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Assessment of the socio-spatial effects of urban transport investment using Google Maps API

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ABSTRACT

We analyze the spatially distributed impacts of transport investment in urban highways and public transport with a novel methodology based on the capabilities of online technology to replicate the (unobserved) condition without highways. This is based upon the intensive use of Google Maps API (GMA) to obtain travel times between each origin-destination pair at a highly detailed level to reveal the effects of new infrastructure on different zones and groups within a city. Santiago is used as a case study, as the city introduced 150 km of urban highways, a reorganization of surface transit, and new subway lines in a relatively short period. We show that the high-income segment of the population has been the most favored, simultaneously increasing the difference between transit and car travel times in those areas where car ownership is low, stimulating the acquisition of a car.

1. Introduction

At the beginning of this century, a huge program of urban highways was launched in Santiago, Chile, spending more than 1400 million dollars for the construction of 150 km approx (Quijada et al. 2007), and guaranteeing revenues to the private investors of up to 75% of the initial investment (Herrmann-Lunecke et al. 2020). In parallel, a well-advertised program to modernize surface transit, to integrate it with metro, and to charge a single fare per trip regardless of the combinations – Transantiago - was conceived in 2002 and implemented during 2007; with a budget of a little more than 200 million dollars (Quijada et al. 2007), it ended up in an unprecedented disaster following an ill design that contemplated a suboptimal number of buses of larger than optimal capacity (Jara-Diaz and Gschwender, 2009). In the period 2001–2012, an explosive increase in car ownership occurred, jumping from 125.7 to 177.9 vehicles per thousand inhabitants in Santiago according to the origin-destination survey (SECTRA 2014), which is presently causing congestion particularly in the eastern part of the city, the affluent zone. Simultaneously – and considering only motorized modes -, the share of public transport trips dropped from 50% to 39% while the car share increased from 32% to 40% in the same time lapse (SECTRA 2014), exactly the opposite effect of the main declared objective of Transantiago.

The actual role of the network of urban highways within the evolution synthesized above has not been studied with care; the main problem has been the lack of appropriate data to compare the situations before and after the highways' construction. On the one hand, the traditional OD surveys (run every ten years) cover approximately 1% of the population, the use of the highways is not documented in those surveys and the spatial information is quite imprecise (Bagchi and White 2005), On the other hand, detailed information on (stop-to stop) trips and routes exist for public transport through smart-card data (Munizaga and Palma 2012), but not for cars although there is public information regarding the flows on each highway at any moment.

Given the absence of adequate time-series information, we apply a novel methodology to study the structural effects of highway investments and Transantiago by taking advantage of the fact that online maps provide travel times at a very detailed spatial level. Briefly explained, the main idea is to look at travel times using Google Maps API (GMA) considering public transport and cars, adding the case of car route choice imposing the condition that highways cannot be used. In this way, a comparative analysis permits the estimation of proxies of highway-induced travel time changes; later on, the results are crossed with spatial information regarding the socio-economic level and modal use. As new urban highways are being planned in Santiago, it is quite relevant to offer an assessment of the effects of past investment. We aim at finding out: a) which population segments (income and location) have been mostly favored by highways and Transantiago, and b) what is the

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impact of those projects on low car ownership segments. To do this we use GMA to define indices that permit to establish relations between the presence of highways and the quality of displacements for the different zones in Santiago. Our main findings relate to travel times and are myriad: 1) urban highways have benefited mostly the wealthiest population that live in the peripheries; 2) wealthy people (car owners) have been benefited objectively by diminishing their travel time, while peripheries have been (potentially, if they have cars) favored by the highways layout; 3) public transport serves the city quite homogeneously, leaving only some specific (western-low income) zones or municipalities disfavored; 4) highways have increased the time advantage of the car against transit in the whole city, but mostly in the peripheries (regardless of income); 5) GMA has a strong methodological potential for this type of studies.

In the next section, we review the most relevant references in the literature concerning both the impact of infrastructure investment in transport systems and the use of online maps to study travel times. In Section 3 we provide a picture of what Santiago looks like in terms of various (spatial) indicators, the location of the highways and metro lines, and other aggregate information according to the last Origin-Destination (OD) survey; then we describe the data and set up a novel methodology to look at the impact of transport infrastructure without observations in a time-series (or before-after). In Section 4 we apply this methodology to the case of Santiago and its new urban highways - public transport system. Section 5 concludes.

