SPATIAL ANALYSIS OF PUBLIC TRANSPORTATION INFRASTRUCTURE IN SANTIAGO, CHILE

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ABSTRACT

Santiago, the capital city of Chile, has seven million inhabitants in an area of 850 km2. This city has a metro network with seven lines extending 140 kilometers and transports approximately 2.6 million people daily. The bus system has undergone significant transformations over the last three decades. The most relevant change having been Transantiago, the public transportation system implemented in 2007 for Santiago, Child, which combines the use of Metro and buses (BRT). Metropolitan Mobility Network (called Red) is the latest version of the public transportation plan.

This paper aims to analyze the current subway infrastructure using the continuous approximation method for Santiago, Chile. We previously proposed a macroscopic methodology to identify the needs for an adequate level of service in urban mobility and transportation, and we applied it to Santiago's Metro network. Our work focuses on functionality and demand distribution. Santiago's demand varies spatially in volume and extension throughout the city. Using the latest origin-destination survey from 2012, we deduct the critical components in this current network structure. It is worth mentioning that the metro design bases its network on a ring-radial structure.

With our macroscopic model applied to Santiago, Chile, we have detected infrastructure needs in the current transit network. The supply of infrastructure should increase for two reasons: first, to achieve balanced cost levels between users and the agency and second, to reduce subway occupations. The optimal model outcomes for Santiago define the optimal network in which the system requires five rings and ten end-to-end longitudinal lines (20 radial routes), including lower levels of occupation. The obtained results are a good preliminary solution, considering the subway infrastructure supply could be sub-estimated in the public transportation plan.

1. INTRODUCTION

Santiago de Chile is an extensive city of 850 km^2, with a population of 7 million inhabitants. The city's road network tends to have a concentric structure with the city's original principal roads crossing the city from East to West. However, only one of the rings proposed with the urban planning tools is in operation. Regarding public transportation, Transantiago is the urban public transportation system that operates in Santiago's metropolitan area, the Chilean capital city.

Transantiago is the result of a sequence of efforts by several governments to improve the public transport system since the early 1990s. Precisely, in 2007, the government launched the system that includes a network of trunk and feeder services whose structural mode is Santiago's subway called Metro, with an integrated and electronic payment system using the Bip card. Unfortunately, the operation exposed errors in design and implementation, which have attracted criticism so far. In 2019, Transantiago changed its name to Metropolitan Mobility Network (Red in Spanish) to improve the existing service.

Santiago's Metro is the articulated mode of transportation for Transantiago. The Metro transports more than 2.6 million people daily on its seven lines extending 138 kilometers and 136 stations. The Metro will continue to expand in the next decade, and is expected to reach 220 kilometers of extension with three new projected lines, lines 7, 8, and 9, in addition to the extension of existing lines 2, 3, and 4.

Several scientific works analytically study the operation of a transit system, e.g., classic articles such as Vuchic and Newell (1968), Wirasinghe and Ghoneim (1981), Chua (1984), and others. Some of these works analyze concentric cities using a structure of polar coordinates for radial networks, such as Haight (1964) and Smeed (1965, 1968).

In this paper, we analyze the current transit infrastructure in Santiago, Chile. The objective is to analyze the Metro network using a proposed macroscopic methodology to identify infrastructure needs to reach an adequate service level in urban mobility and transportation. The continuous approximation method uses analytical formulations and transit information from the latest origin-destination survey in 2012 to deduct the critical components in this current network structure. Our work focuses on functionality and demand. We assume that demand varies spatially in volume and extension over the city. A balance between user and agency costs provides the most efficient network configurations. The city of Santiago has a heterogeneous distribution considering its demand and network distribution.

The next section presents the city of Santiago and its structure, delving into the public transportation network. After that, we explain the methodology, which we apply to the Santiago case. Finally, we present the outcomes and conclusions.

2. GENERAL FEATURES OF SANTIAGO, CHILE

2.1 Santiago's Metropolitan Region and its urban structure

Santiago, founded in the 16th century around the Mapocho River. Currently, Santiago also known as *Gran Santiago* is the capital of Chile. The city belongs to the Metropolitan Region of Santiago, which has six provinces. The province of Santiago is the central province, which has 32 city councils called *Communes*. Fig shows *Gran Santiago* includes these 32 zones plus two more zones: San Bernardo and Puente Alto. The last two zones belong to other provinces; however, these zones are considered as part of the city.

Regarding private transportation, Santiago concentrates 37% of the Chilean automobile market. The city has over eight hundred cars in which the car rate is one car per 7 inhabitants. The primary road is Bernardo O'Higgins Avenue, well-known as Alameda. This road lies from the southwest to the northeast direction of the city, connecting Los Pajaritos Avenue to the west and avenues Providencia and Apoquindo to the east (Fig).

Several longitudinal roads cross the main avenue from the north to the south of the city, e.g., General Velásquez, Panamericana, Independencia, Gran Avenida, Recoleta, Santa Rosa, Vicuña Mackenna, Macul, and Tobalaba. Finally, the ring road called Américo Vespucio surrounds the intermediate zone of the city (Fig).

