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Research paper

Assessing free-fare public transport in Chilean cities through optimization models

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ABSTRACT

Many public transport services receive operating subsidies from national, regional, or local Governments, part of which are directed to reducing fares. In recent years, different cities, most of them located in Europe, have advanced in the provision of free-fare public transport, which could help reduce car use and thus limit negative externalities related to its use. Using cost minimization models with variable mode share, in a circular structure with radial lines, optimal fares for bus services were estimated for 33 small and medium-sized cities in Chile. Through a linear regression model, we determined that the optimal fares decrease for cities with higher population, lower average income, a higher proportion of students, and with a CBD surrounded by natural boundaries such as seacoast. Based on the model's results, together with feasibility criteria that included competition of buses with other transportation modes, the regulation of existing systems and the quality of available data, recommendations are provided to select the best cities for a test of free-fare public transport in Chile. The methodology is applicable to cities in other countries, and future research may incorporate the effect of the valuation of crowding by users, as well as the generation of additional trips due to a drop in bus fares.

1. Introduction

Over the last decades, various cities, most of them located in Europe and North America, have implemented free public transport. However, in most cases these experiences are limited to certain areas, user groups, dates, or times. Free public transport systems in operation are mainly limited to small and medium-sized cities in Europe, of which Tallinn, the capital city of Estonia, is by far the largest (Cats et al., 2017).

The experiences of free-fare public transport, as well as the advantages and disadvantages of this policy that have been identified in the relevant literature, are summarized below.

1.1. Free-fare public transport experiences, advantages and disadvantages

The characteristics of free public transport systems have been extensively studied from a variety of approaches, including experiments with free travel cards (Bull et al., 2021; Thøgersen & Møller, 2008), ex-post studies based on existing systems (Cats et al., 2017; Donin, 2013; Štraub, 2020) and comparisons between free and non-free systems (Cordier, 2007). Extensive summaries of the existing literature are found in Kębłowski (2020) and Volinski (2012).

There are many experiences of free-fare public transport limited to certain dates, such as voting or high pollution days, certain times – for example, in the early morning to encourage less use in the peak period – some routes, such as lines within the campus of universities, and specific groups of users, in general for the young or the elderly. Many of these limited free-fare public transport experiences correspond to large cities such as Singapore, Boston (United States) and Melbourne (Australia).

However, almost all experiences of free-fare public transport for any user and throughout the network correspond to small and medium-sized towns, most below 100,000 residents. Keblowski (2020) identified 99 cities that implemented free-fare public transport between 1970 and 2017, more than half of them in Europe and the rest mainly in North America and Brazil. Among the larger cities that applied this policy, only Tallinn (Estonia) has maintained it for more than 3 years.

Free-fare public transport in Tallinn resulted in an increase in public transport trip share from 55% to 63%, although more than half of the trips were derived from walking. The largest increase in public transport ridership was observed in the young, the elderly and people with lower incomes (Cats et al., 2017).

Besides, as public transport in Tallinn is free only for registered residents, and the local government collects part of the residents'

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income tax, free-fare policy benefitted the local government, since the additional tax collection by new registrations exceeds the extra subsidies for public transport operation (Kębłowski et al., 2019).

Other reported benefits of free-fare public transport include the reduction of negative externalities produced by car use, such as congestion (Volinski, 2012) and accidents (Storchmann, 2003). Free-fare transit can also provide greater accessibility for low-income users (Hodge et al., 1994) and was praised for its contribution to achieve climate justice (Kipfer, 2012). Besides, free-fare transit reduces operation costs associated with fare collection (Scheiner, 1976) and makes vehicle loading and unloading faster (Perone, 2002). On the contrary, scholars pointed out the weakness to derive trips previously made by car (Cats et al., 2017; Fearnley, 2013) as well as the high financial impact of subsidies (Cervero, 1990) and the generation of additional worthless trips (Duhamel, 2004). As much of the additional transit patronage is derived from sustainable modes such as walking and cycling, infrastructure for non-motorized transport should be built (Fearnley, 2013) so that the extra subsidies required for the operation are offset by the benefits.

Although the existing literature is wide and diverse, no models based on the real characteristics of the cities were found that allow estimating, *ex-ante*, in what kind of cities (if any) it would be more convenient to test a free-fare public transport policy. Cost minimization models in transport networks offer an adequate theoretical framework for this.

1.2. Optimal public transport fares

Optimization models have been applied by various authors to estimate which characteristics of public transport, such as the frequency and distance between stops, minimize the sum of costs or maximize the total welfare considering both operators and users. Comprehensive reviews can be found in Ibarra-Rojas et al. (2015) and Kepaptsoglou and Karlaftis (2009).

The variation of public transport fares has no effect on the optimal configuration of the system if the number of trips is constant, since the fares represent a cost for the users but an equivalent income for the operators. However, if user behavior is sensitive to fare variations, a trade-off occurs between lower operating costs and higher costs associated with users' travel time when they are forced to walk more, so finding the fare that minimizes the total costs (or the one that maximizes the income of the operators) is not trivial.

This has been analyzed by several studies that included public transport fares among the variables to be optimized in transport networks (Chien & Spasovic, 2002; Chowdhury & Chien, 2019), or estimated optimal fares, either flat or variable by distance, in corridors (Tang, Ceder, & Ge, 2017) or in transport networks (Huang et al., 2016; Yook & Heaslip, 2014). Except for Yook and Heaslip (2014), who considered the maximization of demand as the objective, none of these studies revealed zero as the optimal (base) fare.

None of the models mentioned here has been applied to a sample of cities to estimate, based on their characteristics, the convenience of applying free-fare services.

1.3. Article contribution and structure

Through a widely used methodology to estimate the ideal characteristics of an urban transport system, we analyze *ex-ante* the convenience of implementing free-fare bus services in a sample of small and medium-sized cities in Chile, whose size is according to past and existing free-fare transit applications. Beyond the mathematical limitations of the model, which are detailed in the next section, the applied methodology – which also includes socio-political considerations – aims to be a useful guide for the application of a relevant (and costly) public policy in a specific context. Moreover, the methodology can be replicated for other countries.

Following this introduction, we explain the methodology in Section 2. Section 3 presents the results of models, which are finally discussed in Section 4.

2. Methodology

This section is divided into four parts. First, the main equations of the cost minimization models are presented. Section 2.2 describes the mode share model used. In Section 2.3, the cities in the database are described along with their modeled characteristics. Finally, section 2.4 presents the strengths and weaknesses of the models.

2.1. Cost minimization models

We compared the generalized social cost, that is, the sum of the costs of construction, operation, externalities, and the equivalent cost assumed by users, for the transport system in a given city consisting of bus systems with varying fleet, line and stop density and fares, as well as cars and non-motorized modes, considering radial representations of cities.

The cost minimization models are represented by the following equation [1]:

$$min_{b,bv,n,s,\tau} CT = \sum_{m} \left[C_c + C_o + C_{ext} + \sum_{i,} n_{i,m} \cdot \left(C_{a,m} + C_{w,m} + C_{t,m} \right) \right] \quad [1]$$

$$s.t.\ Cap_{i,bus} \geq Dem_{i,bus}, i \in (P, O)$$

Where CT is the total social cost, for all modes "m" operating in a given city, which can be separated in two main components:

- User-related social costs, corresponding to the valuation of travel times. Here, $n_{i,m}$ represents the number of trips per period "i" for each mode "m", which is estimated through Logit mode share models explained in Section 2.2. Meanwhile, $C_{a,m}$, $C_{w,m}$ and $C_{t,m}$ are the average cost per user corresponding to the access, waiting and in-vehicle trip stages respectively for each mode.
- Operator-related and external social costs, where C_c is the cost of construction and infrastructure maintenance, C_o the cost of operation and fleet purchase, and C_{ext} the cost of externalities.