2. Travel times and urban highway investment: Antecedents

According to the literature, there are three types of effects after an investment in urban roads: short, medium, and long run.

- In the short run, as the capacity and quality of roads increase, car users experience a reduction in travel times.
- In the medium run, this attracts users from public transport to cars, increasing both congestion and transit times due to frequency reductions, such that all users are worse off regarding travel time. This has been well explained with the so-called Downs-Thomson paradox (e.g., Mogridge et al., 1987), which has been empirically supported by case studies in the USA (Duranton and Turner 2011; Noland and Lem 2002) and the UK (Goodwin and Noland 2003; Noland and Lem 2002), while the reverse effect (reduced traffic when road space is reallocated for different use) has been found in several cities around the globe (Cairns et al. 1998, 2002). Two observations should be made. First, this paradox requires that all users have a choice between modes under all conditions; if after the investment some users cannot switch to car, those that still use transit will be worse-off but travel time can go either way for private car users since the capacity gain may overcome the extra car flow from former transit users. Second, if an investment is made simultaneously in public transport, results will depend on the way both investments are made.
- In the long run, the city itself adjusts to the new infrastructure. Previous research suggests that cities expand due to highways (Baum-Snow 2007), that the price of land rises close to transit stations (Rodriguez and Mojica, 2008), and that urban sprawl is reduced with good quality public transport (Burchfield et al. 2006). In this paper, we are dealing mostly with the medium-run effects, looking at the travel times a few years after the investment.

Estimating travel times has not always been an easy task. When streets can be toured with no congestion, they can be calculated using some classic combinatorial tools as Dijkstra's algorithm or others specifically designed for real-world networks, like the one by Sanders and Schultes (2005). Recently, some online tools have been developed such that travel times between a specific pair of points in a city at different periods can be obtained; Google Maps API (GMA, the for-programming version of Google Maps) is probably the most famous of these tools, whereas OpenStreetMap (OSM) is an alternative tool with the virtue of being free to access but, unfortunately, does not admit excluding tolled highways in the calculation of shortest paths.

Travel times have been estimated using these tools for various purposes in different cities. Considering vehicle times only, Wang and Xu (2011) use GMA to calculate the ease to arrive at a health center in Baton Rouge, USA, whereas Widener et al. (2017) use OSM focused on the chances to access groceries stores at different periods of day and night in Toronto, Canada. Vehicle travel times computed via GMA is also used by Dumbliauskas et al. (2017) to calculate mean travel times for each origin in Kaunas City, Lithuania, at several periods a day; by García-Albertos et al. (2019) in Madrid, Spain, who combine this information with an estimation of the OD matrix using the information of the movement of smartphones by looking at the (anonymous) record of their calls; and by Xia et al. (2018), who estimate accessibility indices throughout Australia combining the travel times information with the locations of people's residences.

Using GMA, Qi et al. (2020) compared times by car and by public transport in Sydney, Australia, but considering the CBD as the only destination; they combine this information with the "public transport needs" of each origin, depending on the characteristics of people living there. McGurrin and Greczner (2011) used OSM for a similar comparison in Seattle, USA, but connecting different pairs of centroids. OSM can also be used to estimate the pedestrian walking times to access a transit network, an approach that is followed by Pereira (2019) to estimate the impacts of a partial or total construction of a BRT in Rio de Janeiro, Brazil, and by Owen and Levinson (2015) who used this information to calculate travel times by car and public transport in the Twin Cities, USA, which is in turn used to propose methods to predict the modal share.

Other public sources of data have also been used for similar purposes. For instance, in Montreal, Canada, El-Geneidy et al. (2016) and Boisjoly and El-Geneidy (2016) have used public data from transit agencies to evaluate equity and accessibility across the city, respectively. In Santiago, Tiznado-Aitken et al. (2018) used OpenStreetPlanner to calculate walking distances to access the transit network, while Gibson et al. (2016) used smartcard data to estimate the travel time gains of a median busway, data that were complemented with OSM by Kickhofer et al. (2016) to compute the so-called MATSim scenario for Santiago. In Brazil, Bittencourt et al. (2020) have used data from local transit agencies to study the relationship between accessibility and segregation in different cities. In Chile, actual in-vehicle transit travel times (stop to stop) can be estimated using ADATRAP (DTPM 2020).

