

Housing and accessibility after the COVID-19 pandemic: Rebuilding for resilience, equity and sustainable mobility

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ABSTRACT

A more sustainable post COVID-19 world requires urban transport policies aiming for resilience, social equity and decarbonisation. Instead of just focusing on the transport sector, the authors propose an integrated approach to housing and mobility. This approach acknowledges the challenges posed by inadequate housing and dependence on motorised transport during the COVID-19 crisis. In contrast, adequate housing and cycling became paramount resources while confronting the pandemic. Using Santiago de Chile as a case study, this research examines how different relocation scenarios for its current housing deficit cannot only affect the ability to implement stay-at-home measures, but also the potential of cycling as a relevant commuting alternative. The current location of the families suffering this deficit is compared to three scenarios: compact, pericentral and extended. In light of the learnings from the COVID-19 crisis, a housing-cycling policy becomes a tool for resilience; equity is achieved by enforcing the right to housing, by increasing job opportunities among the poor, and by reducing the dependence on expensive motorised transport; decarbonisation is achieved by promoting active transportation and reducing the dependence on motorisation.

1. Introduction

All around the world, urban transport systems are facing new challenges posed by the COVID-19 crisis. These challenges demand us to comprehend a number of preexistent issues, such as health needs, the Climate Crisis, and persistent inequalities (United Nations, 2016). To embrace sustainability, novel policy options arising from this pandemic should increase resilience of basic infrastructure services, support public health, and contribute towards reduction of carbon emissions and inequality.

In this regard, particularly in ‘developing’ countries, attempts to implement social distancing measures evidenced the lack of adequate housing to enable stay at home measures (Lall and Wahba, 2020), and of large enough capacity of transport systems to keep providing safe mobility services in times of both epidemiologic and economic crises (Canon Rubiano and Darido, 2020). In regions from the Global South, such as Latin America, segregated and sprawled metropolitan areas force the poor to live in distant land, and to rely on overcrowded

motorised transport to access jobs and services (Borsdorf and Hidalgo, 2010). In these cities, unequal access to urban land multiplies vulnerability to a pandemic such as the COVID-19, especially among those that have very few resources and tools to protect themselves.

In this article, the Santiago Metropolitan Area in Chile is used as a case study. On the one hand, during the 1980s and 1990s, Santiago was pointed by multilateral organisations as an exemplary ‘good practice’ regarding housing demand subsidies (Gilbert, 2002, 2004). In more recent years, the results of these housing policies have been strongly criticised because of its consequences in terms of social segregation and lack of access to services (Sabatini and Brain, 2008; Awad, 2014; Pérez, 2017; Tiznado-Aitken et al., 2018, 2021). On the other hand, the mass transport system became increasingly under stress in Santiago as it had to enable commuting trips that mostly connect mono-functional, predominantly poor, residential areas in the periphery, with the financial district located in the most affluent area of the city (Figueroa Martínez et al., 2018; Suazo-Vecino et al., 2020). In 2007, a new and controversial transport system was implemented, Transantiago, which has been

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deemed as a policy failure by politicians and the public opinion (Quijada et al., 2007; Muñoz and Gschwender, 2008; Ureta, 2014). Immediately before the COVID-19 outbreak in Chile, an increase in public transport fares in Santiago sparked five months of continuous demonstrations and clashes between protesters and police forces, including repeated Human Rights violations, and an agreement to do a referendum on a new constitution (Garcés, 2020).

The experience of the Santiago Metropolitan Area should be useful for planners in other countries from the Global South, as many of its conflicts and policy failures are shared with other Southern metropolitan areas. Our analysis departs from the idea that post COVID-19 government spending on housing and transport infrastructure has to fulfil the mission of guaranteeing adequate housing and transport for the urban poor, contributing simultaneously to disaster resilience, reduction of carbon emissions, and social equity. Consequently, we propose an integrated housing and transport policy to locate subsidised housing within cycling distance from areas that concentrate jobs. In our analysis, we define specific subsidised housing locations by cycling accessibility, in order to satisfy the entire social housing demand in Santiago, and then model the potential commuting trips that could be made on bikes in Santiago.

In this proposal, resilience for future pandemic disasters is achieved via ensuring adequate household space and transportation choices that allow physical distancing measures, and by enabling commuting trips on modes that do not depend on user density for financial sustainability. Carbon reduction is possible thanks to lowering commuting distances, which diminishes dependency on motorised transportation. Equity is achieved by increasing accessibility among the low-income households, and by providing fare-free active transportation alternatives which can increase available income for the most vulnerable. Finally, by fostering active transport, this urban configuration should contribute to reduce pollution, sedentarism and traffic fatalities.

2. Learning from the COVID-19 crisis: cycling and housing as tools for resilience

2.1. Cycling

The COVID-19 pandemic will very likely affect long-term travel behavior patterns in cities all around the globe. This moment has the potential to be a catalyser of positive change towards more sustainable and resilient human settlements (Barbarossa 2020; De Vos 2020). Studies published so far have found that users tend to shift away from public transport towards cars, walking and cycling (Bucsky, 2020; de Haas et al., 2020; Anke et al., 2021), although these changes vary according to different socio-economic, age and gender groups, and areas of a city (Campisi et al., 2020; Molloy et al., 2021; Doubleday et al., 2021), the presence of dedicated infrastructure can enhance the growth in cycling (Hong et al., 2020; Scorrano and Danielis 2021) while increasing the perception of safety in potential and unexperienced users (Rossetti et al., 2018, 2019), and in some cases road safety was negatively affected by cars moving at higher speed (Katrakazas et al., 2020).

Furthermore, the potential for cycling has been illustrated by shared bike systems that have benefited from the pandemic period, according to case studies from Korea, Irán, Greece and the United States (Park et al., 2020; Nikiforiadis et al., 2020; Teixeira and Lopes 2020; Saatchian et al., 2021). Moreover, scholars have found positive roles of cycling in relation to lockdowns and SARS-CoV-2, suggesting that cycling can mitigate some effects of the disease (Brailovskaia et al., 2021) while also be beneficial for mental health during the pandemic in general (Park et al., 2020), which is consistent with findings, from Santiago, suggesting that cyclists have a more pleasant and rewarding experience while traveling than users of other modes (Echiburú et al., 2021).

Beyond cycling, transport in general has been a concern regarding physical distancing measures to avoid contagions (Zheng et al., 2020). When depending on riding cars, buses and couches that are the basis of

motorised transport, ‘citizen mobility could increase the probability of contagion’ (Carteni et al., 2020:2). Moreover, an additional problem is the possible link between air pollution and the spread of the pandemic. In this regard, ‘studies have found that human mobility restrictions could not only prevent the spread of COVID-19, but also improve the air quality because of the reduction of industrial production, transportation and traffic. It is noteworthy that air quality is also closely related to the risk of COVID-19 infection’ (Zhu et al., 2020:1).

Furthermore, analyses performed in countries that implemented physical distancing measures, showed that sharp restrictions to public transport did not imply an immediate reduction of trips. People still needed to travel for basic needs. For instance, a study from Italy, one of the most affected countries during the first months of the pandemic, found that ‘public transport (transit) trips decreased over time faster than those observed for private cars due both to the reluctance of users to use such transport services during the pandemic (which do not guarantee adequate social distancing), and to the reduction in the supply of transport services (e.g. reduction in departures/day); whereas public transport trips decreased more rapidly over time, the overall mobility rate, i.e. the average number of people making at least one trip/day (e.g. trips to buy food, pharmaceutical products or other basic necessities), followed a more gradual trend comparable with that observed for car mobility’ (Carteni et al., 2020:4).