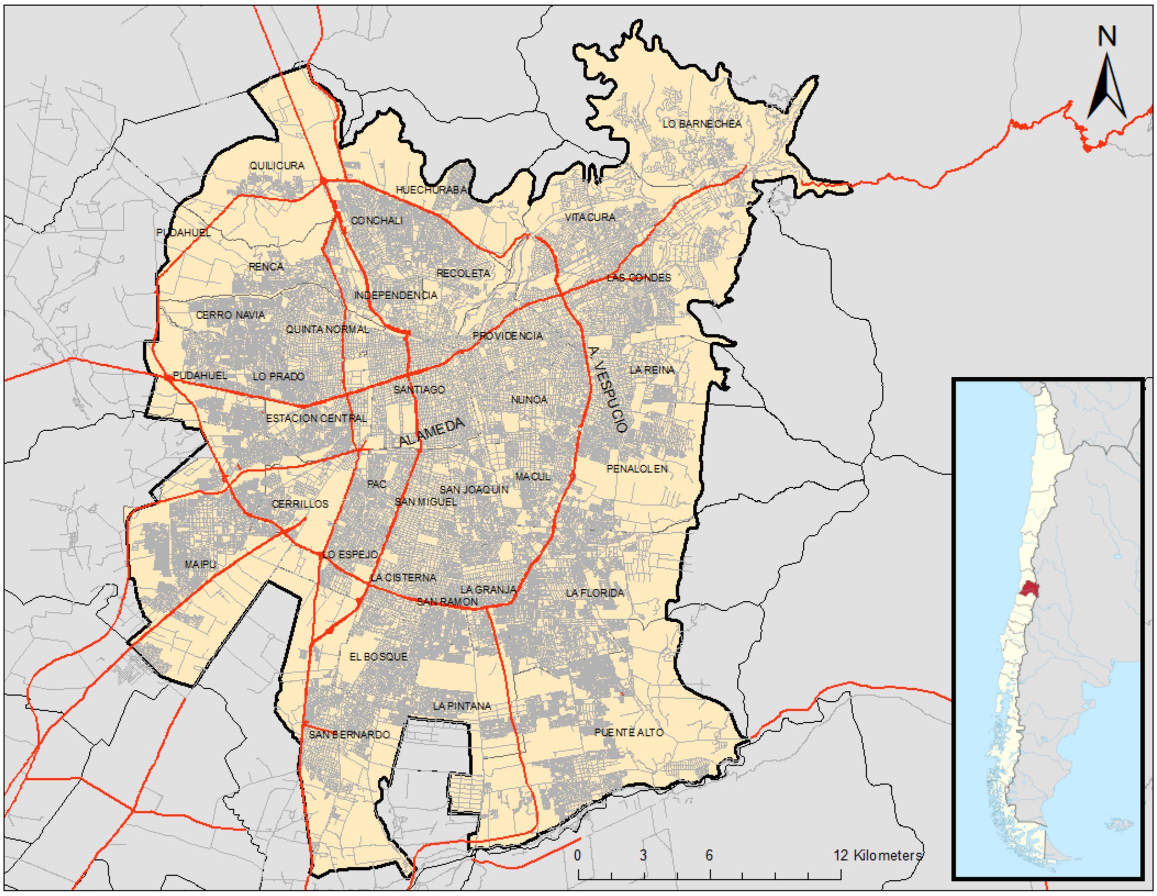


Figure 1: Map of Santiago's urban structure and primary road network.

Most of these roads are very old, even some of them are pre-Hispanic. The roadway had an intercity role from the founding city to other towns. In recent decades, the horizontal growth caused a conurbation of Santiago and the surrounding towns. The foundational Santiago is currently the central commune, a small area representing around 3% of Santiago's total area. Intercity roads become the primary urban roads of the city. Thus, Santiago's town tends to have a radial road structure, although urban planning in Santiago also has mixed development. The planning instruments in Santiago have defined several rings, but only one currently exists.

In 2000, Santiago began the construction of tendered urban freeways. First, Central Freeway runs inside the city from north to south using the old Panamericana road, incorporating General Velásquez Avenue. Second, Américo Vespucio Avenue changed into a freeway, and this road will soon be the first ring freeway in Chile. Third, the Norte Costanera freeway runs parallel to Mapocho River's riverbed and even runs under the river on a road segment. Subsequently, Santiago incorporates the San Cristóbal tunnel and the Access Northorient Highway. All freeways have a free flow toll system in an extension that exceeds 200 kilometers.

Furthermore, Santiago has a fleet of 25 thousand taxis and 11 thousand collective taxis. The latter refers to shared cars with a defined route. In recent years, Santiago promotes bicycles through an incipient network of bike-sharing and the investment of cycleways.

Regarding public transportation, Santiago has a transportation system with extensive subway coverage and buses. Moreover, it has a commuter train. The next sub-section presents information about those in detail.

2.2 History of Public Transportation in Santiago, Chile

Until the early 1970s, Chilean State maintained total control in the passenger transportation industry. The privatization of the urban transportation system began in 1975, increasing the bus fleet and, in the same way, the atomization of the system. In the same year, the first subway car operates a short stretch of the first line of the Chilean subway called *Metro*. Three years later (1978), the agency inaugurated a second metro line. By the early 1980s, the Metro was already an extension of 25 kilometers. On the other hand, surface transportation grouped small companies into Gremial Associations allowing a better operation to set fares and service routes (DTPM, 2019).

In 1989, Santiago's Metro became an independent company of the state apparatus. Metro continues to grow in the following years, incorporating a tunneling construction method without opening the surface and altering urban dynamics. The technique allowed the construction of Line 5 in 1997, starting the construction of Line 4 in 2002 and extending other lines.

On the other hand, the bus system has a new regulation process in 1990, unifying the atomized system through the *Yellow Buses* system. The new framework allows the fare integration between Metro and buses through a new service called Metrobus. The latter opened the system incorporating foreign companies in 2003, consolidating integration creating intermodal stations (subway & bus) in 2004.

The year 2003 began the urban transportation project called Transantiago, implemented in two primary stages. In the first phase, in 2005, the system incorporated the first articulated buses transforming transportation labor unions into traditional companies to operate the system. Also, the system created the financial manager (AFT). In a second phase, in 2007, Transantiago launched changes in all buses' network structure and fare integration. Moreover, it incorporates a single means of access and electronic payment called the *Bip* card. Finally, the system created a specialized unit dedicated to plan and coordinate the operation.

Transantiago covers an area of 2,353 km^2 called *Gran Santiago*. Initially, two sub-systems comprise Transantiago. The former is the trunk line network, whose basis is the Metro's network and bus services operating on the city's main roads, including BRT systems. The latter is the bus feeder network, consisting of local bus services operating on local streets of restricted geographical areas.

From 2010, the Chilean government adjusted the Transantiago system negotiating deals of transportation providers and complimentary services. The new deals came into force in 2012, eliminating the structure of trunk-feeder services and route exclusives for a company. Each company forms a business unit of transportation, which has a defined color. Moreover, 1,120 new high-tech buses entered with high levels of safety and comfort for users. In 2017, the suburban train service called Metrotren incorporated a train to Nos, which links Central Train Station with the southern part of the city.

In the following years, the system added new electric buses. Since March 2019, the transit aims to grow in quality by renaming the Metropolitan Mobility Network, known as the "*Red"* system.

3. PUBLIC TRANSPORTATION NETWORK STRUCTURE

Santiago has three modes of public transportation: subway (Metro), buses (BRTs and traditional buses), and a commuter train (*MetroTren*).

3.1 Metro network

Metro's current system has six lines. The opening of the last one (line 3) was in 2017. The future network plan incorporates three new lines and three extensions for old routes. Figure 2 presents the current subway network and the projected lines, including line extensions.