The described tools for travel time estimation have been subject to scrutiny as well. For instance, Lahoorpoor and Levinson (2020) compared GMA, OSM, and another tool called ArcGIS Network Analyst, finding that GMA predicts the lowest traveling times. Also, they have been used to extend the range of results, as in Huber and Rust (2016) who proposed a function in C++ that relies on OSM to estimate traveling times by foot, bicycle, or car between two points described by their geographical conditions.

As described, all these tools have been used to obtain travel times essentially as black boxes devoid of specific details regarding operations or the behavior of users. General characteristics are known: e.g., whether travel time is measured point-to-point or stop-to stop in the case of transit, or whether parking time is included in the case of cars. However, some specific features are unknown, such as the way users choose a particular route in the case of transit or the way congestion is taken into account in the case of car trips.

There is one direction in which online tools have not been used to their full potential: travel time calculation assuming that highways are not available to users. This is exactly the direction in which we want to extend the approaches developed so far using API to assess the impact of urban highways. Specifically, we will approximate the situation without highways by deleting the use of them in the present situation. This way we obtain travel time indices between zones by three "modes": car

imposing that highways cannot be used (car-streets); car letting the highways be part of the possible route choice (car-highways); and public transport (transit). Using this detailed information we will create quality indices to a) capture the effect of highways, and b) study how they correlate with each zone's socioeconomic characteristics. This is explained in the next section.

3. Case study, data, and procedures

3.1. The city and the transport system

Santiago, the capital city of Chile, has some 7 million inhabitants distributed in space in a fairly segregated way according to income, car ownership, and public transport use, as synthesized in Fig. 1 where six zones are depicted, covering some 650 square km; information comes from the last available OD survey.

The Eastern zone differs sharply from the rest of the city, with roughly three times the income per capita and car ownership, and less than half of the percentage of trips made by public transport. This hints that Santiago is a very segregated city, which is confirmed by considering how concentrated some groups are within the city, and how homogeneous are residential areas (Sabatini et al. 2001). Such segregation does not only entail that different groups live in different places; the environments are quite different as well. For instance, rich areas present larger green areas (Romero et al. 2012), and concentrate relevant activities such as shopping, education, or health care (Martínez et al. 2018). Although some indices reveal that segregation seems to have decreased during the last decades, social exclusion has become more severe (Sabatini et al. 2009; Ureta 2008). Ethnic segregation has emerged in the last years as well (Borsdorf et al., 2016).

Regarding the role of income in transportation in Santiago, in Fig. 2 we show in more detail what the aggregate numbers in Fig. 1 suggest: car ownership (left) and modal shares (right) as a function of income per capita. It shows clearly that car ownership and total car trips increase