Travel demand and accessibility should be a primary concern for more resilient post-COVID-19 futures. However, something that seems to be missing from the debate is the link between transport and housing. Although both are absolutely integrated in people’s lives, and are crucial when attempting to implement physical distancing measures, finding studies linking the two is remarkably difficult.

2.2. Housing

An obvious link between transport and housing is location: disadvantages regarding these dimensions are structurally linked to inter-sectional inequalities (Duque 2020). A study on Black and Hispanic minorities affected by COVID-19 in New Jersey found that they ‘resided in densely populated regions (...) with higher number of housing units. The location of their residencies also correlated with a lower annual median income than most parts of New Jersey. As a result, underrepresented minorities including Blacks and Hispanics may endure the most of health and health care disparities since they do not have the luxury of social distancing or physical isolation in the era of a pandemic’ (Okoh et al., 2020:4). To reside in deprived and overcrowded areas, and to lack access to basic services that include health care, will most likely have consequences both on adequacy of housing for physical distancing, and on the need to travel on crowded mass transport systems.

Moreover, access to adequate housing has been a major issue during the response to the COVID-19 pandemic, both in the Global North and the Global South. Activists in Lisbon put it simple: ‘How Can We Quarantine Without a Home?’ (Mendes, 2020). In this vein, studies on structural economic factors determining mortality rates in France and the United States have signaled housing overcrowding and poor housing conditions as a determinant of higher COVID related mortality (Goutte et al., 2020; Ahmad et al., 2020). Another study that surveyed 1694 patients in a hospital service area, found that housing conditions were linked to risk of infections (van den Broek-Altenburg et al., 2021). Likewise, epidemiologists have warned that overcrowding is a risk factor to both coronavirus and psychiatric illnesses (Corburn et al., 2020; Amerio et al., 2020), and have also pointed specifically towards housing evictions as an additional risk factor during the pandemic (Benfer et al., 2020).

Trying to share some learnings from previous research on risk factors associated to HIV that could be useful during the COVID-19 pandemic, Rosenberg et al. (2020) highlight that the ‘term “household” takes on different meanings when housing scarcity and community ties create webs of shifting units of people living together, from temporary stays to

lifelong arrangements, and from homeowners to renters, to those with no legal ties to the place they stay' (Rosenberg et al., 2020:2007). This means that for some people who are precariously housed, social distancing as one household unit can require a dramatic change in living arrangements, necessitating living at only one place. (...) Even with efforts to carefully follow recommendations to the best of their ability, people may be placed at increased risk, along with all those in their housing network. Since such networks are located in areas where many residents have similar arrangements, the risk for entire communities may be elevated' (Rosenberg et al., 2020:2008).

Thus, both housing and transport needs require to be a cornerstone of future resilience strategies. When considered separately, both the transport and the housing sectors are key to implement physical distancing measures. However, envisioning longer-term resilient, sustainable and just cities after the COVID-19 pandemic demands complexity and complementarity to be embraced by scholars and policy makers. In the following section, we take on the benefits that an integrated housing and cycling policy can offer.

3. Contribution of a housing-cycling policy towards sustainability

Regarding mobility paths beyond the emergency, there is a fair degree of consensus among scholars that the challenge of sustainable mobility has three main components: excessive dependence on private cars, overconsumption of land area (often good quality farmland), and an unacceptably large ecological footprint (Ortúzar, 2019). A housing-cycling policy is aligned with solutions to these three components, since accessibility-oriented locations promote non-motorised transport, avoid urban sprawl, and thus have the potential to lower overall environmental harm caused by human settlements. However, we more directly focus on the justification of an integrated housing-cycling policy based on its potential benefits on public health, decarbonisation and social equity. These benefits are, of course, an addition to the contribution of adequate housing and cycling to physical distancing measures in the context of future health emergencies similar to the COVID-19 pandemic.

3.1. Public health

Epidemiological evidence suggests that sustained moderate exercise, for at least 30 min a day, can contribute to substantial health benefits (Carlson et al., 2010), which include the prevention of chronic diseases, and a reduction of both blood pressure levels and obesity prevalence (Oja et al., 2011; Garrard et al., 2012). A number of cross-sectional studies have found an inverse correlation between cycle-commuting and blood pressure, body mass index, and lipid levels (Hu et al., 2007; Wen and Rissel, 2008). Furthermore, the sum of the aforementioned benefits outweighs the risk of being exposed to traffic and air pollution (De Hartog et al., 2010). For the Chilean case, Garrido-Méndez et al. (2017) also found that a 30 min increment in active commuting was associated with a lower body mass index and waist circumference. Thus, it appears that to encourage cycle-commuting up to 30 min -each way-may be an effective way to promote physical activity and public health.

Health benefits also have economical consequences. For instance, cycling to work is associated with less sickness absence. The more often people cycle-commute, and the longer the distance traveled, the less they report sick (Hendriksen et al., 2010). In the Netherlands (Fishman et al., 2015), people have a half-a-year-longer life expectancy, and ~6500 deaths are prevented each year, because of cycling. These health benefits are equivalent to more than 3 percent of the Dutch gross domestic product, confirming that investments in bicycle-promoting policies will likely yield a high cost-benefit ratio in the long term. Another example is the study by Rabl and De Nazelle (2012) which found that people who shifted from driving to cycling to commute a distance of 5

km - one way - every day, obtained a health benefit from physical activity worth about 1300 €/yr. This same study found that in a large city (>500,000 people), the value of the associated reduction of air pollution reaches around 30 € per year.

3.2. Decarbonisation

By 2010, the transport sector was responsible for approximately 23% of total energy-related CO₂ emissions (Sims et al., 2014). More recently, a review of nearly 7,000 studies by Ivanova et al. (2020) calculated the mitigation potential of a list of 61 possible changes in household consumption that can lead to reduced carbon footprints. The most effective transport consumption option found in this study was to live a car-free life.

By enabling a shift from driving to cycling, cities reduce their greenhouse emissions and improve local air quality (Macmillan et al., 2014). A study focused on four European cities (Barcelona, Sofia, Freiburg, and Malmö) demonstrated that all of them could achieve notable reductions in greenhouse gas emissions up to below 0.4 t CO₂/cap if city infrastructures were adapted for pedestrians, cyclists and public transport (Creutzig et al., 2012). The same was found for London, where Woodcock et al. (2007) shows how increased active transport could help achieve substantial reductions in emissions by 2030, while improving population health, through improving walking and cycling infrastructures, increasing access to cycles, and investment in transport services for essential needs.

For the case of Santiago, Bell et al. (2006) demonstrated that current emission trends project an enormous health burden. However, this burden could be prevented with relatively modest air pollution control, via policies encouraging active transportation, diminishing health effects and the subsequent economic impact.

3.3. Social equity

Epidemiologists have acknowledged that cycling, as an important active transportation mode, has the potential to go beyond carbon emission reduction, and to be a tool for social equity. One of the reasons is that 'much investment in major road projects does not meet the transport needs of poor people, especially women whose trips are primarily local and off road' (Woodcock et al., 2007:1078). As stated in an article in *The Lancet* by Woodcock et al. (2007), a move towards transport equity requires to shorten trip distances, especially among the poor. This is particularly crucial in the so-called 'developing' countries. As thoroughly discussed by Olvera et al. (2013) while looking at Sub-Saharan Africa, access to the city and mobility work as a complex puzzle, involving significant travel suppression among the poor, as well as high numbers of non-motorised trips that are limited to closer destinations. These issues are often invisible in official data and planning instruments.