The variables to adjust in equation [1] are the total bus fleet "b", of which "bv" vehicles operate during off-peak hours, the number of lines "n", number of stops per line "s", and bus fares "τ" considering multiples of 100 Chilean pesos (about 0.12 US $) for adult fares. Besides, a simple capacity (Cap_i) restriction is assumed for the bus mode in both peak (P) and off-peak (O) periods, so that maximum bus occupation (Dem_i) is below 5 pax/m2.

The base equation [1] is further developed in Section 2.2 below, with the corresponding expressions for each of the modes considered.

2.2. Mode share model assumptions and cost breakdown

The population of each city was divided into 3 groups: "students", "adults" and "seniors". Using data of the last population Census in Chile (Instituto Nacional de Estadísticas, 2018) for each municipality, we considered as "students" half of the population aged 29 or under, while the other half was considered as "adults". The minimum legal retirement age in Chile is 60 for women and 65 for men (Superintendencia de Pensiones, 2023) and the trip generation rates are lower for elder persons. We therefore considered as "seniors" half of the population aged 65 of over for trip generation purposes, shown in Table 1 below.

There is little specific information on vehicle availability by age group. Own estimates were set, based on general references. Regarding Value of Time, most students have a lower income than adults, which should result in a lower willingness to pay for transportation. The same applies to seniors, as pensions in Chile are substantially lower than

Table 1
Mode share mode characteristics.

Characteristics by group	Students	Adults	Seniors	References (based on)
% of trips – variable per city	17.8 to 22.7	72.4 to 74.6	3.6 to 9.5	Instituto Nacional de Estadísticas, 2018
Car availability (% of users)	10	50	20	Maturana et al., 2021; SECTRA, 2010 – 2017
Bicycle availability (% of users)	20	10	5	SECTRA, 2010 – 2017
Income (VoT) factor	0.5	Variable (1.171–1.191)	0.5	INE, 2018 Superintendencia de Pensiones, 2022
Bus fare factor	0.5	1	0.5	Own estimate, based on a review of existing fares
Walking/bicycle speed factor	1.2	1	0.8	Schimpl (2011)

average wages (Superintendencia de Pensiones, 2022). A factor of 0.5 was applied to both "students" and "senior" groups, and the factor for the "adults" group is derived from the trip % assigned to each group. Many cities of Chile have reduced fares for both students and elder users, so we proposed a 50% fare reduction for these groups in the models compared with adult fares. Finally, diverse studies (see for example Schimpl et al., 2011) show a decrease in walking speeds with age, which accelerates towards the end of life. We propose a similar trend for bicycle speeds considering the user groups.

Mode share for each group and location was estimated through a multinomial Logit model considering up to 4 options (walking, bicycle, car, and bus) per user. Each utility function considers access, waiting and trip times as well as user cost, represented by fares in bus and by operation cost and parking for cars. Besides, a positive mode constant – equivalent to 30 and 10 min of vehicle travel for car and bicycle respectively – was added, in order to consider user preference for individual modes over public transport due to other factors such as perceptions of comfort and security. Finally, a scale factor μ of 0.1 was implemented.

Mode share was estimated for each user group and for every feasible combination of parameters, considering different trip distances for each city. In order to estimate social cost, an initial mode share assumption is set, from which preliminary time estimates are derived. The mode share model is then applied, and travel times – which vary with congestion, and the number of boardings and alightings – are reestimated. This procedure can be applied iteratively until reaching convergence in the mode share. Finally, the social costs for each feasible combination are calculated and the optimal parameters for each city are obtained.

Fig. 1 below shows an example of the resulting mode share per group:

The model incorporates the following features that allow a more realistic modelling of travel times and costs compared with other optimization models:

- BPR curve congestion calibrated for cities with mixed traffic, where bus car-equivalent factor grows with stop density.
- Irregularity of bus services depending on the frequency, based on the bus headway model calibrated by Godachevich Contreras (2017) for Santiago de Chile, both for peak and off-peak hours.
- Probability of non-stop at bus stations according to a standard Poisson distribution.
- Externalities due to pollution, accidents, use of pavements and others, which were estimated for the city of Santiago, Chile, by Rizzi and De La Maza (2017) as a marginal cost per km. Cost derived from externalities are considered in the objective function only, not in user and operator cost functions.

Table 2 below presents a detail of each cost component per mode, considering operators, users and externalities. In order to estimate total costs, every component is normalized to cost/passenger units.

Walking has the simplest cost structure as it only implies a user cost for the single trip stage. Equivalent cost per trip is represented by the walking time (i.e. walking distance divided by speed, $\frac{d_w}{s_w}$) multiplied by the value of time VoT_w, which is affected by a penalization for access α. The construction cost for walking was not considered, given that the street network (see Section 2.3) is independent of the bus system characteristics.

Trips by bicycle imply two stages: a generally short walking time $\frac{da_b}{sa_b}$, followed by in-vehicle travel. Cost estimation for both stages is similar in structure, but only the access part is penalized with the coefficient α. As with walking, construction cost was not considered. In turn, vehicle operation costs and externalities (mainly accidents with pedestrians) are insignificant compared with those of cars and buses and thus were not included.

As for cars, an infrastructure cost associated with pavement maintenance was considered, which arises from multiplying the cost per car-km cm_c by the average travel distance by car d_c, divided by the number of passengers per car ρ_c. The expressions for operating cost and externalities are analogous, with factors per car-km co_c and ce_c respectively. Since we consider that car ownership does not depend on the characteristics of the bus system, the amortization component of vehicle purchase is not included. Meanwhile, the expression of the travel cost for users is analogous to that of bicycle trips, with the addition of the congestion factor γ_c that multiplies the base in-vehicle time.

Finally, the expression for the buses is the most complex, both for the estimation of the cost of operators and externalities and for the one corresponding to the travel stages of users.

As for the users, the access and in-vehicle travel stages have similar expressions to those of the car. A waiting cost is added, which corresponds to the multiplication of the mean waiting time $\frac{k}{h}$, where "h" is the average headway and "k" a regularity factor, whose minimum value is 0.5 (perfectly regular service) and increases as the interval decreases, up to a maximum value of 1, by the corresponding waiting value of time $VoT_t * \omega$.

Regarding the costs assumed by operators and non-users, the expresions for pavement damage and externalities are analogous to those of cars. The infrastructure cost has two additional components, which correspond to the construction and maintenance of stops and to the leasing of terminals. Cost construction of stops corresponds to their unit cost "cs", multiplied by the number of stops per route "ns" and by the number of routes "η", while the cost of terminals is proportional to the number of buses "B" multiplied by a unit cost "λ". Finally, stop and terminal costs are multiplied by a factor "δ" to consider el maintenance, and the resulting valued is divided by the number of trips "N_i" during the infrastructure lifetime. Operating costs have an analogous expression to those of cars, with the addition of fixed costs associated with driver wages cf_t during h_t hours per day, as well as the amortization of buses with a unit procurement cost θ_t normalized by the number of trips "N_b" during vehicle lifetime.

Table 3 below shows the values used in the models. To the extent possible, recent values from Chile were used. For other parameters, which vary according to the bus system, such as the demand hour profile and the directionality of the trips, our own estimates were applied to try to represent a typical bus system.