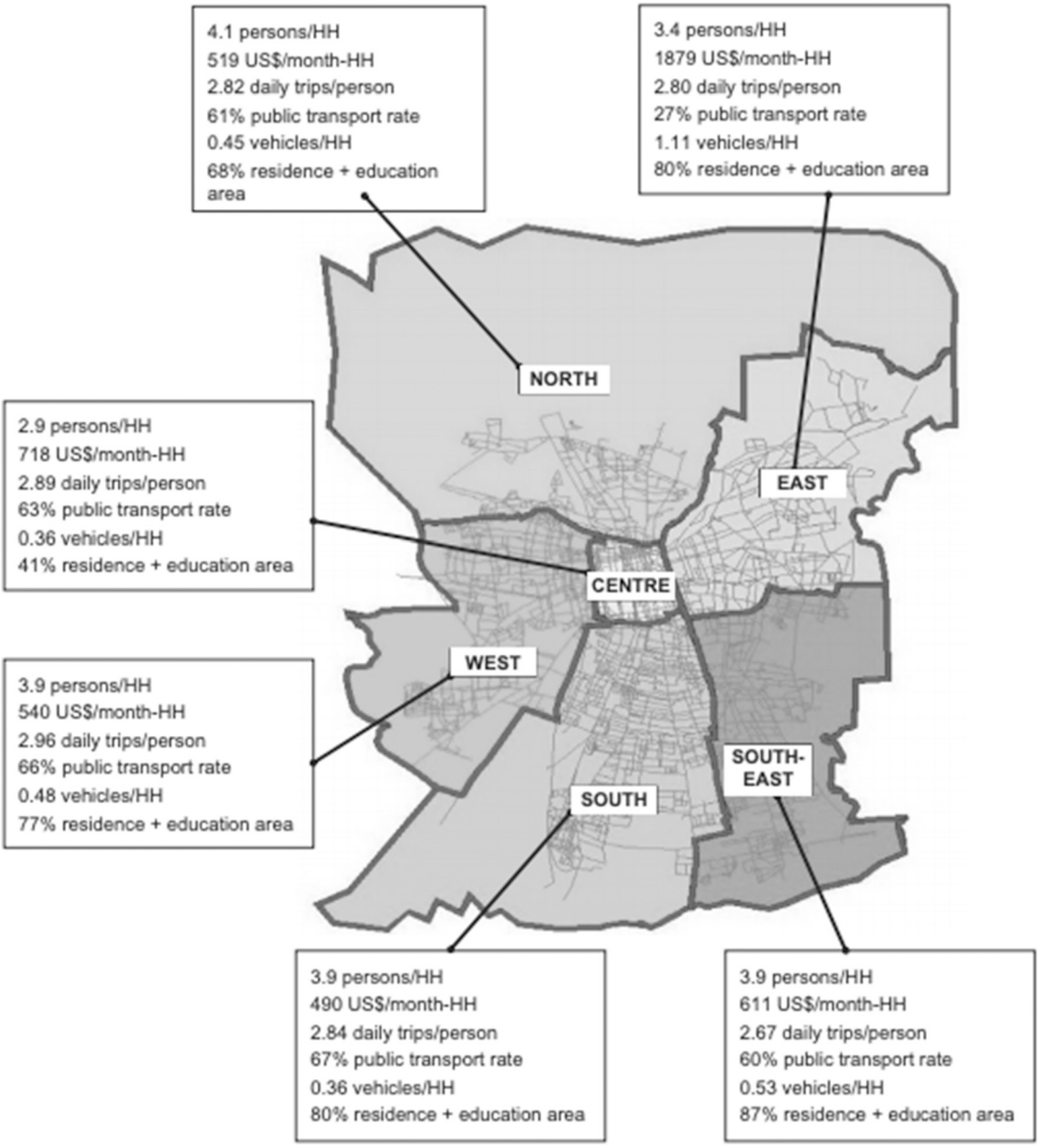

Fig. 1. Santiago de Chile, 2012: an aggregate view.
(Source: Jara-Diaz et al. (2016); Jara-Diaz et al., 2013)

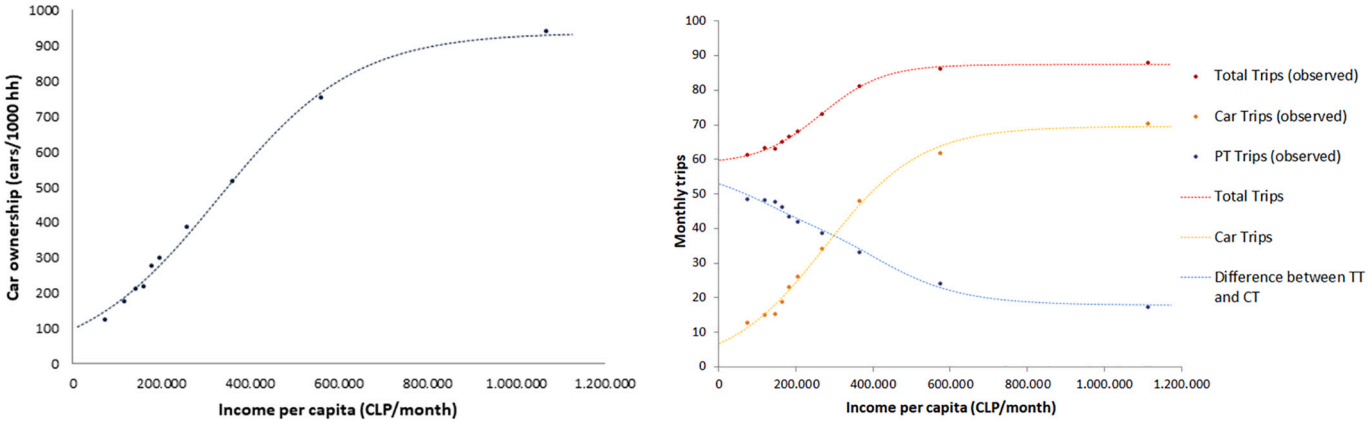

Fig. 2. The role of income in car ownership and modal trips in Santiago.
Source: Jara-Diaz et al. (2016).

sharply with income, while it has an inverse effect on public transport trips.