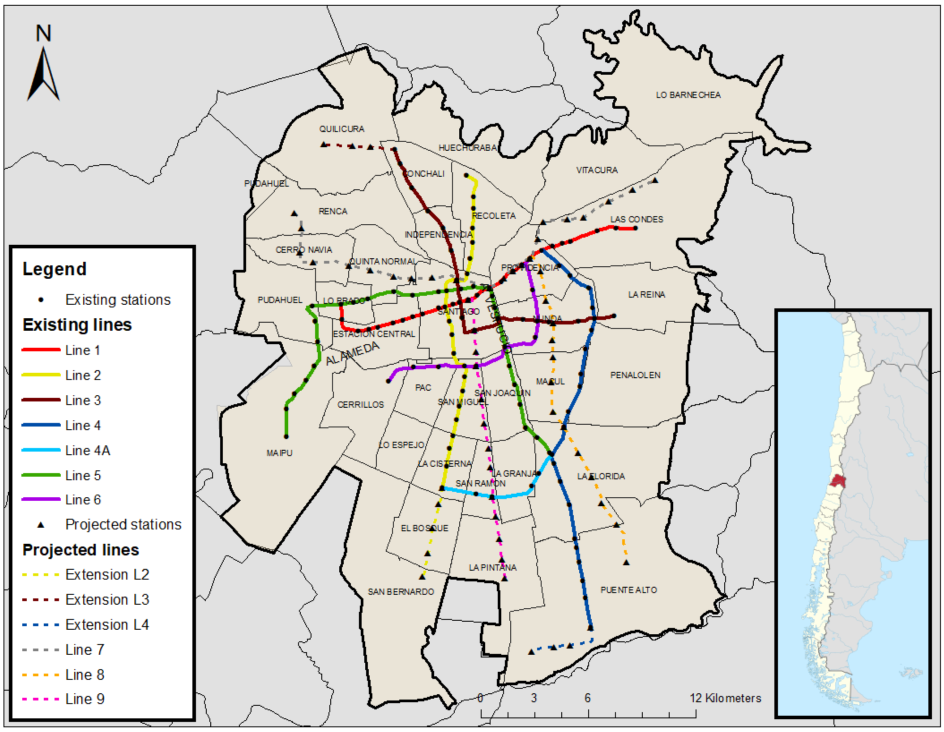


Figure 2: Metro network map: existing lines and future projects.

3.2 Buses network

Transit operators are transportation companies regulated by the National Ministry of Transportation and Telecommunications through the Executive Office called DTPM. Currently, the Red system has six business units, in which a company manages a set of bus services. The service identification is through numbers, letters, and colors. The buses meet the Euro VI emission standard or are electric. The most modern buses are red and white and have WIFI, USB ports and, air conditioning (DTPM, 2019).

The Santiago system has an infrastructure dedicated to bus services. The system has three infrastructure types: corridors, exclusive roads, and bus lanes (FiscalizacionMTT, 2019).

- Bus corridors: Roads include exclusive lanes for buses. These lanes are usually on the central zone of a road, separated from the other lanes. The objective is to increase the commercial speed of buses.
- Exclusive roads: Roads that transit services use exclusively at a schedule.
- Bus lanes: Lanes destined for buses located on the right side of a road, according to the direction of traffic operating at all times and days of the week.

Figure 3 shows the infrastructure dedicated to transit services. Santiago has 19 corridors (red lines), 11 exclusive roads (blue lines), and 53 bus lanes (purple lines). The figure shows that the infrastructure dedicated exclusively to buses has a radial structure from the city center without ring corridors. Moreover, the transit infrastructure reaches neither continuity nor high coverage in the city.

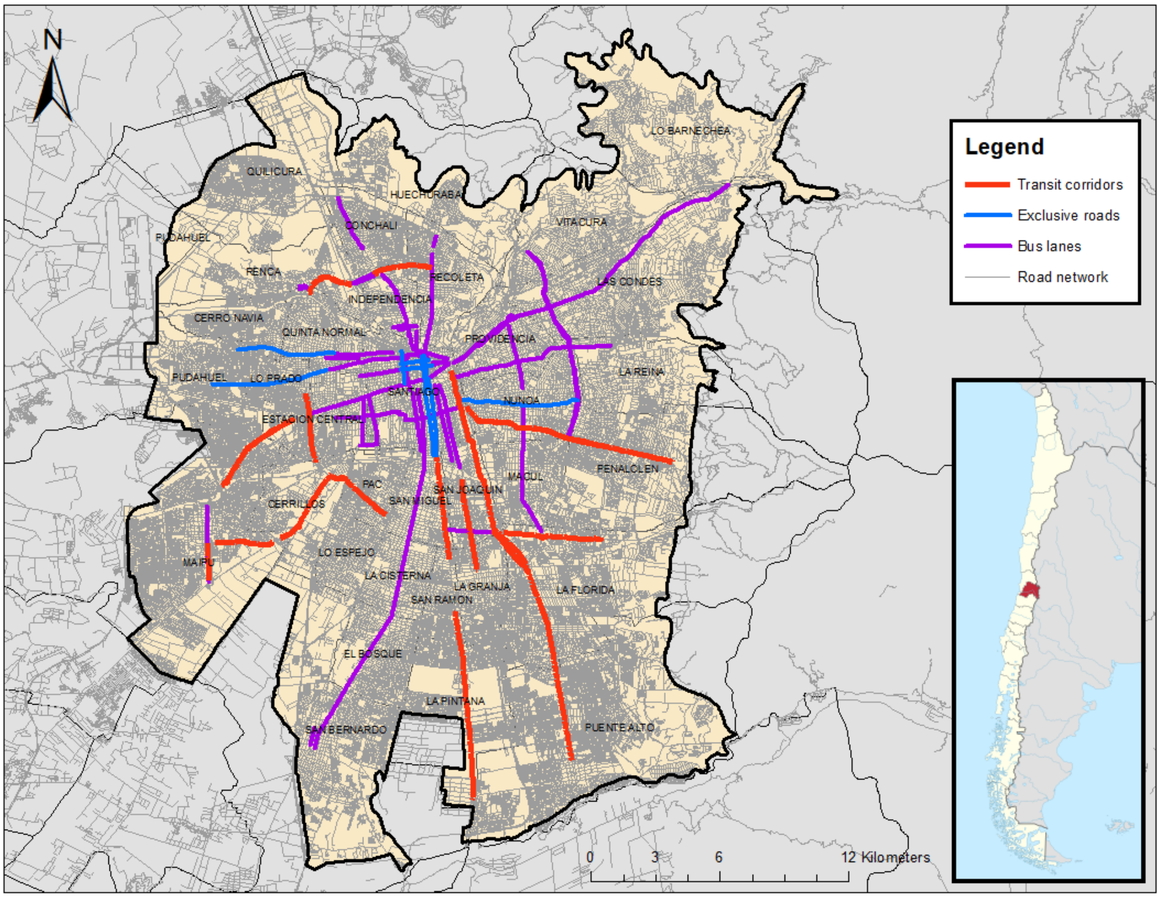


Figure 3: Buses networks: corridors, exclusive streets, and bus lanes.

4. METHODOLOGY

The mathematical model considers the continuous approximation (CA) method proposed by G.F. Newell. The method has applications for transit problems (e.g., Medina-Tapia, Giesen, & Muñoz, 2013; Medina-Tapia, Robusté, & Estrada, 2020, 2021), private transportation issues as well (e.g., Estrada, Salanova, Medina-Tapia, & Robusté, 2021; Medina-Tapia & Robusté, 2018, 2019), and logistics problems (e.g., Pulido, Muñoz, & Gazmuri, 2015).

The region of the modeling is a concentric city of radius R [km]. Santiago is not a perfectly circular city; thus, we adapted the urban area to the modeling but using the real parameters from surveys. The concentric city has ring and radial routes considering the rush hour of the city (P_m) as the period of analysis. We assume non-homogeneous continuous distribution over the city in which each point (r, θ) in polar coordinates has a different density value $D(r_f, \theta_f, r_t, \theta_t)$ in [user/km^4·h] represents the trip density distribution from a point (r_f, θ_f) to (r_t, θ_t).