Although the usual emphasis on promotion of cycling tends to be its decarbonisation potential by switching people from private vehicles to bikes (Ivanova et al., 2020), investment on segregated walking and cycling infrastructure that reaches the poor has strong social equity potential. For instance, a study on sidewalks and segregated bike lanes in Bangalore, India, showed that low-income groups were strongly benefitted and allowed them to reduce their dependence on public transport (Rahul and Verma, 2018). In the Global South, a social equity dimension of the promotion of non-motorised modes has to do with avoiding a painful dependence on unreliable, expensive, and sometimes chaotic, mass transport systems (Olvera et al., 2013).

However, in Latin American cities, most of the improvements for cyclists are centered in middle to high-income areas with good accessibility. Peripheral areas, which tend to be the poorest and have the lowest accessibility by transit, are the ones that have improved the least (Niehaus et al., 2016; Pritchard et al., 2019). Therefore, the inclusion of the bicycle is not enough to counteract all of the other forces causing

unequal access to the city. One way to improve accessibility through cycling inclusion, is to apply an intermodal approach (Sagaris et al., 2017), integrating the bicycle into the public transport system at an operational level. However, as discussed by Hidalgo and Huizenga (2013) regarding Latin American cities, a more efficient way to curb unsustainable and socially unequal mobility paths may be to redistribute resources that are spent on transportation, and rather focus on providing access to goods and services by relocating activities. The latter would imply a shift from a paradigm that allocates people - especially the poor - in distant cheaper land, only to demand more resources later to provide transport infrastructure and services. A new paradigm would involve investing on well-located housing to avoid future expenses in urban highways and the metro network.

3.4. The key role of trip distance

The question for an affordable distance for cycle-commuting is unresolved. It seems to depend on the built environment and the cycling infrastructure level of service, but also on the cycling experience at a personal level. A research from Sidney suggested that for an inexperienced adult cyclist more than 90 percent of car trips of up to 5 km (58 percent of trips) could be cycled within 10 min of the time taken by car. As the level of cycling experience increased, the bikeable distance increased: the majority of commuter adults could cycle the median commuting distance in Sydney of 11 km with little additional travel time compared with a car (Ellison and Greaves, 2011).

A few studies, for the case of Santiago, have found that shorter trip distance is the main driver behind cycle-commuting (Ortúzar et al., 2000; Oliva et al., 2017; Gutiérrez et al., 2020) while longer commuting distance negatively affects the willingness to cycle-commute and the frequency of it. Although recent findings suggest this effect might be less relevant under 8 km. Moreover, it could be even positive to increase perceived satisfaction and influence frequent bicycle usage (Echiburú et al., 2021). In Santiago, 67% of car trips are shorter than 7 km which represents a universe of ~3 million trips (SECTRA, 2015) that could, potentially, shift to active transport modes if adequate conditions were given. Moreover, the vast majority of cycling trips are concentrated under 8 km which appears to be the limit for cycling trips distance under the present conditions in Santiago city.

4. The case study of Santiago

In line with the critique of Latin American cities made by Hidalgo and Huizenga (2013), Cociña (2018) has characterised urban inequality in Santiago as mostly defined by market-oriented social housing policies. Since the 1980s, unprecedented quantities of subsidised housing units have been built, almost eradicating informal settlements during the 2000s (Valenzuela-Levi, 2017), although a new rise in housing informality occurred during 2020 (Techo, 2021). Santiago sprawled partially via massive concentration of subsidised housing for the poor in distant land, leading to debates about ‘ghettoization’ as a result of government action (Sabatini and Brain, 2008; Awad, 2014). Furthermore, in more recent years, an increasing housing demand among the poor has grown in the form of overcrowding of the existing housing stock (Pérez, 2017). Just before the pandemic, the housing shortage was estimated in 270,014 units in the Santiago Metropolitan Area (Ministerio de Desarrollo Social, 2018), most of which are localized in peripheral and pericentral areas of the city (Gomez and Correa, 2019).

Similar to what has happened in other Latin American cities (Hidalgo and Huizenga, 2013), transport infrastructure and services in Santiago needed to grow and operate in a socially segregated context (Rasse, 2016), generated by the location of the poor in distant peripheral areas (Rodríguez, 2007; Cox and Hurtubia, 2016, 2020), and the concentration of jobs in just one affluent area, attached to the financial district (Garreton, 2017). This context motivated the reform of the public transport system in 2007.

However, the new system, named Transantiago following the example of Transmilenio in Bogotá, became an emblematic policy failure (Maillet, 2008). Some problems were that the network redesign was accompanied by an important reduction of the bus fleet and increase of transfers, due a trunk-feeder structure and a failed attempt to make the system subsidy-free (Hurtubia and Leonhardt, 2021). Also, fare integration allowed many users to use the metro network, leading to overcrowding in the trains and stations (Muñoz et al., 2014). Furthermore, a permanent operational deficit has produced strong debates about government subsidies and financial sustainability (Serebrisky et al., 2009; Ureta, 2014). The deficit became more severe when trips made by users who evaded fares reached one third of the total (Delbosch and Currie, 2019).

More than a decade after the failed public transport reform, transport in Santiago is an emblem of the city’s stark social inequalities. A sign of the level of dissatisfaction and conflict caused by transport was the ‘social outburst’ started in October 2019, which lasted until the COVID-19 struck Chile. A period of five months of continuous protests started on the 18th of October after a call for massive evasion as a response to a USD 0.4 increase in the public transport fare (Garcés, 2020).

Beyond social unrest, existent data confirms strong transport inequalities in Santiago. The highest income quintile of the city makes 1.2 times more trips than the lowest quintile, generating 6.7 times more pollution and using 7 times the energy of the lowest income (Iglesias et al., 2019). This might be so because the use of private cars in the top quintile is 5.3 times greater than the lowest quintile. Moreover, this group has been the beneficiary of 2.5 times more investment in both transport infrastructure and new construction space for commercial activities and services than the lowest quintile (Iglesias et al., 2019). In terms of bicycle use, the last official transport survey for Santiago, Chile, (SECTRA, 2015) the bicycle modal split grew from 2 percent in 2001 to 4 percent in 2012, experiencing the highest increase of all modes. Likewise, while car usage is correlated with higher income, cycling is homogeneously distributed among the wealthy and the poor.

Unfortunately, there is no official data of mobility patterns before and after COVID-19. Although results from a mobility survey during the pandemic showed a decrease of 44% of trips in Santiago, with metro (55%), ride-hailing (51%), and bus (45%) presenting the highest reduction. Along with, while 77% of workers from low-income households had to go out and work, 80% of workers from high-income households worked from home. (Astroza et al., 2020).

Regarding bicycle use after COVID-19 breakdown and the subsequent confinement, another survey conducted in Renca -a pericentral district from Santiago-showed that 58% declared changes in their main transport mode during the pandemic. While all forms of public transport decreased, the automobile and bicycle demand increased in 78%, while walking grew up at +235% (Echiburú and Hurtubia, 2021).