2.3. Cities database and modeled structure

The database for the model application consists of 33 cities of Chile with less than 200,000 residents, excluding cities which belong to larger

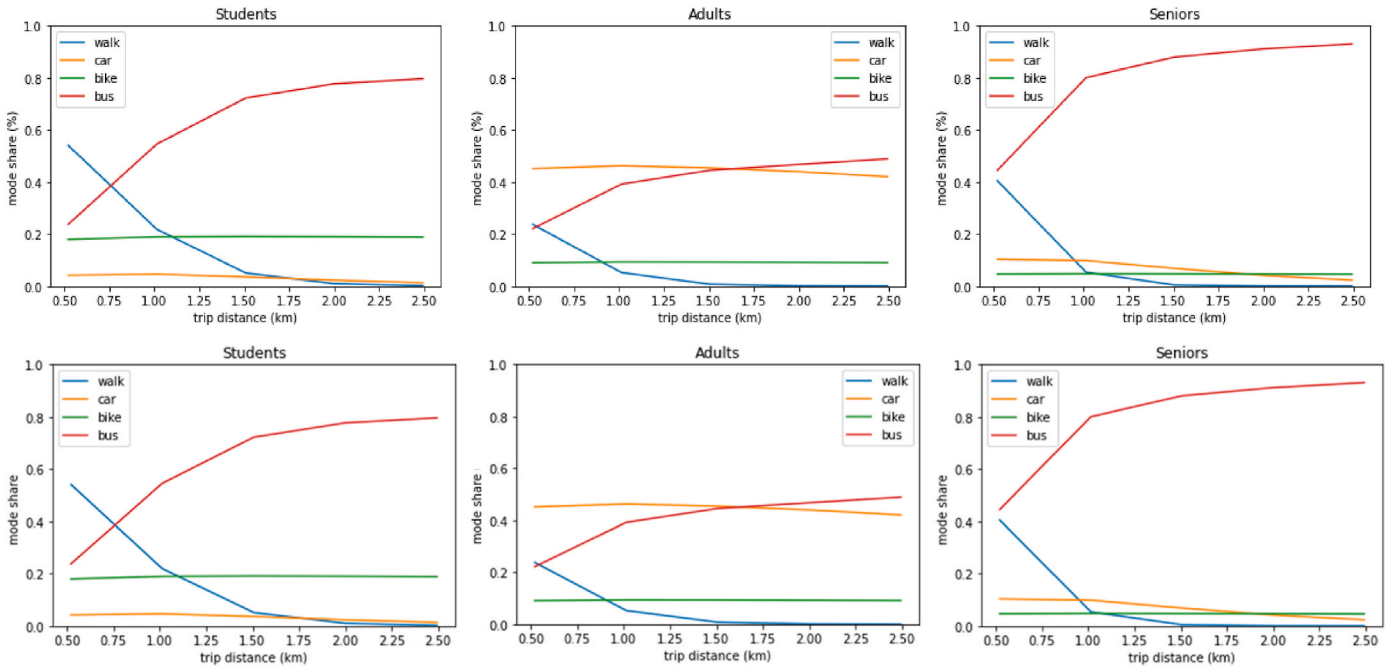


Fig. 1. Example of mode share (y) per user group and trip distance (x).

Table 2a
Breakdown of costs per mode (operators + externalities).

Modes (m) *Component*	Walking (w)	Bicycle (b)	Car (c)	Bus (t)
C_c – construction & maintenance cost	0	0	$d_c * \frac{cm_c}{\rho_c}$	$[(\eta * cs * ns) + (B * \lambda)] * (1 + \delta)/N_i + d_t * \frac{cm_t}{\rho_t}$
C_o – operation & fleet cost	0	0 [b]	$d_c * \frac{co_c}{\rho_c}$	$\left(B * h_t * \frac{cf_t}{n}\right) + \left(d_t * \frac{co_t}{\rho_t}\right) + (B * \theta_t * (1 - r)/N_b\right)$
C_{ext} – externalities cost	0	0	$d_c * \frac{ce_c}{\rho_c}$	$d_t * \frac{ce_t}{\rho_t}$

Where: d_m = average trip distance for mode "m"/cm_m = pavement maintenance cost/vehicle-km for mode "m"/ρ_m = average number of passengers per vehicle in mode "m"/η = number of bus lines/cs = construction cost per stop/ns = number of stops per line/B = bus fleet/λ = leasing of depots per bus/δ = bus infrastructure maintenance factor/N = bus passenger demand during bus life-time/co_m = variable operation cost per km for mode "m"/h_t = operation (hours/day) of bus system/cf_m = fixed operation cost per hour for mode "m"/n = bus passenger demand per day/θ_t = procurement cost/bus/r = bus resale value coefficient/ce_m = externalities cost per km for mode "m".

Table 2b
Breakdown of costs per mode (user trips).

Modes (m) *Component*	Walking (w)	Bicycle (b)	Car (c)	Bus (t)
C_a – access cost per user	0	$\frac{da_b}{sa_b} * VoT_b * \alpha$	$\frac{da_c}{sa_c} * VoT_c * \alpha$	$\frac{da_t}{sa_t} * VoT_t * \alpha$
C_w – waiting cost per user	0	0	0	$\frac{k}{h} * VoT_t * \omega$
C_t – in-vehicle trip cost per user	$\frac{d_w}{sa_w} * VoT_w * \alpha$	$\frac{d_b}{s_b} * VoT_b$	$\frac{d_c}{s_c} * VoT_c * \gamma_c$	$\frac{d_t}{s_t} * VoT_t * \gamma_t$

Where:/da_m = average access distance for mode "m"/sa_m = average walk speed for mode "m"/VoT_m = average value of time for mode "m"/α = walking value of time multiplier/k = bus headway regularity factor (0.5–1)/h = average bus headway/ω = waiting value of time multiplier/s_m = average base speed for mode "m"/γ_m = average congestion factor (BPR) for mode "m".

metropolitan areas. The cities considered have public transport systems, served by buses and/or by taxi-colectivos.[1]

The population limit is due to three reasons. First, as seen in Section 1, most of the free-fare public transport experiences correspond to small and medium-sized cities. Second, the urban structure of small and medium-sized cities in Chile is less complex than those of larger cities (Henriquez et al., 2017) so it can be more adequately represented by a simple structure. Finally, almost all Chilean cities with higher populations have run mobility surveys recently (SECTRA, 2010–2017), so the performance of their transit systems could be analyzed with more specific models.

A circular representation of cities was considered. This simple structure has been considered in several network optimization models, both in linear routes (see for example Byrne, 1975; Badia, 2020) or ring-radial networks (see for example Saidi, Wirasinghe, & Kattan, 2016).

Each person makes a commute trip to and from a CBD with radius "r", which is located at the circle center in most cities. Constrained angles (at 180, 90, or 45°) were used for locations bordered by natural boundaries, such as sea or lake shorelines, in which the CBD is located at the geographic center of the involving circle. City angle ϑ can therefore take 4 values, according to the topography of each real city.

Moreover, an inversely decreasing population density to the radius outside the CBD was considered. Even though this is simpler than the usual variations of negative exponential functions considered in mono-centric city representations (see for example Smith, 1997) it simplifies calculations as any ring of radius "dr" generates the same number of

[1] Taxi-colectivos are cars authorised to transport up to 4 passengers, either on fixed routes or in certain areas of cities or towns. Although colectivos have a regulated fleet size, lines and schedules are not coordinated with other public transport modes (Domarchi, 2017).

Table 3
Values used in models.