4.1 Variables

The transit system's network design has four variables: two spatial variables and two temporary variables (Table 4).

Type	Route	Variable	Explanation
Spatial variables	Circular routes	$d^c(r)$	Distance between ring routes with a radius r [km/route]
	Radial routes	$\Phi^r(\theta)$	Distance as an angle between radial routes with an angle θ [radian/route]
Temporary variables	Circular routes	$h^c(r)$	Headway between vehicles at a ring route on r [h/veh]
	Radial routes	$h^r(\theta)$	Headway between vehicles at a radial route on θ [h/veh]

Table 4: Descriptions of decision variables.

4.2 Cost functions

The model formulation contains two components: user (T_T^u in [user·h/P_m]) and agency (C_T^a in [\$/P_m]) costs as show in Equation 1, where can also see that the travel time value (μ in [\$/user·h]) multiplies the user cost function.

$$TC_T = \mu \cdot T_T^u + C_T^a \tag{1}$$

4.2.1 User costs

The total time of users ($T_T^u = T_A + T_W + T_V + T_T$ in [user·h/P_m]) contains four functions (Equation 2): access (T_A), waiting (T_W), trip (T_V), and transfer time (T_T). These equations comes from Medina-Tapia et al. (2021). The time functions in Equation 2 represent the total time for each trip stage of a transit system. The calculation of these functions comes from the integration of the local time function over a circular region:

- Access time: Passengers lose time to get to the closest station or the destination from the origin. First, the demand in rush hour ($f^A(r,\theta) \cdot T$ in [user/km2·P_m]) is the density of users that board and alight at a station/stop during the rush hour. Second, the average accessibility time per user, $t^A(r,\theta)$ in [h], depends on the time perception and the average access time.
- Waiting time: The passenger density that boards a vehicle is $f_l^W(r,\theta) \cdot T$ in direction $l \in L$ during rush hour ([user/km2·P_m]). The average waiting time per passenger at a station is $t_l^W(r,\theta)$ in [h], which depends on the time perception factor and time headway of a service (Medina-Tapia et al., 2013).
- In-vehicle travel time: The total travel time depends on two components: the user load density in rush hour ($f_l^V(r,\theta) \cdot T$ in direction $l \in L$ in [user/km·P_m]), and the travel time per kilometer ([h/km]).

- Transfer time: Two factors comprise this local time function. The user density that transfers at a point (r, θ) to direction $l \in L$ ($f_l^T(r, \theta) \cdot T$ in [user/km2]) and the average transfer time function.

4.2.2 Agency costs

The agency cost has three components (C_T^a in [\$/P_m]): capital (C_K), operational (C_O), and infrastructure cost (C_I). The last two costs have sub-components. The operational cost ($C_O = C_G + C_V$) includes the on-vehicle crew cost (C_G), and in-operation vehicle cost (C_V). The infrastructure cost ($C_I = C_P + C_S$) includes the linear (C_P) and nodal infrastructure (C_S). The explanations of Equations 2 are at Medina-Tapia et al. (2021).

- Capital cost: The cost value ($C_K = \sum_{l \in L} F_l \cdot \varphi^k$ in [\$/P_m]) depends on the fleet in direction $l \in L$ (F_l in [veh]) and the cost per vehicle (φ^k in [\$/veh·P_m]).
- Operational cost: First, the total salary ($C_G = F \cdot \eta^d \cdot T \cdot \varphi^g$ in [\$]) is in proportion to three components: the fleet ($F_l, l \in L$), the number of work shifts on a vehicle (η^d), and the salary in rush hour ($T \cdot \varphi^g$). Second, the total operating cost (C_V in [\$]) comprises two components: the number of vehicles that run on a corridor ($2T/h^c(r)$ or $2T/h^r(\theta)$ respectively), the operation cost per unit of distance traveled on a cruising speed (φ^o) considering the width of a transit corridor $d^c(r)$ or $\Phi^r(\theta)$.
- Infrastructure cost: The linear infrastructure cost (C_P) depends on the number of routes and its length of rings and radial routes ($\frac{1}{d^c(r)}$ or $\frac{1}{\Phi^r(\theta) \cdot r}$ in [km·route] in direction $l \in L$), and the unitary cost (φ^p in [\$/km·route·P_m]). The unitary cost per km in the rush hour has a fixed component and another variable part ($\varphi^p = \varphi^{p(f)} + \varphi^{p(v)} \cdot T$ in [\$/km·route·P_m]. The nodal infrastructure (C_S) depends on the number of intersections $\frac{1}{\Phi^r(\theta)} \cdot \frac{1}{d^c(r)}$ and the unitary cost φ^s in [\$/station·route·P_m], considering each intersection has four stations or stops.

4.3 Problem formulation and optimization

The TNDFSP (transit network design and frequency setting problem) minimizes the system's total cost, taking a heterogeneous demand distribution into account. The formulation of the total cost of a transit system (Equation 1) in monetary units ([\$/P_m] contains two components (Estrada, Roca-Riu, Badia, Robusté, & Daganzo, 2011): the user cost component (T_T^μ in [user·h/P_m]), which is multiplied by the travel time value (μ in [\$/user·h]), and the second component of agency costs (C_T^a in [\$/P_m]).

$$Min\ TC_T = \mu \cdot (T_A + T_W + T_V + T_T) + (C_K + C_V + C_I) \tag{2a}$$

$$\max_{\theta, l \in \{c_c, c_a\}} \left(f_l^V(r, \theta) \cdot d^c(r) \cdot h^c(r)\right) \leq K^v \quad \forall\, r \tag{2b}$$

$$\max_{r,l\in\{r_i,r_o\}} \left(f_l^V(r,\theta)\cdot\Phi^r(\theta)\cdot(R+r)/2\cdot h^r(\theta)\right)\leq K^v \quad \forall\,\theta \tag{2c}$$

$$d^c(r)\geq K^{d(c)} \quad \forall\,r \tag{2d}$$

$$\Phi^r(\theta)\geq K^{d(r)} \quad \forall\,\theta \tag{2e}$$

$$h^c(r)\geq K^h \quad \forall\,r \qquad \text{(2af}$$

$$h^r(\theta)\geq K^h \quad \forall\,\theta \tag{2g}$$

The problem framework is a fixed spatial transit system whose mathematical problem is a nonlinear system that includes inequality constraints.

First, the problem has four decision variables ($d^c(r),\Phi^r(\theta),h^c(r),h^r(\theta)$) according to the spatial and temporal deployment of resources. In this problem, the fixed variables do not change along a corridor. Second, the problem has three sets of constraints. The first of these (Equations 2b and 2c) ensures that occupancy does not exceed the capacity of each vehicle (K^v in [user/veh]). Second, the minimum distance between stations ensures that transit vehicles reach the cruising speed before arriving at the next station and can correctly brake (Equations 2d and 2e).