Another survey conducted by the same authors, in another district near to Santiago’s CBD (Providencia), exhibited similar results: Almost half of the respondents shifted to teleworking. Among those who stayed commuting daily, the people cycle-commuting increased from 25 to 32%, while the automobile use grew from 19 to 30%. On the other hand, all forms of public transportation fell down from 45 to 17% (Echiburú et al., 2021; 2).

5. Data

Our analysis is based on secondary data from Santiago that has been made publicly available by governmental agencies. On the one hand, travel survey data comes from the latest Origin-Destination Survey [Encuesta Origen-Destino] (EOD) collected by the Transport Secretariat in 2012 and published in 2015 (SECTRA, 2015). On the other hand, housing, population and surface data comes from the 2017 census (Instituto Nacional de Estadísticas, 2018). Census tract data was aggregated in order to match the 866 EOD areas. Fig. 2 shows the scale and distribution of the EOD survey areas, which are the basis of our

analysis, along with the municipal district boundaries, and density of job opportunities for the three lowest income quintiles in Santiago.

6. Methodology

The methodology, summarised in Fig. 1, consists of several steps: first, current housing location is determined, estimating housing shortage per EOD Survey area. In parallel, a workplace accessibility index for each zone is estimated, based on the density of job opportunities and travel distances, using a gravitational accessibility measure, to define the level of work accessibility for each part of the city.

In addition, four intervention areas are defined to be analyzed, corresponding to four scenarios: base situation, compact (*operación sitio* areas), pericentral (within the Americo Vespucio ring area) and urban expansion area. For each scenario, new housing units are allocated, prioritizing the zones with higher accessibility.

The new spatial distribution of housing is then used to estimate trip distribution and, consequently, trip lengths for each scenario. These results are then analyzed on the basis of the number of trips that are potentially performed by bicycle (with lengths below 7 km). We favor this approach instead of using a mode choice model since the latter would require explanatory variables not available in our scenarios and would also underestimate the bicycle modal share, due to the relatively low number of bicycle trips at the time of the Origin-Destination survey compared to those observed nowadays.

6.1. Housing location scenario construction

Using Geographical Information Systems (GIS) and the available data, we model four different housing location scenarios in Santiago. First, the base scenario of the subsidised housing demand is calculated estimating a total housing shortage figure using census data. The housing shortage of 270,014 units is estimated through the summarize of overcrowded housing (considering houses with 2.5 or more people per bedroom), additional households in a dwelling with more than one household, and households with substandard materiality - like informal buildings or slums. The distribution of the housing shortage is shown in Fig. 3.

To compare with this base scenario, we estimate three additional scenarios: expanded, pericentral and compact. These new scenarios are all built on the basis of workplace accessibility for the three lowest income quintiles. The accessibility index for each zone (*i*) is constructed using the following gravity-based measure (Hansen, 1959; Geurs and Van Wee, 2004):

$$Acc_i = \sum_j N_j exp(-\varphi \cdot C_{ij}) \tag{1}$$

Where N_j is the number of job opportunities in zone j , C_{ij} is the generalized travel cost between i and j and φ is an impedance parameter which defines the decline speed of accessibility as travel cost increases. In our case study N_j is a proxy of job opportunities, which was calculated as the number of trips with a work purpose for the three lowest income levels which had zone j as a destination from the EOD travel survey. A

simplified measure of travel cost, consisting in network based distances (in meters) between centroids of zones was considered. Since our objective is to locate housing in zones with high accessibility by bicycle, the impedance parameter was empirically calibrated in order to reproduce observed trip length distribution by bicycle of the travel survey ($\varphi = -0.0005$) which renders an accessibility lower than 3% for distances larger than 7 km.

The expanded scenario aims to illustrate the probable situation if current market-oriented housing and land policies continue in Santiago. In order to do so, we locate new subsidised housing units in the urban expansion areas defined in the current Metropolitan Regulatory Plan, approved in 2013. Second, the pericentral scenario explores a re-urbanisation policy that has been widely discussed in Santiago, which proposes to densify areas that were originally urbanised for social housing in the 1960s (Tapia, 2019; Castillo and Gray, 2019). These areas are called '*operación sitio*' [operation plot] or '9x18' because of the dimensions in meters of the original lots. They represent '466 neighborhoods, and 216.000 lots between 160 and 250 square meters, with a 38 percent of public space surface and an excellent pericentral location' (Tapia, 2019:72). Finally, the compact scenario locates housing within the boundaries of the *Americo Vespucio* beltway, which is since the 1960s the tacit frontier between the pericenter and the periphery of the city (Garreton, 2017). Fig. 5 shows the areas that correspond to each one of the three proposed new scenarios.

In order to assign new housing units by EOD area, locations are defined by highest to lowest accessibility (workplace accessibility shown in Fig. 4). All the EOD areas included in each scenario are ordered by workplace accessibility score for the three lowest income quintiles. Housing units are added by EOD area in correlate order, moving to the one below in accessibility score, switching after reaching the limit of the average existing density in all the urban land within the boundaries of the scenario that is being analyzed. Current housing density in the Santiago Metropolitan area is illustrated in Fig. 6. This operation is repeated until the total 270,014 housing units are placed. These density upper limits are set as 50 houses per hectare for the expanded scenario, 75 houses per hectare for the pericentral scenario, and 100 houses per hectare for the compact scenario. The criteria of matching the average densities implies to focus on the zones with the lowest housing density within each studied area, and to imagine re-urbanisation that is kept within the dynamics developed so far in these neighbourhoods. As discussed in the results (Section 7), a less conservative scenario in terms of densities to reach could provide better accessibility results.

6.2. Trip distribution

For each scenario of housing location, trip distribution was modelled using a classic gravitational (maximum entropy) trip distribution model (Wilson, 1969), which was empirically calibrated using data from the latest travel survey for Santiago (SECTRA, 2015). Generated trips per zone (O_i) come from applying commuting trip generation rates to the housing units of each scenario while attracted trips (D_j) are estimated following the spatial distribution of destinations of commuting trips for the three lowest income quintiles. Travel costs between zones (C_{ij}) are