Factor	Value	Source/notes
Construction & maintenance		
Bus stop (US $/stop)	10.000	Based on Schmitt (2018)
Depots leasing (US $/sqm/month)	1	Own estimate
Bus infrastructure lifetime (years)	20	Based on Rodrigue (2020)
Bus pavement damage marginal cost (US $/bus-km)	0.038	Rizzi and De La Maza (2017)
Car pavement damage marginal cost (US $/car-km)	0.001	
Bus operation		
Bus purchase cost (US $)	180.000	Batarce et al. (2016)
Bus lifetime (years)	10	DTP Metropolitano (2021)
Bus residual value (%)	20	Batarce et al. (2016)
Bus fixed operation cost (US $/h)	8	Ministerio de Transportes y Telecomunicaciones de Chile (2013)
Bus variable operation cost (US $/km-bus)	0.65	Based on Centro Mario Molina (2021), adjusted for diesel prices.
Bus coefficient of variation of headway	0 to 1	Based on Godachevich Contreras (2017)
Bus base stop time (s)	15	Wang et al. (2016), Tirachini (2013)
Extra stop time per boarding passenger (s)	2	Tirachini, Hensher, and Jara-Díaz (2010)
Extra time in terminals (min)	3	Own estimate
Base non-stop speed (km/h)	30	Own estimate
User behavior & demand patterns		
Base Value of Time (CLP/h)	2000	Average hour income, based on Casen (2017).
Access/waiting time coefficient	2.4/3.3	Raveau et al. (2017)
Walking speed (km/h)	3 to 5	Own estimate, based on Proboste (2020) and Langmuir (1984) [a]
Peak/non-peak operation (hours)	4/12	Own estimate
Base peak/non-peak directionality (main direction %)	80%/60%	Own estimate
Base peak/non-peak hour factor (% of total daily trips)	10%/5%	Own estimate
Other		
Exchange rate (CLP/US $)	800	Own estimate
Average people/car	2	
Parking cost (CLP/trip)	0 to 1500, grows w/city population	
Fare discount for students and seniors	50%	
Bus externalities, peak hour (US$/bus-km)	1.76	Rizzi and De La Maza (2017)
Bus externalities, off-peak hour (US$/bus-km)	0.74	
Car externalities, peak hour (US$/car-km)	0.51	
Car externalities, off-peak hour (US$/car-km)	0.15	

[a] Average walking speed value (4.5 km/h) was taken from Proboste et al. (2020). Different speeds were considered for flat (5 km/h), rolling (4 km/h) and mountainous (3 km/h) topography, based on the rule by Langmuir (1984).

trips per day. As a result, demand profiles are triangular out of the CBD and the average trip distance is r + 0.5 (R – r). Finally, radial streets every 20° were assumed, setting a maximum for bus line density and a minimum for traffic congestion.

Fig. 2 below represents the modeled structure.

The characteristics of the cities used for modelling are the following:

* Population, estimated from the last Census (Instituto Nacional de Estadísticas, 2018)
* Radius: Polygons representing the area of each city or town were gathered with Google Earth® and surface corresponding to each shape file was calculated in QGIS3®. City radius R corresponds to [2]:

$$R = \sqrt{\frac{2.S}{\theta}} \quad [2]$$

Where S is the polygon surface and ϑ the represented angle for each city as shown in Fig. 2.

* Access/Walking speed, which arises from classifying cities into 3 categories according to the average slope of the streets. An average speed of 5 km/h was considered for flat cities, 4 km/h for rolling terrain and 3 km/h for mountainous cities, based on Langmuir (1984).
* Income factor, corresponding to the quotient between the average monthly income per household of each region and of Chile (Ministerio de Desarrollo Social y Familia, 2021).
* Percentage of trips made by “students”, “adults” and “seniors”, as explained in Section 2.2.

Table 4 below shows the location and characteristics of the cities in the database.

2.4. Strengths and limitations of models

Through simple models, which reflect real characteristics of cities and their people, it is possible to evaluate *ex-ante* the convenience of free-fare public transport in diverse locations. Although the application is limited to cities of Chile, models can be extended to other countries as well.

The mode share model applied considers differences by groups and includes the valuations of the main utility components, although crowding valuations were not included. It is necessary to have more detailed information from each city to obtain more complex utility functions, which could include spatial heterogeneity and income differences within each user group.

The modeled structure makes it possible to distinguish cities located on the coastline and cities with a central CBD, although the actual shape of the cities, the structure of trips and public transport routes are undoubtedly more complex than modeled.

In turn, street provision and vehicle ownership were considered as exogenous to the characteristics of bus services, as no reliable estimations for the variation of such factors were found. As a result, the models are insensitive to construction cost and vehicle purchase for cars.

Finally, the models take into account cross-elasticity between modes through modal share, but do not consider the effect of additional trips when lowering public transport fares. Such analysis would require a more complex approach to estimate the social welfare generated by these additional trips, which can have a positive or negative effect on the objective function.

The results of the models are presented in Section 3. Then Section 4 analyzes the implications of the results for public policy, taking into account the limitations indicated.

3. Results

This section is divided in two sections: first, we show the optimal characteristics of bus systems for each city represented, and we compare the minimum social cost for free-fare systems with the optimal and the current fare levels. In Section 3.2 we identify which city characteristics are relevant for explaining the optimal fare per distance, through linear regression models.

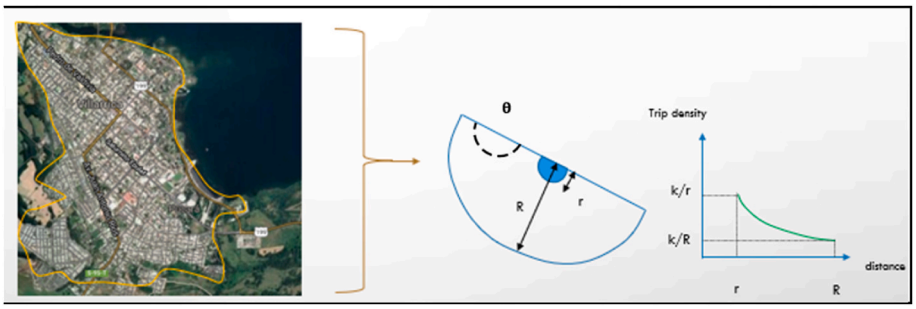
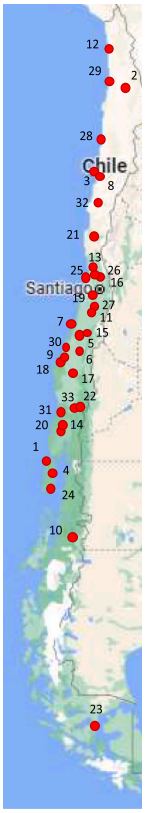


Fig. 2. Modeled urban structure.

Table 4
Cities database.