In the case of radial routes (Equation 2e)), $K^{d(r)}=K^{d(c)}/r_{min}$, where r_{min} is a minimum radius in which this constraint applies in [km/route] or [rad/route], respectively. Finally, the operator requires a minimum separation (time) between consecutive vehicles (TRB, 2013). Equations 2f and 2g ensure that the optimum frequency is feasible (K^h in [h/veh]).

5. RESULTS

The section has three parts. First, the section presents the parameters used in the modeling, including continuous demand density functions. Second, the section also presents the optimal solutions obtained from the model. Third, the section analyzes a comparison between the obtained optimal solutions and the metro network for Santiago, Chile.

5.1 Modeling inputs

5.1.1 Parameters

The modeling considers Santiago's urban shape approaching a concentric city, explained by Medina-Tapia et al. (2021). The modeled city has a radius of 15 km (R), and the rush hour lasts 1.5 hours (T). Table 5 shows the parameters in each stage of a trip, using the time perception from TRB (2013).

Demand parameters							
T [h]	α	β	γ	δ	v^w	χ^T	$v^a(r)$
	[dimensionless]	[dimensionless]	[dimensionless]	[dimensionless]	[km/h]	[m]	[km/h]
1.5	2.2	2.1	1.0	2.5	3.0	40	$v^a(r) = 3.0 + 1.4\bar{6} \cdot r$

Operational parameters												
v^t	a^a	a^d	τ	τ'	τ''	τ'''	τ^s	t^f	η^d	K^v	K^d	K^h
[km/h]	[m/s²]		[s/station]					[min]	[shift/veh]	[user/veh]	[km/route]	[s/veh]
80	1.3	1.3	19.2	5	35	0	42.1	6	1	1,494	0.481	123

Economic parameters							
μ	φ^k	φ^g	φ^o	$\varphi^{p(f)}$	φ^p	$\varphi^{s(f)}$	φ^s
[$/user·h]	[$/veh]	[$/shift·h]	[$/km·veh]	[$/km·route·$P_m$]		[$/station·route·$P_m$]	
1.48	135.6	27	3.7	245.1	248.8	169.9	172.4

Table 5: Parameters used for user and agency cost functions.

5.1.2 Trip generation and attraction functions

The proposed model considers a concentric city, which has a public transportation system with two types of transit services: ring and radial routes. Santiago is a concentric city but does not have a perfect circular form; however, the modeling assimilates that the city has this urban form. The last Origin-Destination survey (MTT, 2012) sets over 700 zones for *Gran Santiago* city; however, the modeling simplifies zoning by dividing the city into 9 OD macro-zones: a central zone, four inner zones, and four outer zones (Fig). Table shows the information of subway trips at rush hour comes from the Santiago OD survey (MTT, 2012) using the OD grouping of the nine macro zones.

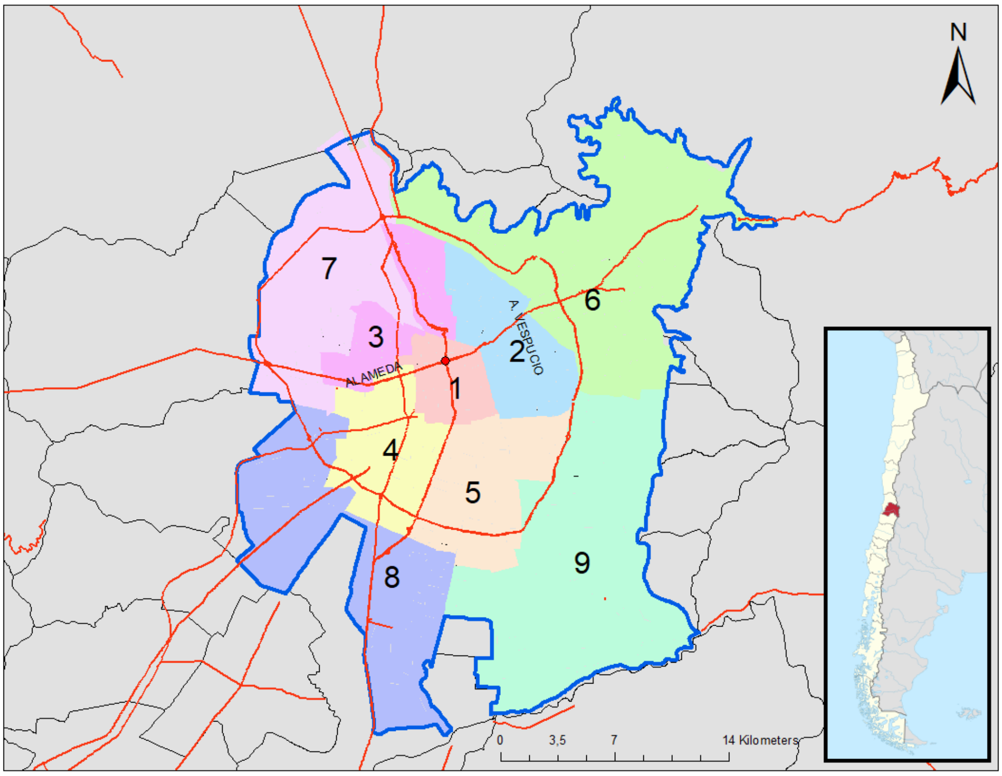


Figure 4: OD macro-zones used for the Santiago of Chile modeling.

	1	2	3	4	5	6	7	8	9	Total
1	10575,5	7440,5	2346,0	1588,0	2728,5	9605,5	1326,4	624,7	1712,3	**37947,4**
2	22458,0	19583,3	1659,0	981,5	2973,0	9652,2	1023,6	609,0	4306,6	**63246,2**
3	12596,8	6248,9	9025,0	2018,6	727,9	3685,2	4103,0	974,6	694,6	**40074,7**
4	17550,9	5922,7	779,9	9656,3	3624,0	3462,8	1702,7	5936,3	2074,1	**50709,7**
5	14958,5	9937,8	494,7	1350,1	16573,4	7533,6	1859,1	1382,2	8933,3	**63022,7**
6	15385,9	16619,7	1985,5	1666,7	3754,5	24629,7	2246,1	334,7	2250,3	**68873,2**
7	20471,6	14257,2	13896,9	1983,4	1533,2	14097,3	32123,3	2548,4	374,4	**101285,8**
8	25495,8	13724,3	3938,1	8662,8	5836,0	7327,9	2766,1	50812,3	7306,0	**125869,4**
9	31559,0	30074,8	4648,4	5759,6	17143,4	18355,3	2062,1	3917,2	66970,2	**180490,0**
Total	**171052,0**	**123809,4**	**38773,5**	**33666,9**	**54893,9**	**98349,6**	**49212,4**	**67139,4**	**94621,9**	**731519,1**

Table 3: Santiago's OD macro-matrix in [trip/P_m] obtained from OD Survey (MTT, 2012).