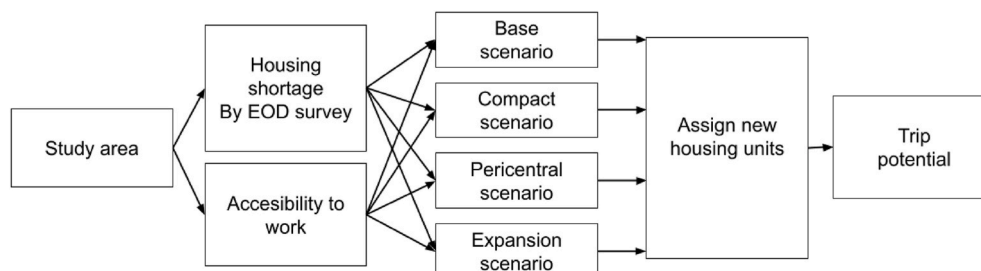
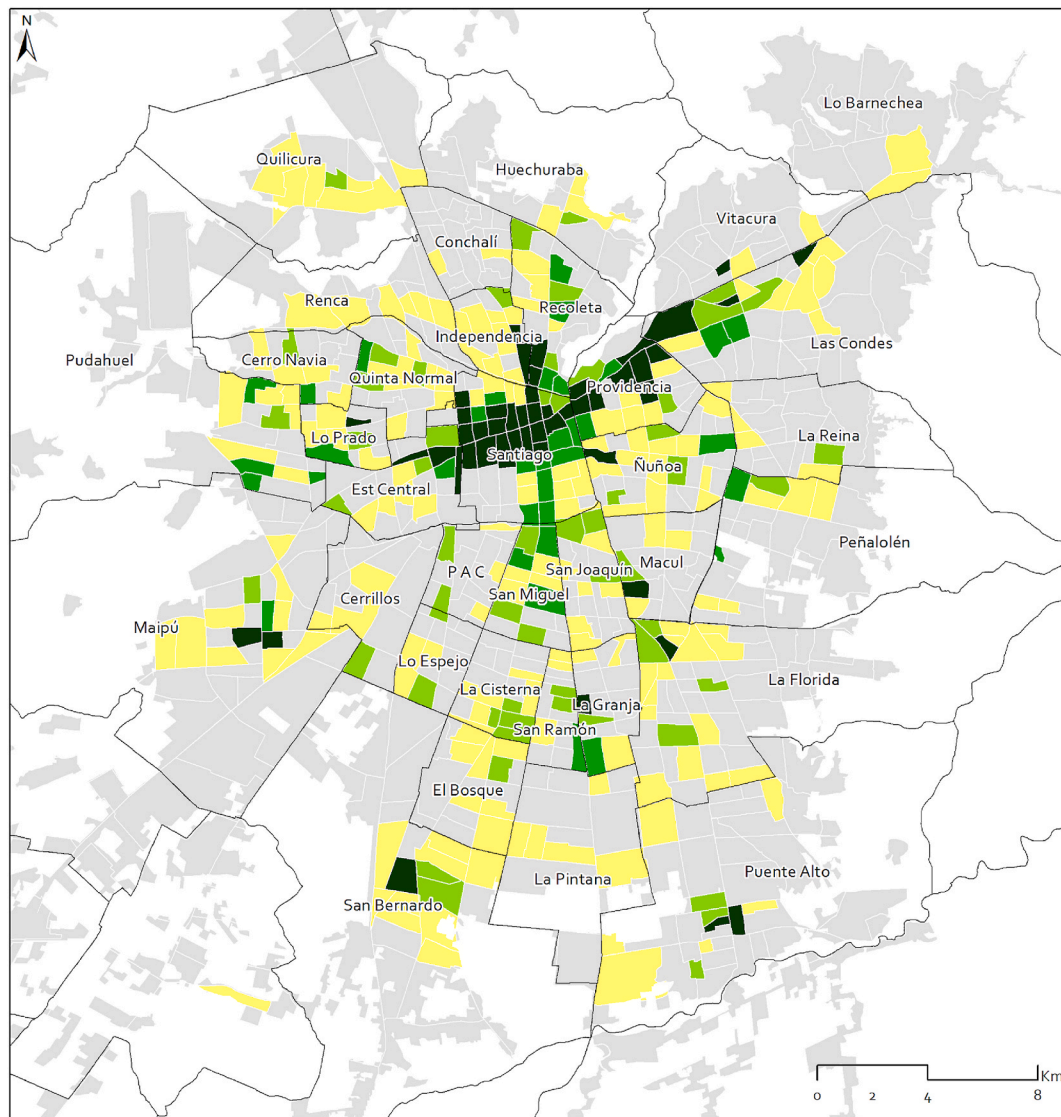


Fig. 1. Summary of the methodology.



Legend



Source: The authors with data from SECTRA, 2015

Fig. 2. Density of job opportunities for the three lowest income deciles, by EOD (travel survey) areas, with district (municipal government) limits.

represented through a simplified measure of network-distance (in km) between centroids of zones.

$$V_{ij} = A_i O_i B_j D_j \exp(-\beta C_{ij}) \tag{3}$$

Where A_i and B_j are balancing factors that are iteratively estimated in order to ensure that $\sum_j V_{ij} = O_i$ and $\sum_i V_{ij} = D_j$, which renders the following expressions:

$$A_i = \left(\sum_j B_j D_j \exp(-\beta C_{ij}) \right)^{-1}, B_j = \left(\sum_i A_i O_i \exp(-\beta C_{ij}) \right)^{-1} \tag{2}$$

The impedance factor ($\beta = -0.003$) was calibrated to approximate the observed length distribution for commuting trips of the three lower income quintiles. The simulated trip distribution obtained with this

parameter reasonably fits the observed trip distribution ($R^2 = 0.72$).

7. Results

Modeling results are shown in Fig. 7. Each scenario presents a different potential for cycling according to housing location. A first remarkable aspect of these results is that the base scenario is the best one in terms of job accessibility. Under the parameters for housing relocation defined in our model, the best expected scenario, compact, provides slightly worse overall accessibility than the base. In the base scenario, the potential trips under 7 km - which is considered reachable in less than 30 min cycling - is ~85,500, which represents 60.6 percent of total work-related trips generated by the relocated households. The compact scenario results in ~60,000 trips under 7 km, which represents 45.2 percent of work-related trips generated by the relocated households.

