than using standard CBA.

If the capital cost of infrastructure for the bus corridor is included in the CBA, the project will not be socially worthy. However, if the infrastructure is used for six bus lines similar to the analysed one, the benefits would cover the total cost of the project. This implies that the demand for the bus must be over 18,000 passenger/hr. This result is consistent with the recommendation for implementing bus corridors with central exclusive lanes (ITDP, 2007).

Finally, regarding policy effectiveness, increasing bus speed seems to be very effective in reducing car usage when crowding is not considered. However, after equilibrium is established, the final bus demand is lower than the demand before equilibrium. Therefore, the crowding effect is key in the evaluation of policies to promote public transport.

5. FINAL COMMENTS

This paper values the effect of crowding in public transport using data from a stated preference survey. The level of crowding was measured as in-vehicle passenger density and presented to respondents by means of appropriately designed pictures. We used discrete choice models to value crowding and specified modal utility functions where passenger density increased the effect of travel time on utility. Thus, we assumed interactions between passenger density and travel time. The results show that crowding has a significant effect on the marginal utility of travel time. Indeed, the marginal disutility of travel time in a vehicle with 6 passengers/m^2 is two times higher than the marginal disutility in a vehicle with only 1 passenger/m^2.

A policy implication of this study is that the effect of crowding is similar to road congestion. The improvement in travel times for a bus line increases its demand. In turn, this new demand increases crowding and, consequently, the generalized cost of travel (travel disutility). These two effects have opposite signs and counterbalance, which may reduce the effectiveness of transport policies oriented to increase the operating speed of public transport without increasing capacity to avoid crowding. Two examples of this effect are the BRT system of Bogota and the Metro system of Santiago. Both systems offer a very fast travel experience compared with the alternatives attracting very intense passenger flow (both reaching around 45,000 passenger/hr-direction in their critical link-period). However, in both cases in-vehicle passenger density becomes higher than 6 passengers/m^2. This high crowding prevents them to attract more demand coming from car users.

Our results can be used to include the cost of crowding (or congestion) in public transport, in cost-benefit analysis. Planners and policy makers might examine whether financing an increase in vehicle capacity to control for the negative effects of crowding is socially worthwhile. In this respect, the more consistent way of introducing crowding effects is to use the compensating variation to measure user benefits. If the official method consists of valuing travel time savings, the social value of time must depend on the level of crowding and, consequently, be different for car and public transport.

Finally, if users consider the level of crowding when choosing a public transport line or route, the final demand of each line will be the result of an equilibrium state. This equilibrium is similar to that in a road network with congestion. This implies that it is necessary to develop transit network assignment models that consider a similar effect to road congestion, but on bus routes. This is a good topic for future research.

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REFERENCES

Batarce, M. & Galilea, P. (2013) Cost and fare estimation for the urban bus transit system of Santiago. **92nd TRB Annual Meeting**, Washington D.C.

Ben-Akiva, M. & Morikawa, T. (1990) Estimation of travel demand models from multiple data sources. **Proceedings 11th International Symposium on Transportation and Traffic Theory**, Yokohama.

Ben-Akiva, M., Walker, J., Bernardino, A.T., Gopinath, D.A., Morikawa, T. & Polydoropoulou, A. (2002) Integration of choice and latent variable models. In H.S. Mahmassani (ed.), **In Perpetual Motion: Travel Behaviour Research Opportunities and Challenges**. Pergamon, Amsterdam.

Bliemer, M.C.J. & Rose, J.M. (2008) Construction of experimental designs for mixed logit models allowing for correlation across choice observations. **87th Annual TRB Meeting**, Washington, D.C.

BRT Centre of Excellence, EMBARQ, IEA and SIBRT. **Global BRTData,** Version 3.4. Last modified: July 8th. Available at: http://www.brtdata.org

Cherchi, E. & Ortúzar, J. de D. (2002) Mixed RP/SP models incorporating interaction effects. **Transportation**, 29, 371-395.

De Cea, J. and Fernández, E. (1993) Transit assignment for congested public transport systems: an equilibrium model, **Transportation Science,** 27, 133-147.

DeSerpa, A.C. (1971) A theory of the economics of time. **Economic Journal**, 81, 828–846.