The method calibrates a continuous function in which the total trips of each origin-destination (Table) is the value in the OD trip matrix (T_{ij} where i is the origin zone, and j is the destination zone), as shown in Equation 3. The coordinates $\theta^i_{f(2)}$-$\theta^i_{f(1)}$ and $r^i_{f(2)}$-$r^i_{f(1)}$ define the origin zone. Meanwhile, the coordinates $\theta^i_{t(2)}$-$\theta^i_{t(1)}$ and $r^i_{t(2)}$-$r^i_{t(1)}$ define the destination zone.

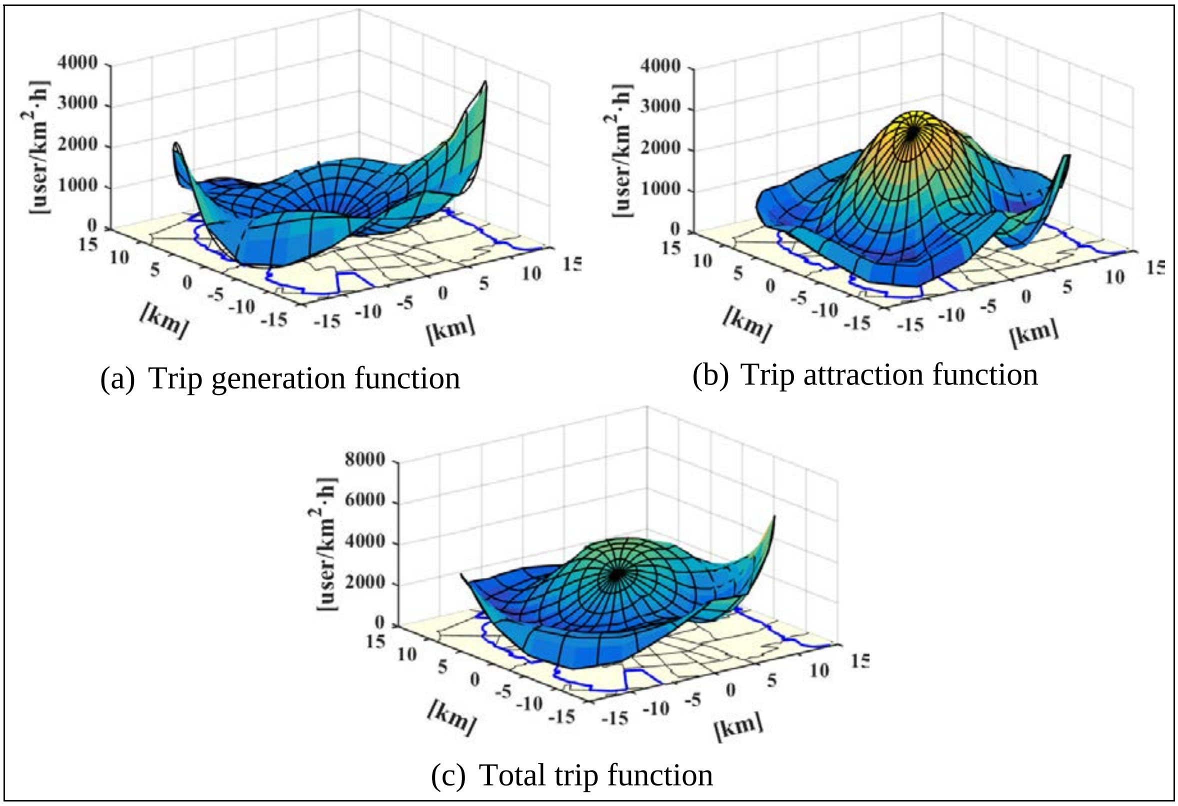
$$T_{ij} = \int_{\theta^i_{f(1)}}^{\theta^i_{f(2)}} \int_{r^i_{f(1)}}^{r^i_{f(2)}} \int_{\theta^i_{t(1)}}^{\theta^i_{t(2)}} \int_{r^i_{t(1)}}^{r^i_{t(2)}} D\left(r_f, \theta_f, r_t, \theta_t\right) r_t \, dr_t \, d\theta_t \; r_f \, dr_f \, d\theta_f \tag{3}$$

Using the function of Equation 3, we obtain the function of generated demand $\lambda(r,\theta)$ at a point (r,θ) in [user/km^2·h] (Equation 4, and attracted demand $\rho(r,\theta)$ at a point (r,θ) in [user/km^2·h] (Equation 5).

$$\lambda(r,\theta) = \int_0^{2\pi} \int_0^R D(r,\theta,r_t,\theta_t) \, r_t \, dr_t \, d\theta_t \tag{4}$$

$$\rho(r,\theta) = \int_0^{2\pi} \int_0^R D\left(r_f,\theta_f,r,\theta\right) r_f \, dr_f \, d\theta_f \tag{5}$$

Fig 5 shows the functions of trip generation (Fig (5a)) and attraction (Fig (5b)) obtained from Equations 5. Fig (5c) represents the total trip density function, i.e., the sum of generated and attracted demand functions.



(a) Trip generation function

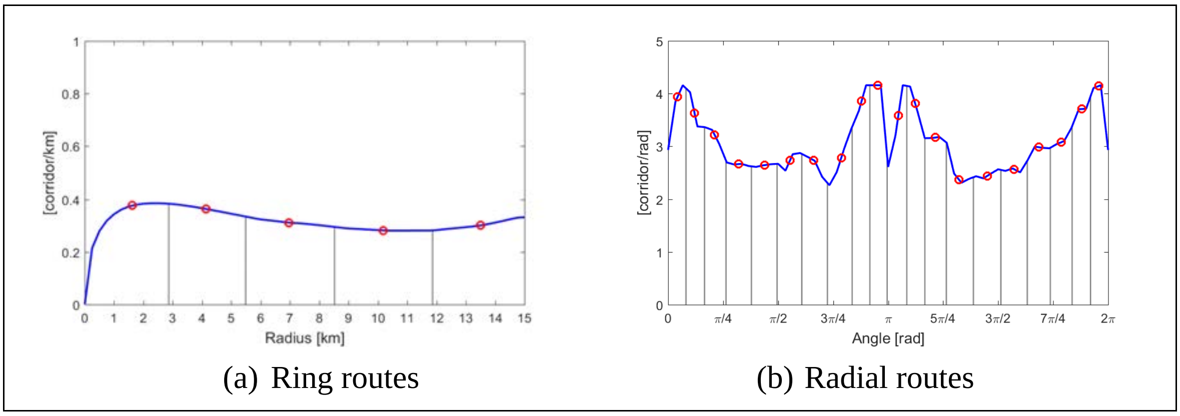
(b) Trip attraction function

(c) Total trip function

Figure 5: Functions of trip generation and attraction estimated from Santiago's OD matrix (MTT, 2012).