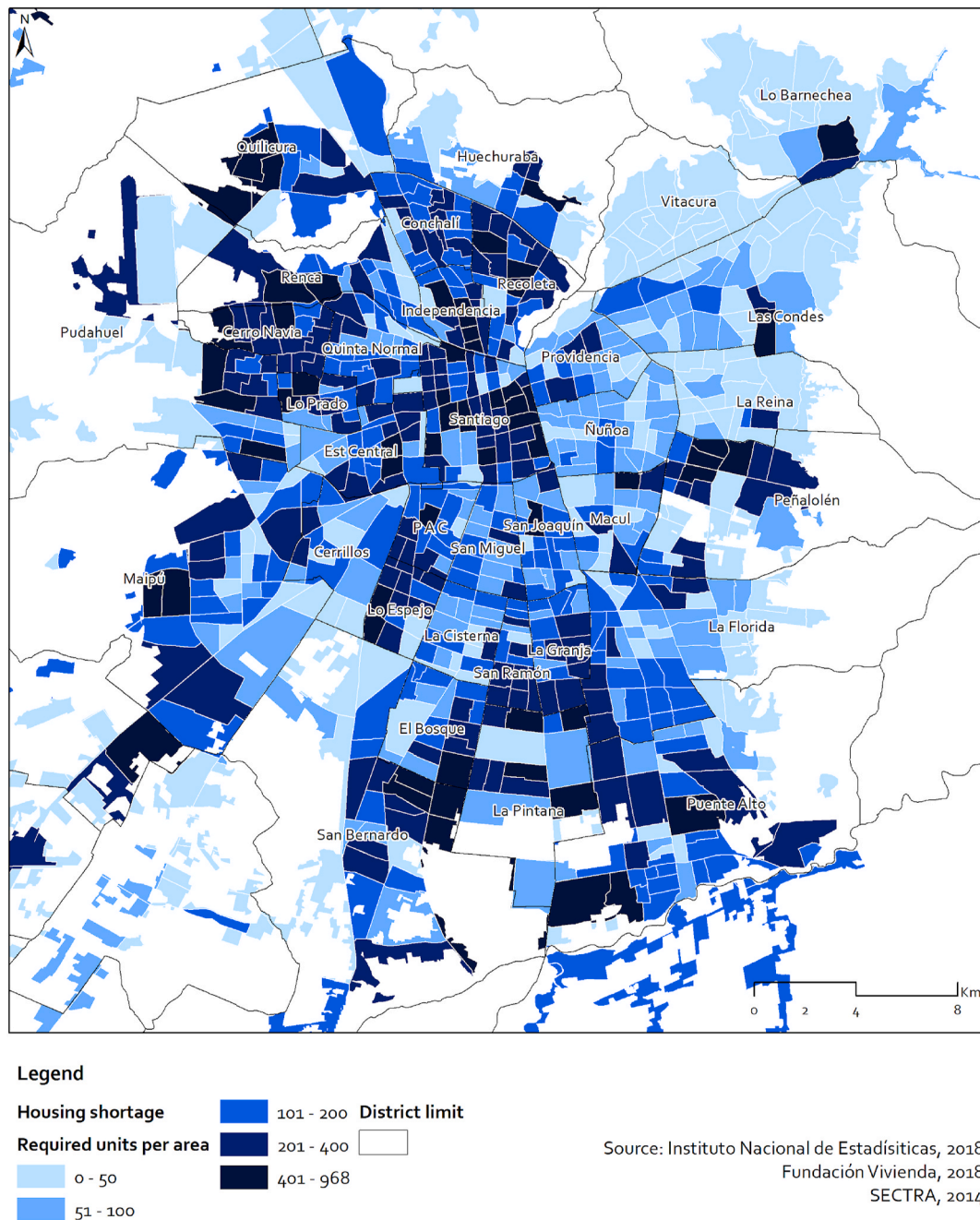


Fig. 3. Housing Shortage in the Santiago Metropolitan Area, by EOD survey area.

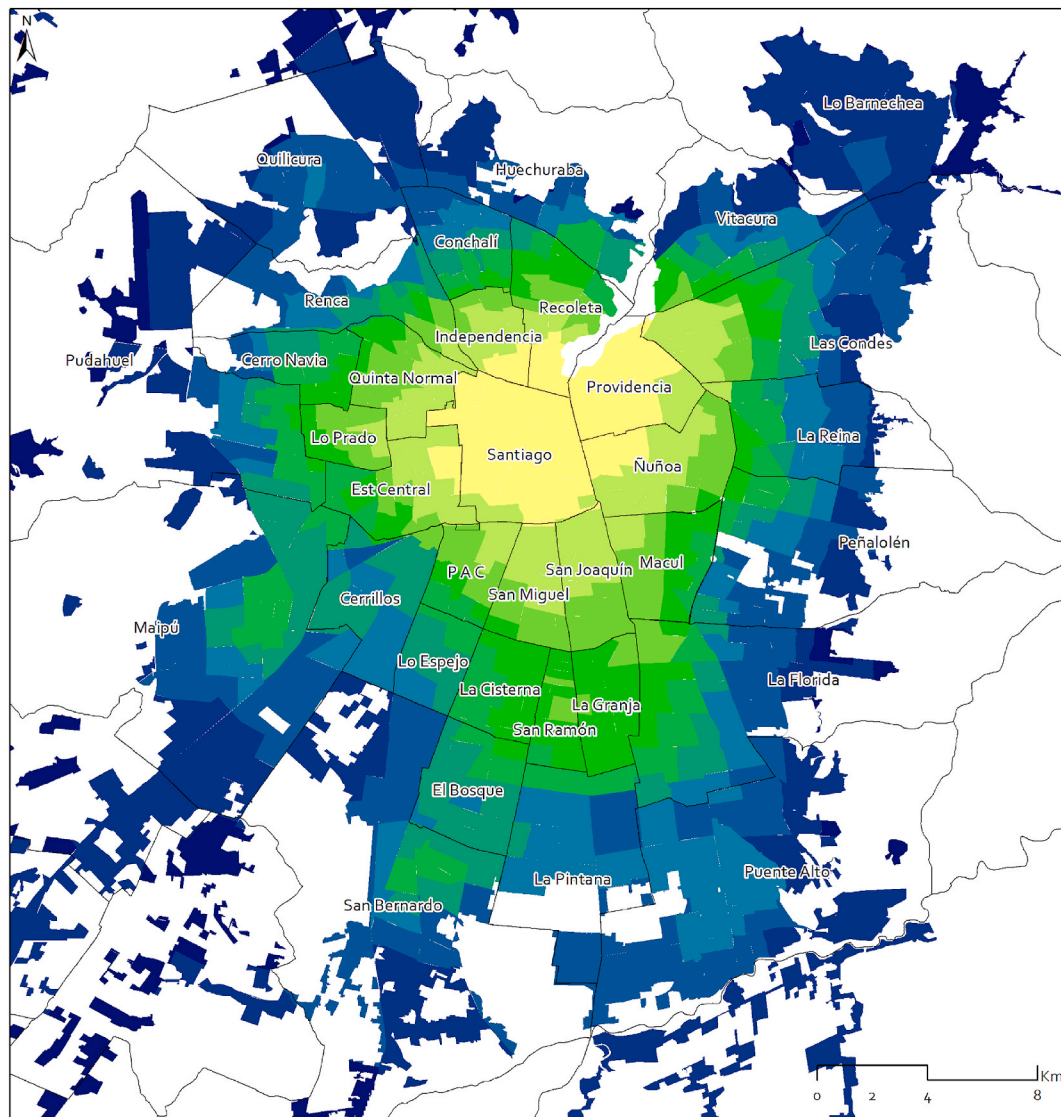
Two elements emerge in a first analysis of the results. On the one hand, the expected trade-off between accessibility and chances of accessing adequate housing becomes evident. However, this trade-off could be avoided by applying more aggressive densification criteria to relocate the housing deficit, which would allow more job-accessible locations. On the other hand, these results highlight the current cycling potential of the existing locations, if adequate cycling infrastructure was in place.

A second aspect of these results emerges from the comparison between the three proposed scenarios. As expected, the compact scenario provides the best potential cycling to work accessibility. Also as expected, the expanded scenario, which resembles the business as usual, strongly diminishes cycling to work potential in the Santiago Metropolitan Area. Compared to the base scenario, locating subsidised housing in the periphery extends ~65,000 work-related trips that are

currently accessible by bicycle, making them longer than 7 km, and therefore more likely to depend on motorised vehicles. The cycling potential within work-related trips diminishes from 60.6 to 15.4 percent of the trips generated by the studied households.

Finally, the pericentral scenario, which is modelled relocating the housing shortage in the '9x18' or 'operación sitio' lots, although provides better accessibility than the extended scenario, is not a strong prospect for maximising cycling trips. Instead of the ~85,500 potential cycling to work trips in the base scenario, and ~60,000 in the compact scenario, pericentral housing locations only produce ~48,000 of these potential trips, which represents 45.2 percent of the trips generated by the relocated households.

The relative difference between the three scenarios is quite significant. However, the potential cycling trips depend not just on housing locations. These results also highlight the relevance of combining these



Legend

Workplace accesibility score by decile	Medium	District limit
Medium high	Medium high	
Low	High	
Medium low		

Source: The authors with data from SECTRA, 2014

Fig. 4. Workplace Accessibility of the three lowest income quintiles, Santiago Metropolitan Area, by EOD survey area.