# - City	Population	Radius (km)	Angle	Access speed (km/h)	Income factor	Students (%)	Seniors (%)
1 – Ancud	32,089	2.74	1.57	4	0.795	18.2	7.4
2 – Calama	147,666	2.65	6.28	4	1.184	22.7	3.6
3 – Caldera	12,800	2.05	3.14	4	0.907	21.0	5.7
4 – Castro	35,000	2.64	6.28	4	0.795	19.3	6.1
5 – Cauquenes	31,000	1.28	6.28	5	0.704	17.8	9.5
6 – Chillán	188,000	3.04	6.28	4	0.642	19.8	7.0
7 – Constitución	41,000	1.83	3.14	4	0.704	20.4	5.9
8 – Copiapó	150,804	2.34	6.28	4	0.907	22.3	5.0
9 – Coronel	108,000	3.85	3.14	4	0.773	21.2	5.6
10 – Coyhaique	63,600	1.60	6.28	4	1.137	20.4	5.3
11 – Curicó	125,275	2.53	6.28	5	0.704	20.0	6.3
12 – Iquique	188,003	3.28	3.14	4	0.973	21.4	5.1
13 – La Ligua	22,000	1.00	6.28	4	0.901	18.8	7.5
14 – La Unión	25,600	1.35	6.28	5	0.759	18.9	8.0
15 – Linares	73,602	2.03	6.28	5	0.704	19.4	7.2
16 – Los Andes	69,041	1.69	6.28	5	0.901	19.9	6.9
17 – Los Ángeles	187,000	2.61	6.28	5	0.773	20.5	6.2
18 – Lota	49,000	1.80	3.14	3	0.773	19.6	7.2
19 - Melipilla	72,212	1.60	6.28	5	1.289	20.8	6.1
20 – Osorno	147,666	2.85	6.28	5	0.795	19.7	6.6
21 – Ovalle	75,864	1.75	6.28	4	0.715	20.6	6.8
22 – Pucón	13,800	2.33	1.57	5	0.699	20.7	6.0
23 - Punta Arenas	123,403	3.94	3.14	4	1.176	19.5	6.4
24 – Quellón	13,700	1.65	3.14	4	0.795	21.5	4.2
25 – Quintero	18.700	3.56	0.79	4	0.901	20.0	7.4
26 – San Felipe	64,543	1.59	6.28	5	0.901	20.7	6.4
27- San Fernando	58,367	1.71	6.28	5	0.737	19.5	6.2
28 – Taltal	13,493	1.25	3.14	4	1.184	21.7	5.2
29 – Tocopilla	23,352	2.00	3.14	4	1.184	21.9	5.7
30 – Tomé	41,200	2.31	3,14	3	0.773	18.7	8.1
31 – Valdivia	150,848	5.16	1.57	4	0.759	20.9	6.3
32 – Vallenar	52,100	1.49	6.28	4	0.907	20.5	6.8
33 – Villarrica	33,000	1.95	3.14	5	0.699	20.1	6.7

3.1. Optimal fares and system characteristics

Optimal fares and basic system characteristics (cost, fleet size, lines and transit mode share for each city) are shown in Table 5 below. The models were solved by discrete programming in Python 3, selecting the configuration that minimizes generalized social cost for each city by a screening of all feasible configurations, applying the equations of Table 5.

In general, the optimal fleet, line and stop density per line increase as the population of cities grows. The optimal social cost and transit mode share also increase with population.

In no case does free-fare policy yield the minimum social costs. Although free-fare would benefit transit users, particularly those with lower incomes and who have no reasonable alternatives, additional buses are required, which have costs associated with their operation, the use of infrastructure, and the externalities they generate.

Fig. 3 below compares social cost per trip, for free-fare versus optimal fares (a) and for current versus optimal fares (b).

As the population increases (a), free-fare public transport would represent a lower extra cost in relation to the optimum fare level. When comparing the performance of transit systems between the optimal and current fares (b), the differences are minor, and have no apparent relationship with the population. Four of the cities in the database have a current fare equal to the one which yields the minimum social cost.

However, the impact of a free-fare bus system on some cost components and for some user types is relevant, as discussed in Section 4.

Table 5
Optimal characteristics of bus systems.

# - City	Adult fare (US $)	Peak hour fleet	Off-peak hour fleet	Number of lines	Stops/line	Social cost/trip (US $)	Transit mode share (%)
1 – Ancud	0.875	15	15	3	9	0.888	47.1
2 – Calama	1.5	72	72	18	8	0.958	49.0
3 – Caldera	1.125	6	6	3	6	0.939	36.1
4 – Castro	0.875	15	15	3	9	0.857	46.2
5 – Cauquenes	1.5	5	5	5	3	0.709	7.3
6 – Chillán	0.50	108	108	18	9	1.013	77.9
7 – Constitución	0.625	16	16	4	7	0.760	45.3
8 – Copiapó	1.125	72	72	18	8	0.936	55.0
9 – Coronel	0.875	72	72	9	11	1.058	75.5
10 – Coyhaique	1.25	30	30	10	6	0.810	37.8
11 – Curicó	0.50	80	80	16	8	0.981	74.4
12 – Iquique	0.625	117	99	9	10	0.900	76.0
13 – La Ligua	1.5	5	5	5	3	0.694	13.1
14 – La Unión	1.5	5	5	5	3	0.745	10.0
15 – Linares	0.875	33	33	11	6	0.904	43.2
16 – Los Andes	1.00	27	27	9	5	0.791	37.0
17 - Los Ángeles	0.50	108	108	18	8	0.921	74.8
18 – Lota	0.75	20	20	5	8	0.800	47.1
19 - Melipilla	1.25	27	27	9	5	0.741	35.8
20 – Osorno	0.75	90	90	18	8	0.994	67.9
21 – Ovalle	0.875	36	36	12	6	0.884	44.7
22 – Pucón	0.625	6	6	2	6	0.834	40.2
23- Punta Arenas	1.25	72	72	9	11	1.025	62.5
24 – Quellón	0.875	6	6	2	6	0.817	33.8
25 – Quintero	0.875	10	10	2	10	1.000	47.5
26 – San Felipe	1.00	24	24	8	5	0.772	35.3
27- San Fernando	1.00	24	24	8	6	0.844	33.0
28 – Taltal	1.25	4	4	2	4	0.704	29.1
29 – Tocopilla	1.25	12	12	4	7	0.856	40.2
30 – Tomé	0.875	24	24	6	9	0.937	48.2
31 – Valdivia	0.75	144	84	4	12	1.188	83.0
32 – Vallenar	1.125	24	24	8	6	0.833	35.6
33 – Villarrica	0.625	12	12	3	6	0.763	42.7

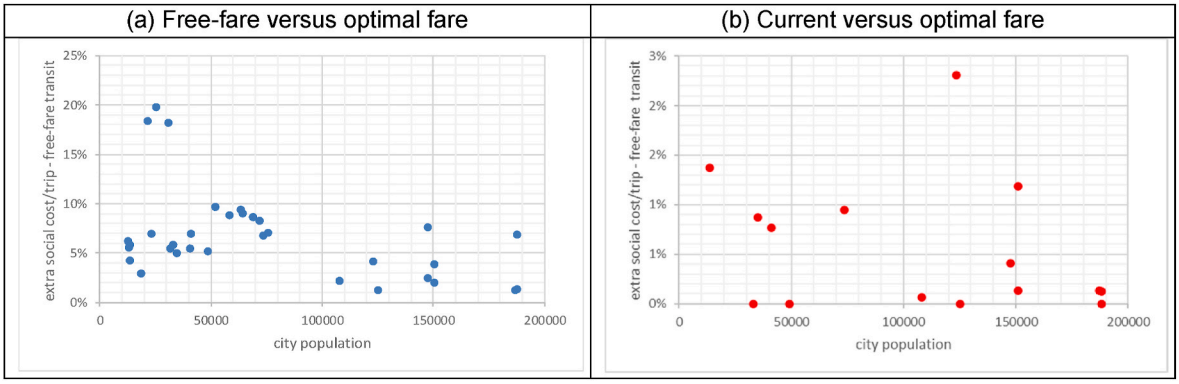


Fig. 3. Minimum social cost comparison.

3.2. Mode share and cost breakdown

Fig. 4a below shows the weighted average bus share mode share reported by the model for all users, and Fig. 4b shows the weighted average share per mode and user type. The optimal bus system layout is considered for each fare, ranging from 0 to 1.5 US $ per trip.

As expected, as the public transport fare increases, its use decreases, while that of the other modes increases. The decline is less pronounced for seniors, who have lower walking and cycling speeds and low car availability. This group is particularly benefited by the reduction in public transport fares, since they also have lower income than adults.

Students, with low car availability and higher walking and cycling speed, are the group who use non-motorized modes to a greater extent. Car use is particularly high among adults, who are more available in this way and have a higher average income.