5.2 Optimal solutions obtained from the model

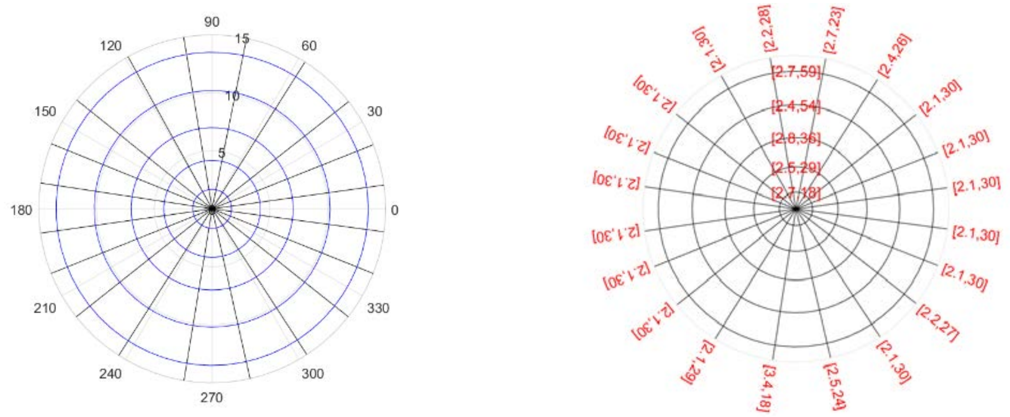
The problem formulation is optimized using KKT conditions. Each point has an optimal solution of density and headway for ring and radial routes. Fig 6 presents the optimal transit density profiles for Santiago, Chile, obtained from the model. The blue line in Fig (6a) represents the optimal ring route density, and Fig (6b) represents the optimal solution for radial routes. The red points represent the optimal location of a route obtained from the discretization process. From optimal transit densities, Fig (7a) shows the macroscopic scheme of transit corridors for Santiago, Chile. Fig (7b) contains the optimal network structure in which a label on each route shows the optimal headway in minutes and the fleet size in trains for rings and radial routes.



(a) Ring routes

(b) Radial routes

Figure 6: Optimal density profiles for Santiago, Chile.



(a) Optimal transit structure (b) Optimal headways

Figure 7: Optimal transit network scheme for Santiago, Chile.

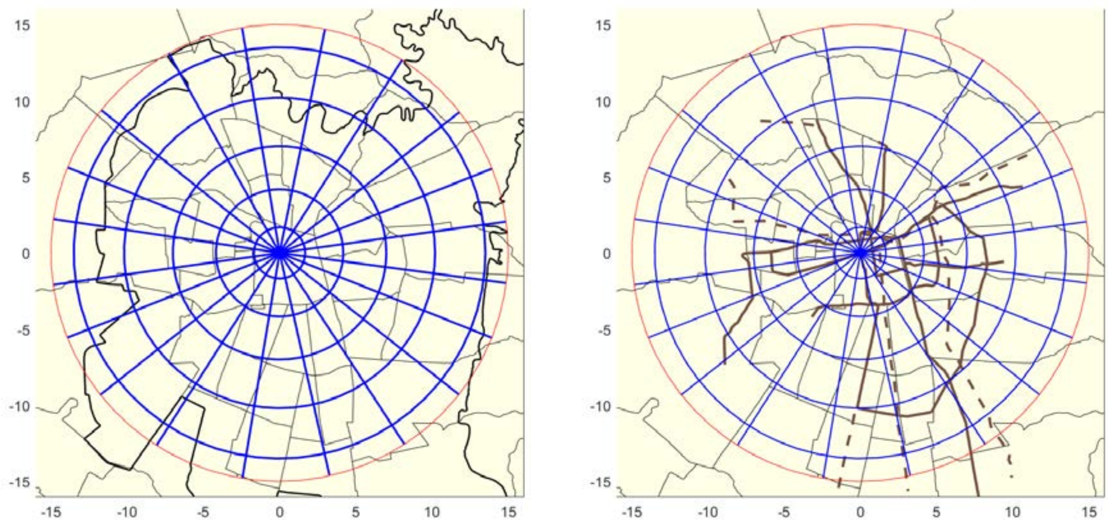
Note: In Fig(b), [X1, X2] in red represents the optimal operation attributes in which X1 is the time headway in minutes and X2 is the fleet size in trains for each route defined optimally.

Regarding ring routes in Fig (7a), the model proposes five transit corridors, whose distribution is slightly higher around the city center. Regarding radial routes in Fig (7a), the model proposes 20 corridors with non-homogeneous distribution with higher density in three zones: East zone (above 0 radians, including Providencia and Las Condes *communes*), West zone (above and below π radians, including Estación Central, Maipú, Pudahuel *communes*), and Southeast (below 0 radians, including La Florida and Puente Alto *communes*). It is worth noting that 20 radial lines could represent ten lines from one side of the city to the opposite.

Regarding ring routes in Fig (7b), headways take on similar values between 2.4 and 2.8 minutes. However, the cycle times on each route are different considering the vehicle-kilometers traveled increases as the route approached the city periphery. Thus, the fleet size that needs a route increases from 18 to 59 trains. Regarding radial routes in Fig (7b), all routes have the same length, but the fleet size depends on the headway and the optimal ring density giving fleet needs from 18 to 30 trains. In a city whose transit vehicles travel long distances, slight headways modify the fleet size significantly.

5.3 Comparison between the optimal solution and Santiago's metro network

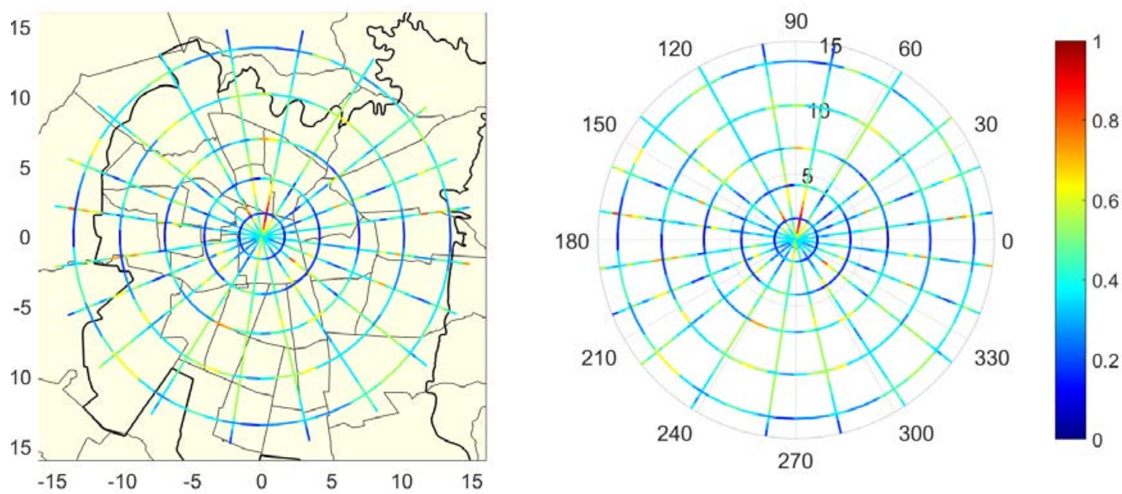
Fig presents a comparison between the subway infrastructure proposal obtained from modeling and future subway projects for Santiago, Chile.