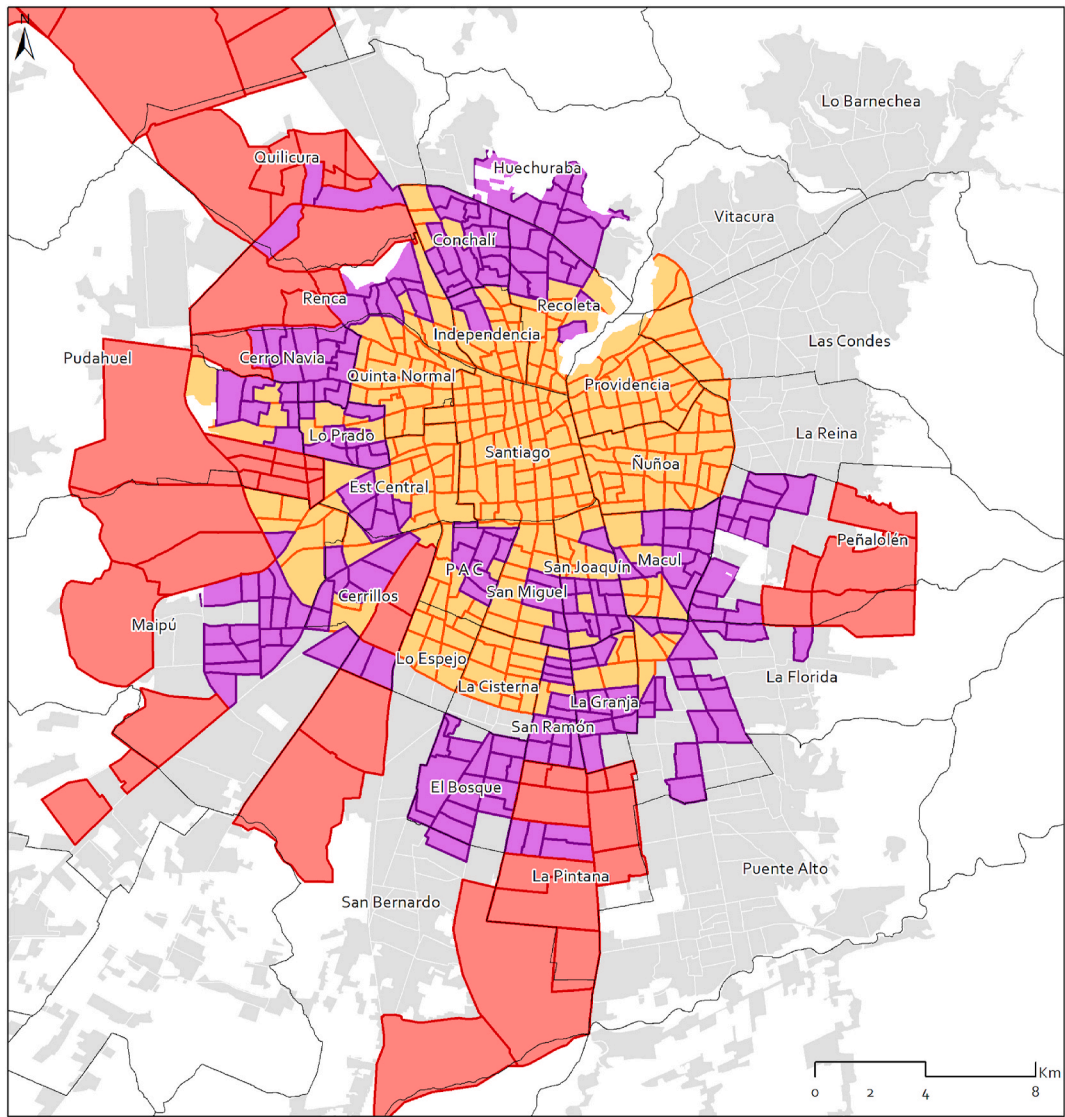
decisions with investment agendas that could help materializing the identified potential. For instance, the high cycling to work potential in the base scenario implies that a short-term bike lane investment program could have a direct impact on physical distance, equity and decarbonisation. In this case, such investments could have a direct effect (Ortúzar et al., 2000; Buehler and Dill, 2016) on decongesting public transport and providing a fare-free transportation alternative to workers. Thus, the trip distance reduction that could be the result of our proposed housing location policy could have a stronger long-term collateral impact. Our expectations, in this sense, are backed by recent findings by Gutiérrez et al. (2020) who found that the most relevant factor that could make non-cyclers to start cycling in Santiago is shortening trip distances, followed by the provision of a well-connected cycling infrastructure network.

Finally, our results lead us to discuss the impact of increasing density

in fostering cycling trips. Oliva et al. (2017) found that bike lanes in Santiago have a positive impact on commuting trips made by bicycle although, in contradiction with what is usually reported in the literature, they found density to have the opposite effect. A possible explanation for this negative density effect on cycling could be found in the hyper-dense buildings built in downtown Santiago during the last decades. In these areas, it is not safe to leave bicycles on the street, while indoor bike parking is scarce, overcrowded and usually located many floors below ground level. Also, small overcrowded lifts make storing bikes inside apartments impractical. All these elements should be considered when discussing and planning new densities.

8. Policy implications

The exhibited results expose that most people prefer to live in



Legend

- | | |
|--|--|
| Potential areas of analyze | District limit |
| ■ Urban expansion area | |
| ■ Operación sitio area | |
| ■ Amerigo Vespucio ring area | |

Source: Instituto Nacional de Estadísticas, 2018
 Fundación Vivienda, 2018
 Ministerio de Vivienda y Urbanismo, 2015
 Vergara y Palmer, 1990
 Tapia, 2012
 SECTRA, 2014

Fig. 5. Proposed housing location areas.

overcrowded housing if doing so enables their access to metropolitan opportunities. However, although living in well-located housing is a necessary condition to access job opportunities by bicycle, it may not be enough.

In the short term, in order to facilitate and promote cycling for commuting purposes, the implementation of “emergency bike-lanes” (for specific proposals applied to Santiago see [CEDEUS 2019](#); [Echiburú and Hurtubia, 2021](#)) that habilitate main city corridors as temporary bus and bicycle streets, could be a cost-effective strategy to offer an adequate provisional solution to the lack of cycling infrastructure, that could be consolidated on the mid-term.

In the long term, the results expose the necessity to re-evaluate the current social cost-benefit analysis methodologies, which are applied at the project level, and are unable to evaluate the simultaneous implications of housing location and transportation-related future expenses

among households. Nowadays, housing projects are evaluated regardless of the transportation investments that will require in the future. In addition, transport projects are evaluated over a trip distribution that is path-dependent on the existent origin-destination matrix, determined by housing and workplace locations. Our findings suggest this is an inefficient way to offer the best housing solution, at the best possible location, with the least resources invested overall.