Fig. 5 below shows the average social cost per trip in US $ for each

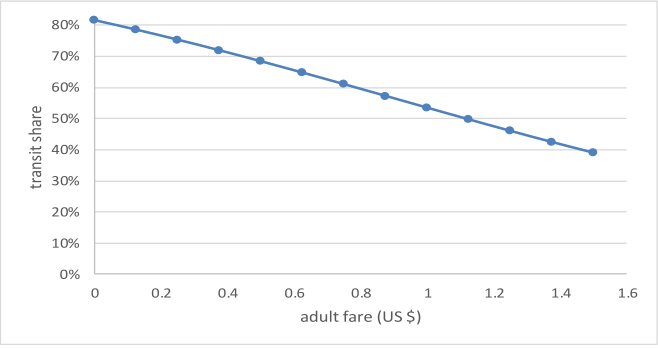


Fig. 4a. Average bus share with varying transit fare.

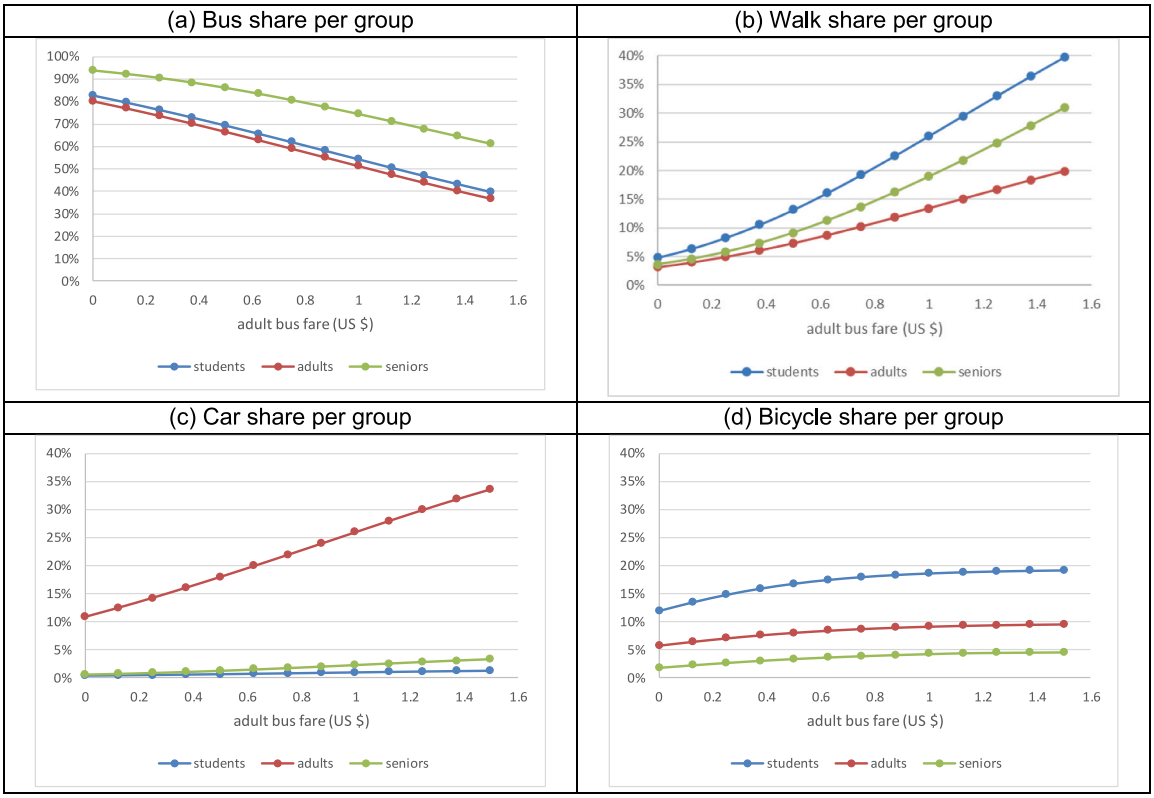
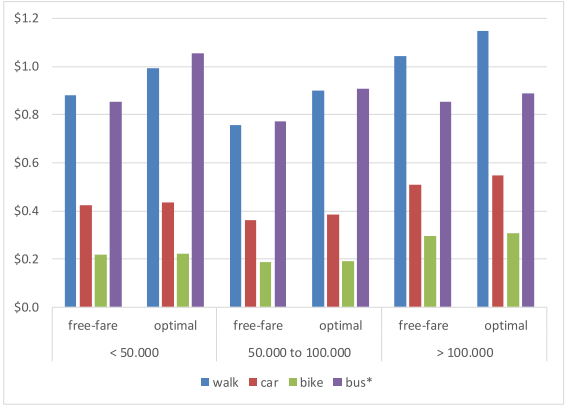


Fig. 4b. Mode share per user group with varying transit fare.



(*) Bus costs excludes fleet procurement for a fairer comparison to car costs.

Fig. 5. Average social cost per mode (y) by city population (x), optimal transit configuration for free-fare and optimal fare
(*) Bus costs excludes fleet procurement for a fairer comparison to car costs.

mode considered, for both zero fares and the optimum fare for each city, grouped by city population.

Regardless of city population, the average social cost of cycling trips reported by the model is the lowest, and that of walking trips is among the highest, which could be explained by the access valuation penalty α assigned to the full walking trip.

Although the average social cost of car travel is lower than that of bus, the difference tends to be lower as city population increases due to the higher congestion costs caused by cars. Part of the gap favoring cars is explained by the omission of car-related infrastructure costs.

For all modes and city sizes, the social cost per trip for free-fare bus is lower than for the optimal fare. Even if this may be counterintuitive, it is due to the greater mode share of buses as the fare decreases.

Fig. 6 below compares the marginal external costs of buses and cars considering the optimal configuration of the bus system both for the free-fare case and for the fare that minimizes total social costs (optimal fare), grouped by city population.

Bus marginal contribution to congestion per trip is lower than for cars, regardless of city size, for both free-fare and optimal fares. The difference is higher for larger cities. In turn, other externalities – such as pollution and accidents – are lower for cars in cities under 100,000 residents, as a low average bus occupation does not compensate the higher externalities per vehicle-km. For cities over 100,000, which have a higher ridership per bus, the average external costs are lower than for cars in both fare scenarios.

3.3. Linear regression model

Although the models do not yield free-fares as socially optimal in any of the cities studied, there is a wide variability in optimal fares, which range from 400 CLP (0.375 US$) to 1200 CLP (1.5 US$) as shown in Table 5.

Given that discrete levels were considered in modeled fares (every 100 CLP, equivalent to 0.125 US$), these were normalized (in $ per km of vehicle trip) in order to obtain a continuous dependent variable which is more suitable to estimate which characteristics of the cities and their people influence the optimal fares through a linear regression model.

The results of the model, estimated in Stata 12®, are shown in Table 6 below.

Although the sample size (n = 33) is too low for the coefficient values to be reliable, it is interesting to interpret the signs of the significant variables. The characteristics of cities and their people that would favour a lower public transport fare are a larger population, a smaller angle (i.e., cities whose centre is located next to a natural boundary), a lower average income, and a higher proportion of students.

The implications of the model results are discussed in the next Section.

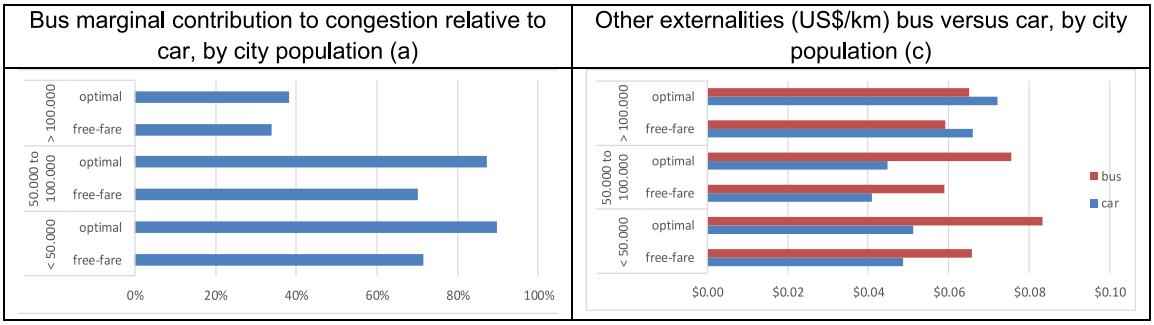


Fig. 6. Average external costs (US$/km) by city population, bus versus car.