Douglas, N. & Karpouzis, G. (2005) Estimating the passenger cost of station crowding. **Proceedings of the 28th Australasian Transport Research Forum**, Sydney.

Gaudry, M.J.I., Jara-Díaz, S.R. & Ortúzar, J. de D. (1989) Value of time sensitivity to model specification. **Transportation Research B**, 23, 151–158.

Guerra, G. & Bocarejo J. (2013) Congestion cost in mass transit systems; pricing and investment policy implications–case study: Bogotá's BRT system. **13th World Conference on Transportation Research**, Rio de Janeiro.

Haywood, L. & Koning, M. (2013) Estimating crowding costs in public transport. **Discussion Paper No. 1293, DIW**, Berlin.

ITDP (2007) **BRT Planning Guide**, Institute for Transportation and Development Policy, New York (https://www.itdp.org/brt-planning-guide-english/, accessed May 2015).

Kessels, R., Goos, P. & Vandebroek, M. (2006) A comparison of criteria to design efficient choice experiments. **Journal of Marketing Research**, 43, 409–419.

Li, Z. & Hensher, D.A. (2011) Crowding and public transport: a review of willingness to pay evidence and its relevance in project appraisal. **Transport Policy,** 18, 880-887.

Lu, H., Fowkes, T. & Wardman, M. (2008) Amending the incentive for strategic bias in stated preference studies: case study in users' valuation of rolling stock. **Transportation Research Record**, 2049, 128-135.

Mackie, P.J., Jara-Díaz, S.R. & Fowkes, A.S. (2001) The value of travel time savings in evaluation. **Transportation Research E**, 37, 91–106.

McFadden, D. (1974). The measurement of urban travel demand. **Journal of public economics**, 3, 303-328.

MDS (2014) **Precios Sociales Vigentes 2014**. Ministerio Desarrollo Social Gobierno de Chile. Santiago.

Munoz, J.C., M. Batarce & I. Torres (2012) Comparative analysis of six Latin American transit systems. **Thredbo 14 Conference**, Oxford.

Ortúzar, J. de D. & Willumsen, L.G. (2011) **Modelling Transport**. Fourth Edition, John Wiley and Sons. Chichester.

Raveau, S., Muñoz, J.C. & De Grange, L. (2011) A topological route choice model for metro. **Transportation Research A**, 45, 138-147.

Revelt, D. & Train, K. (1998) Mixed logit with repeated choices: households' choices of appliance efficiency level. **Review of Economics and Statistics**, 80, 647-657.

Rizzi, L.I. & De la Maza, C. (2014) The external costs of road transport in the metropolitan area of Santiago de Chile. **Working Paper, Department of Transport Engineering and Logistics**, Pontificia Universidad Católica de Chile.

Rose, J.M. & Bliemer, M.C.J. (2009) Constructing efficient stated choice experimental designs. **Transport Reviews**, 29, 587-617.

SECTRA (2003) **Análisis modernización del transporte público, VI etapa − Estructura de costos transporte público**. Ministerio de Planificación, Gobierno de Chile. Santiago.

SECTRA (2011) **Apoyo técnico para mejoramiento físico-operacional de la red vial de transporte público de Santiago**. Ministerio de Transporte y Telecomunicaciones, Gobierno de Chile. Santiago.

Small, K.A. & Rosen, H.S. (1981) Applied welfare economics with discrete choice models **Econometrica**, 49, 105-130.

Tirachini, A., Hensher, D.A. & Rose, J.M. (2013) Crowding in public transport systems: effects on users, operation and implications for the estimation of demand. **Transportation Research A**, 53, 36-52.

Tirachini, A., Hensher, D.A. & Rose, J.M. (2014) Multimodal pricing and optimal design of urban public transport: the interplay between traffic congestion and bus crowding. **Transportation Research B**, 61, 33-54.

Train, K. E. (2009) **Discrete Choice Methods with Simulation**. Cambridge University Press, Cambridge.

Wardman, M. & Whelan, G. (2011) Twenty years of rail crowding valuation studies: evidence and lessons from British experience. **Transport Reviews**, 31, 379-398.

Whelan, G. & Crockett, J. (2009) An investigation of the willingness to pay to reduce rail overcrowding. **First International Choice Modelling Conference**, Harrogate.