(a) Optimal transit structure (b) Comparison of proposal and subway infrastructure

Figure 8: Comparison between subway infrastructure proposal and current and future projects for Santiago, Chile.

Fig (8a) shows blue lines representing the optimal transit structure, the red circle represents the analyzed area, and the map in the background shows the *communes* of Santiago city, Chile. Fig (8b) also includes the current infrastructure and the future subway projects as brown lines for Santiago, Chile, where continuous lines are existing infrastructure, and dashed lines are the future projects. Currently, Santiago's Metro has seven lines; however, it represents nine existing radial routes, including their extensions; meanwhile, the three new projected lines represent four more radial routes. Globally, the subway mobility plan proposes 13 radial routes, which should increase to 20 radial routes, according to the model. Regarding rings, the transit system only proposes two incomplete rings, which should increase to 5 ring routes.



(a) Santiago and occupation levels (b) Occupation levels

Figure 9: Map of occupation levels obtained from the optimal transit network.

From optimal transit densities, Fig (9a) and (9b) show occupation levels of transit routes for Santiago, Chile. The former overlays the optimal transit network with the map of *communes* of Santiago, Chile. Regarding occupation levels, rings have a maximum occupation of up 75%; however, the average occupation is around 25%. On the other hand, radial routes reach an occupation of up 92% with an average occupation around 37%. Therefore, the global transportation system is not stressed by high occupancy levels.

6. CONCLUSIONS

Santiago, Chile, has a consolidated subway network of more than 50 years with seven lines currently operating. The investment plan considers the extension of some of these lines and the construction of three future projects.

The modeling in the paper uses standard values of operating data. However, some parameters were adapted to the Chilean case, such as the value of time, the train capacity, and the transit demand. In this line, the continuous travel distribution function obtained from the travel matrix origin-destination between macro-zones allowed to represent the generation and attraction of trips. A territory does not have a staggered structure with breaks between two OD-zones boundaries. On the contrary, demand generally varies smoothly from one side of an OD zone boundary to the other side.

The model obtained a macroscopic proposal for subway infrastructure needs, i.e., the modeling applied a theoretical mathematical model previously presented, defining a relevant approach to determine the infrastructure needs for the city of Santiago. The proposed model for Santiago considers 5 rings and 20 radial routes. The comparison between this proposal and the current network plus the planned defines Santiago's infrastructure needs: 13 new radial routes (equivalent to 7 more lines) and four more rings.

Future studies could study complementing these central services with tram services, particularly in Santiago's central commune. It is worth noting that slight headway changes modify the fleet size significantly. The fleet size depends on the headway and the opposite optimal route density or transit stations for the modeling. The latter relates to the time spent due to users boarding, alighting, and others, increasing the cycle time.

The proposal network proposes lower occupation vehicle levels: the maximum occupation of rings is 75%, and radial lines have a maximum occupation of 92%. However, the average occupation of rings is around 25%, and the average radial occupation is 37%.

Therefore, Santiago, Chile, should increase infrastructure supply for the subway network in future strategic planning. The results are considered an interesting preliminary proposal; however, the research approach should be refined through complementary studies. These studies should consider information from all available origin-destination zones, periods, transport purposes, and others. Future studies should also analyze current services with complementary modes (e.g., tram services); and personal mobility modes within a sustainability framework.

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REFERENCES

CHUA, T. A. (1984). The planning of urban bus routes and frequencies: A survey. Transportation, 12(2), 147–172.

DTPM. (2019). Directorio de Transporte Publico Metropolitano, Santiago, Chile. Retrieved from http://www.dtpm.gob.cl/

ESTRADA, M., ROCA-RIU, M., BADIA, H., ROBUSTÉ, F., & DAGANZO, C. F. (2011). Design and implementation of efficient transit networks: Procedure, case study and validity test. Transportation Research Part A: Policy and Practice, 45(9), 935–950.

ESTRADA, M., SALANOVA, J. M., MEDINA-TAPIA, M., & ROBUSTÉ, F. (2021). Operational cost and user performance analysis of on-demand bus and taxi systems. Transportation Letters, 13(3), 229–242.

FISCALIZACIONMTT. (2019). Programa de Fiscalización de Ministerio de Transporte y Telecomunicaciones. Retrieved from http://www.fiscalizacion.cl/

HAIGHT, F. A. (1964). Some probability distributions associated with commuter travel in a homogeneous circular city. Operations Research, 12(6), 964–975.

MEDINA-TAPIA, M., GIESEN, R., & MUÑOZ, J. C. (2013). Model for the optimal location of bus stops and its application to a public transport corridor in Santiago, Chile. Transportation Research Record: Journal of the Transportation Research Board, 2352, 84–93.

MEDINA-TAPIA, M., & ROBUSTÉ, F. (2018). Exploring paradigm shift impacts in urban mobility: Autonomous Vehicles and Smart Cities. Transportation Research Procedia, 33, 203–210.

MEDINA-TAPIA, M., & ROBUSTÉ, F. (2019). Implementation of connected and autonomous vehicles in cities could have neutral effects on the total travel time costs: modeling and analysis for a circular city. Sustainability, 11(2), 482.

MEDINA-TAPIA, M., ROBUSTÉ, F., & ESTRADA, M. (2020). Modeling public transportation networks for a circular city: the role of urban subcenters and mobility density. Transportation Research Procedia, 47, 353–360.

MEDINA-TAPIA, M., ROBUSTÉ, F., & ESTRADA, M. (2021). Adaptive transit network design for spatially heterogeneous demand. Submitted to a Journal for Publication.

MTT. (2012). Encuesta Origen-Destino de Viajes 2012. Santiago, Chile: Gobierno de Chile, Ministerio de Transportes y Telecomunicaciones.

PULIDO, R., MUÑOZ, J. C., & GAZMURI, P. (2015). A continuous approximation model for locating warehouses and designing physical and timely distribution strategies for home delivery. EURO Journal on Transportation and Logistics, 4(4), 399–419.

SMEED, R. J. (1965). A theoretical model of commuter traffic in towns. IMA Journal of Applied Mathematics, 1(3), 208–225.

SMEED, R. J. (1968). Traffic studies and urban congestion. Journal of Transport Economics and Policy, 2(1), 33–70. Retrieved from http://www.jstor.org/stable/20052080

TRANSPORTATION RESEARCH BOARD. (2013). Transit Capacity and Quality of Service Manual (3rd ed). Washington, D.C.: Transportation Research Board.

VUCHIC, V., & Newell, G. F. (1968). Rapid transit interstation spacings for minimum travel time. Transportation Science, 2(4), 303–339.

WIRASINGHE, S. C., & GHONEIM, N. S. (1981). Spacing of bus-stops for many to many travel demand. Transportation Science, 15(3), 210–221.