Table 6
Optimal fare regression results (US $/km).

Regression stats			
R2			0.788
Adjusted R2			0.757
N			33
Coefficients and significance			
Variable	Coefficient	*t*-test	significance
Intercept	7.279	6.34	***
Population (ln)	−0.564	−8.17	***
θ	0.241	8.27	***
Income factor	1.253	4.00	***
Students (%)	−0.118	−3.00	**

***, p<0.001; **, 0.01<p<0.001.

4. Discussion and conclusions

This section is divided into four parts. First, we analyze the impact of the characteristics of the cities and their people that reduce the optimal bus fares according to the models. Section 4.2 addresses other effects of free-fare public transport. Then, based on the results of the models, and including considerations of technical and socio-political feasibility, three categories are set to recommend free-fare public transport in Chilean cities. Finally, Section 4.4 presents the conclusions of the study.

4.1. Variables reducing optimal fares

The social benefits of a lower public transport fare, which results in a higher mode share and in less use of the other represented modes as discussed in Section 4.2, can be divided into two types. On the one hand, a reduction in operating costs, congestion and other externalities per person compared to the car, particularly for high occupancy levels of buses. On the other hand, a decrease in travel times compared to walking.

As cities grow in **population**, trip distances to and from the CBD tend to increase as the city area is larger. More populated cities are also denser on average (Craig & Haskey, 1978), resulting in higher trip densities as the same trip generation rates were considered for all cities. A higher density of demand results in lower social costs per km of trip due to scale economies (see for example Mohring, 1972), mainly explained by lower waiting times, which favors bus travel compared with walking.

Cities whose **shape** is limited by natural barriers (e.g. coastline) have a more linear shape. When comparing two cities with the same population and density but with different geometries, the average travel distance is greater in more linear cities. Likewise, in linear cities there is a greater concentration of trips on certain streets. In fact, more linear cities tend to have – other factors being equal – public transport modes with greater capacity (Basnak et al., 2020). In small towns, this represents a greater probability of having bus services and a greater willingness of users to use this mode over the car, which is affected by more congestion as trips are distributed on a smaller number of axes, and over walking, given the lower cost associated with waiting and access time, which is reflected in a lower optimal bus fare.

A lower average **income** implies that mode choice is more sensitive to fare increases. Users who have no car or bicycle are obliged to walk or take a bus in our models, which particularly affects those who live farther from the CBD. **Students**, who are supposed to have lower income and less car availability than adults, are particularly affected by bus fare increases, which explains the lower optimal fare when the proportion of students grows.

Similarly, we would expect for cities with a higher percentage of seniors to result in lower optimal fares, although this variable was not significant in the regression model. Likewise, in cities with higher slopes the access speed is lower, which should lead to lower optimal bus fares, although this relationship was not apparent the regression model.

4.2. Other impacts of free-fare public transport

As explained in Section 1, one of the benefits of free-fare public transport is the **reduction of externalities** (including congestion, environmental and noise pollution, and accidents) associated with car use. The results of the models (Section 3.3) allow a more precise analysis, depending on the type of externality and city population.

By implementing free-fare transit, externalities *per user* are reduced both for bus and for car. The first is due to a higher average bus occupancy, while the second is explained by lower congestion as the car modal share decreases. When comparing both modes, the marginal contribution to congestion per user by bus is lower than by car, regardless of the population of the cities, with greater differences for the largest cities in the sample where each bus transports more passengers. However, the contribution per passenger for the other externalities – estimated according to the marginal valuations of Rizzi and De La Maza (2017) for Santiago de Chile – is greater by bus than by car for cities with less than 100,000 inhabitants.

In turn, our model does not include an additional negative externality of free-fare transit. Public transport users dislike traveling in crowded vehicles, resulting in perceived travel disutilities that can be above twice as high as those corresponding to equal times in an empty vehicle. This has been studied both before the pandemic (see for example Batarce et al., 2016; Tirachini et al., 2017) and after the surge of COVID-19 (see for example Bansal et al., 2022; Basnak et al., 2022). The additional disutility from traveling in crowded vehicles could be considered by using equivalence factors relative to in-vehicle travel time coefficients, such as the factors used for the access or waiting stages in a public transport trip (see for example Raveau et al., 2017). However, this was not considered in the models as there is no information on crowding penalties associated to transit trips in small or medium-sized cities of Chile. Reports on a lower risk perception associated with COVID-19 in rural areas (Chauhan et al., 2021), which also have a lower incidence of cases (see for example Sasaki & Ichinose, 2022) indicate

that the effect of crowding could be lower in small towns compared to large cities.

On the contrary, transit subsidies also have positive long-term impacts that were not considered in our model. Subsidies to buses can reduce household income inequalities (Asensio et al., 2003; Fearnley, 2006) and enhanced public transport provision – which can be achieved through operational subsidies – can reduce car ownership, particularly for second cars in households (Jones & Tanner, 1979; Goodwin, 1993). A free-fare transit policy could thus have a significant long-term impact in car ownership. Time series and cross data analysis among Latin American cities, which have diverse transit subsidy policies (Rivas et al., 2020), could provide an estimate on the current impact of operational subsidies in car ownership in order to improve the models.

Socio-political feasibility conditions are relevant when considering a free-fare transit policy:

It is common for public transport systems to receive state subsidies. These already represent most of the operation costs in several cities in Latin America, Europe and North America, and reach almost 90% in Buenos Aires and Mexico City train services (Rivas et al., 2020). In this sense, free-fare public transport (100% subsidy) would not represent a surprising qualitative leap. However, free-fare public transport systems require a considerable state funding: the estimated amount for a pilot plan in 4 small and medium-sized cities in Chile (Emol, 2021) is 250 million dollars per year.

It is worth asking to what extent it is feasible to implement a *temporary* free-fare public transport test policy. On the one hand, a temporary measure would allow obtaining results for an ex-post analysis at a relatively low cost. However, there would be a considerable increase in fares at the end of this measure. In view of the riots and protests that occurred in different Latin American countries such as Chile and Ecuador in 2019 (Sagaris et al., 2020) and Brazil in 2013 (Harvey et al., 2015) after the announcement of minor increases in public transport fares, it is foreseeable that a return of fares to previous levels after a free-fare test period would bring discontent to users. Moreover, a return to previous fare levels could result in an increased car use if, as reported by Chen et al. (2011), transit demand decrease following an increase in price is higher than the increase in ridership in response to lower prices.

Meanwhile, many of the small and medium-sized cities in Chile have two public transport modes, which often compete with each other: buses, and taxi-colectivos. These are paratransit services operated by cars that can transport up to 4 passengers, either on fixed routes or in certain areas, whose maximum fleet is regulated (Domarchi, 2017).

While current legislation allows the State to subsidize bus service operation, for which operators must meet certain conditions of frequency, regularity, route layout and fares, in practice taxi-colectivos cannot access this benefit (Dictuc, 2018). In recent years, taxi-colectivo's drivers have protested in different cities of Chile due to the lack of "economic support" from the Government and due to the rise in fuel prices (see, for example, Cooperativa.cl, 2021).