9. Conclusion

Combined in an integrated policy, adequate housing location and cycling promotion can be powerful tools for resilience, equity and sustainable mobility. Physical distancing measures that are required during a disaster like the COVID-19 pandemic requires safe housing and transport options, which can be made available thanks to a housing

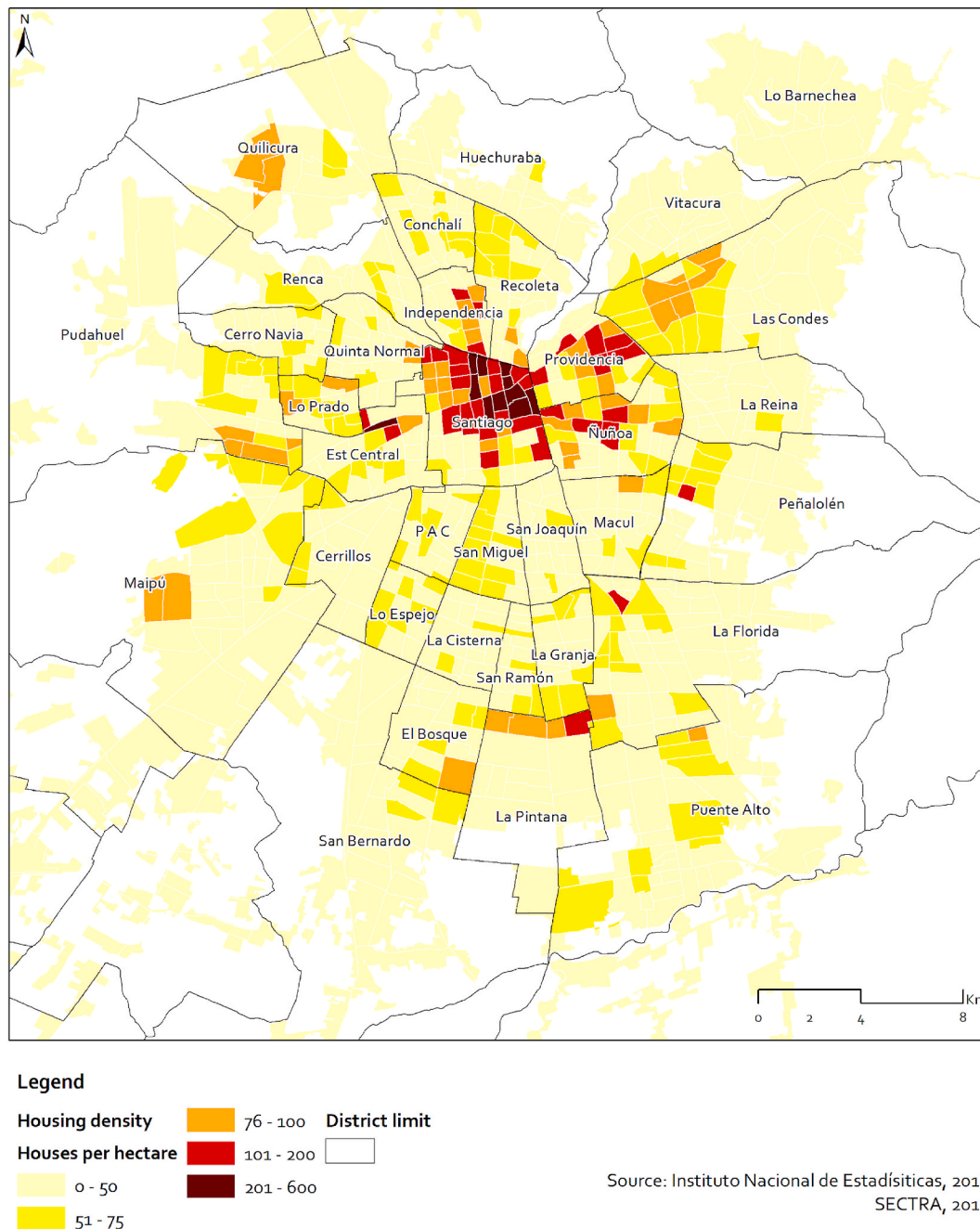


Fig. 6. Housing Density in the Santiago Metropolitan Area, by OED survey area.

policy based on cycling job accessibility. Equity can be achieved by enforcing the right to housing, increasing job opportunities among the poor, and reducing the dependence on expensive motorised transport. Decarbonisation can be achieved by promoting active transportation and reducing the dependence on motorisation.

In our research, we used the case study of the Santiago Metropolitan area to test the cycling potential for work-related trips made by households that are affected by the current housing deficit. We show that market-oriented land and housing policies that have led to urban sprawl will strongly reduce the cycling potential. Re-urbanisation of pericentral plots of land, urbanised during the 1960s - as it has been discussed as a policy option in Santiago - are better than expansion to the periphery, but do not provide the strongest cycling potential. Locating subsidised housing via densification of the central areas seems to be the key for better cycling potential in Santiago.

However, unless aggressive densification via social housing projects in central areas is achieved, a trade-off is identified even in the best analyzed scenario. This trade-off puts accessibility and adequate housing options in tension. Households are facing the cost of overcrowded living conditions and inadequate houses, not only due to land prices, but also to improve their job accessibility, which seems extremely valuable. In our model, accessibility losses occur even in the best relocation scenario. The high cycling to work potential in the existent situation should trigger actions from policy makers. Providing cycling infrastructure could have a great immediate impact in Santiago, if aimed for the three lowest quintiles and not just the middle classes and the elites. The focus of our work has been to analyse the impact of relocating some households among different areas in the metropoli. A similar analysis could be done in which trip attractors for work, study or leisure could be better distributed along the city. We expect that the impact of such a

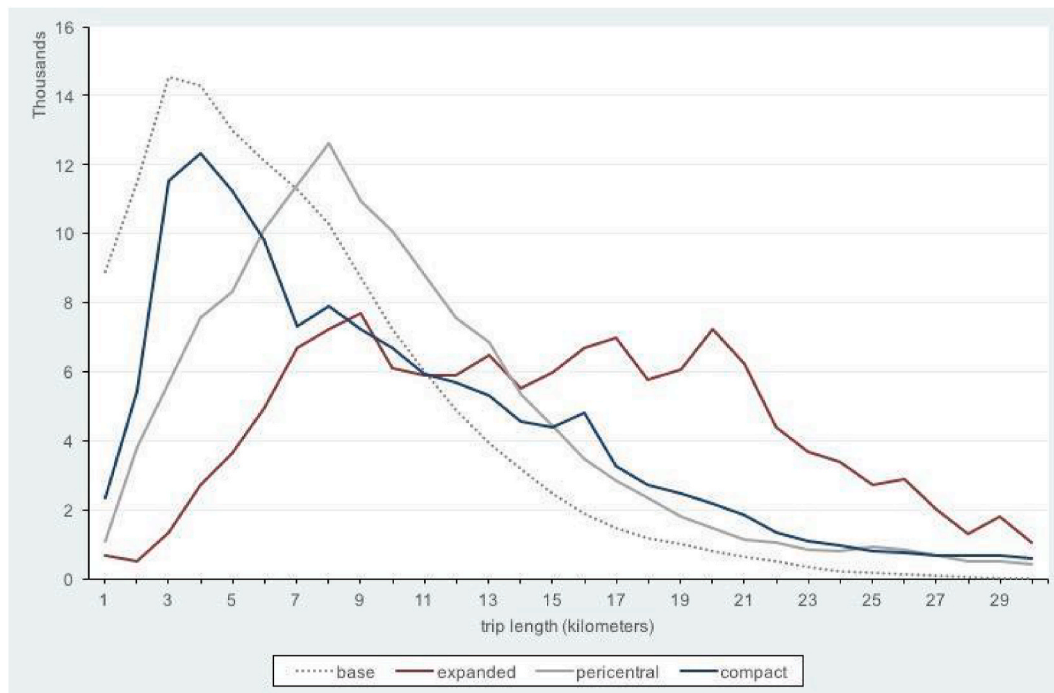


Fig. 7. Simulated distribution of trips by length in each scenario.

policy in improving cycling potential in the city would be similar to the one identified in this paper.

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