According to Ley20.378 (2009), the amount of the subsidy to public transport allocated by the State of Chile to the public transport of Santiago must be the same for all the different regions in the country. About two-thirds of this amount is used to subsidize the operation of transport services and the rest for other purposes, mainly infrastructure (Espacio Público, 2018). Given that the financing of free public transport comes from the National Government, and that it can currently only be allocated to the operation of regulated bus services, which are the minority (see Section 4.3), the decision to increase subsidies only in some systems to finance free-fare services could generate resistance in the rest of the cities, as well as in taxi-colectivo drivers who would see their demand reduced due to the greater difference in fares with the bus.

Beyond model results, both the legislation and the possible resistance of those who would feel affected by free-fare public transport (or by its end) must be weighed. The following section provides specific recommendations for cities in Chile that take these considerations into account.

4.3. Recommendations to test free-fare public transport in cities of Chile

Table 7 below shows a "free-fare public transport test score" for the small and medium sized cities of Chile considered in our models. This score is based on three groups of criteria: the *optimal adult fare* expressed in US $/km as obtained in the cost minimization models, and two qualitative sets: *model accuracy* and *free-fare transit feasibility*.

Model accuracy includes the proportion of transit trips made in bus as reported in mobility surveys and the similarity of the real city shape with the circular representation. *Free-fare transit feasibility* considers if a given city currently has bus services, if these services are regulated, and whether there is a general or specific mobility survey.

As a result, we identified four cities with high test score (**) for free-fare public bus services, and five other cities with moderate score (*). Given that the score combines both quantitative and qualitative factors, and that data is not available for all cities in some of the factors involved, it should be considered as an approximate guideline only.

Valdivia: It is the city with the lowest optimal fare per distance in the model (0.26 US $/km), it has regulated bus services, as well as complete and relatively up-to-date mobility surveys. Although taxi-colectivo and ferry services also exist, the majority of public transport passengers currently use buses. Finally, this city was proposed as an option to test free-fare bus services in the campaign program of the current Chilean government (Emol, 2021).

Quellón: Although the optimal fare per km estimated by the model (0.96 US $/km) is above the sample average, it is the only city in the database that currently does not have taxi-colectivos, so an additional subsidy to buses would not be seen as an unfair competition. In addition, it already has regulated and subsidized bus services, and the current fares (CLP 400) is among the lowest. Even though it does not have complete mobility studies, due to its small size and its linear shape, there should be no major changes in routes or frequencies after implementing free-fare service. Lastly, as it is one of the smallest cities in the sample with less of 20,000 inhabitants, the financing required to offer free-fare public transport should be relatively low.

Chillán: Its optimal fare (0.3 US $/km) is the second lowest among the cities analyzed. Although the existing buses are not regulated, their fare (CLP 400) is one of the lowest. In addition, around 70% of public transport users use buses rather than taxi-colectivos. It has completed (although outdated) mobility surveys in addition to studies focused on its public transport system. Finally, its shape is quite similar to the structure represented.

Osorno: The optimal fare (0.48 US $/km) is lower than the sample average, although it is not one of the lowest. However, it has regulated and low-fare buses (CLP 400), which represent over 70% of public transport trips. In addition, it has comprehensive and recent mobility studies.

4.4. Conclusions and future research

Free-fare public transport is one of the policies that many are advocating for to reduce car use in cities, which is commonly associated with a reduction in congestion and other externalities. We proposed a simple mathematical model that can consider real characteristics of cities and individual mode choice for 3 user categories. We applied the proposed model to a sample of 33 small and medium-sized cities in Chile, and our model suggests that free-fare bus services would reduce congestion per user, but the effect on other externalities such as pollution, noise and accidents would not necessarily decrease in smaller cities.

Although a zero fare did not minimize total cost in any of the cities studied, a higher density of demand, a greater travel distance, and a higher proportion of lower-income users favored the adoption of lower fares according to the results of our models. That said, a free-fare transit policy should also consider socio-economic factors to select cities for testing, such as the budget and the legal framework to subsidize the

Table 7
Free-fare public transport test score.

# - City	Optimal adult fare (US $ / km)	Model accuracy		Free-fare transit feasibility			Free-fare public transport test score
		Proportion of transit trips in bus (1)	Shape similarity (2)	Existing bus services	Regulated bus services	Mobility survey (3)	
1 – Ancud	0.58	0 %	NA	No			
2 – Calama	1.03	NA	0.713	Yes	No	L	
3 – Caldera	1.00	NA	NA	Yes	No		
4 – Castro	0.60	NA	NA	Yes	No		
5 – Cauquenes	2.13	NA	0.426	Yes	No		
6 – Chillán	0.30	69.3% (2003)	0.805	Yes	No	L	**
7 – Constitución	0.62	NA	NA	Yes	No		
8 – Copiapó	0.87	32.5% (2010)	0.685	Yes	No	G	
9 – Coronel	0.41	NA	NA	Yes	No	L	
10 – Coyhaique	1.42	NA	0.598	No	No	L	
11 – Curicó	0.36	66.6 % (2003)	0.501	Yes	No	L	*
12 – Iquique	0.35	NA	NA	Yes	No	G	*
13 – La Ligua	2.73	0 %	0.534	No			
14 – La Unión	2.02	NA	0.928	Yes	No	L	
15 – Linares	0.78	NA	0.734	Yes	Yes	L	
16 – Los Andes	1.08	NA	0.626	Yes	No	L	
17 - Los Ángeles	0.35	54.7 % (2004)	0.984	Yes	No	L	*
18 – Lota	0.76	NA	NA	Yes	No	L	
19 - Melipilla	1.42	NA	0.812	Yes	No	L	
20 – Osorno	0.48	71.8 % (2013)	0.519	Yes	Yes	G	**
21 – Ovalle	0.91	NA	0.488	Yes	No	L	
22 – Pucón	0.49	0 %	NA	No			
23- Punta Arenas	0.58	NA	NA	Yes	Yes	L	*
24 – Quellón	0.96	100 %	NA	Yes	Yes		**
25 – Quintero	0.45	0 %	NA	No			
26 – San Felipe	1.14	NA	0.656	Yes	No	L	
27- San Fernando	1.06	NA	0.612	Yes	No	L	
28 – Taltal	1.82	NA	NA	Yes	No		
29 – Tocopilla	1.14	NA	NA	Yes	No		
30 – Tomé	0.69	NA	NA	Yes	Yes	L	
31 – Valdivia	0.26	61% (2013)	NA	Yes	Yes	G	**
32 – Vallenar	1.37	NA	0.421	Yes	No	L	
33 – Villarrica	0.58	NA	NA	Yes	Yes		*

NA = not available

(1) Data from SECTRA mobility surveys. 0%= no bus services, 100%= no taxi-colectivo services.
(2) 1/slenderness, defined as the quotient between longest and shortest semiaxis of the minimum enclosing rectangle (only available for circular – 360° cities).
(3) G: general, L: limited-purpose. Only surveys performed since 2010 were considered.

operation of services, competition with other transport modes, and the quality of the information available.

The *ex-ante* methodology used can be easily extended to cities in other countries by modifying cost, socio-demographic, and user behavior inputs.

Future research should deal with the main limitations of our simple model, by considering long term benefits of transit benefits such as the limitation of car ownership, and by incorporating an estimate of additional trips generated, as well as more complex urban and travel structures, and an assessment of crowding in users' value of time, in order to obtain more precise estimates.

Declaration of interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

CRediT authorship contribution statement

Paul Basnak: Conceptualization, Methodology, Software, Validation, Formal analysis, Writing – original draft. **Ricardo Giesen:** Conceptualization, Writing – review & editing, Supervision, Funding acquisition.

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