Santiago has four urban highways, which were opened between 2005 and 2006 (Fig. 3, left). Their construction provoked some discussion among specialists (see Jara-Diaz 2004), as they required an investment of at least 1400 million dollars, including "pervasive contract renegotiations" that were harmful to public finances (Engel et al., 2003), and there was a concern that they would induce a more massive use of the car instead of public transport (Fernandez and Osses, 2004), increasing the levels of congestion and pollution. The last OD survey shows that the use of private cars has indeed grown, although only 4% of the total trips during a normal working day use highways, which are usually congested during peak hours. Moreover, the urbanistic impacts of these highways have also been strongly criticized as they can increase inequality and segregation (Allard 2002; Borsdorf et al. 2007; Borsdorf and Hidalgo 2008; Sagaris and Landon 2017). Nevertheless, the highway network has increased since its first opening and more highways are being built.

On the other hand, the public transport system has also experienced significant changes in the last 15 years. The most relevant change was the creation of *Transantiago* in 2007, a plan which integrated the metro and the bus system under a single fare, renewed the whole fleet of buses, and changed drastically the structure of the lines of the bus system reducing initially the total fleet from more than 8000 buses to some 4500. This system worked very badly in its first years and became a political earthquake (for a full description of this process, see Muñoz and Gschwender 2008), which is why it has been modified many times since then. In parallel, the metro system has been growing with new lines and extensions of old ones (see Fig. 3, right). To this date, the public transport system in Santiago operates with 6500 buses approximately, seven metro lines, and one suburban train.

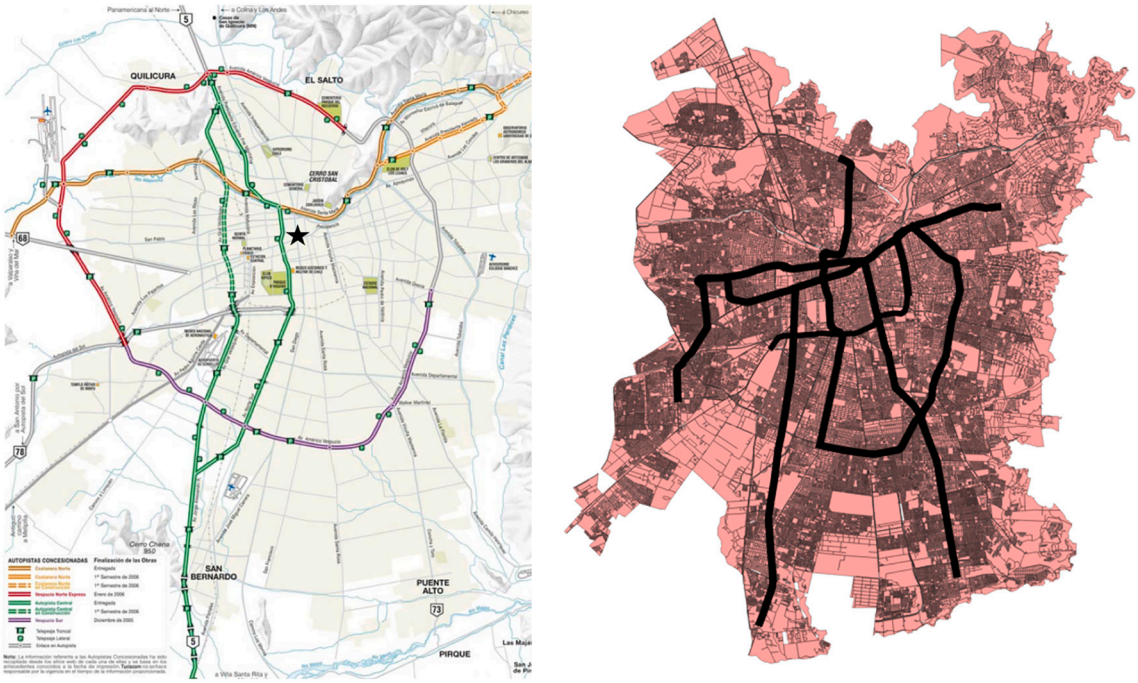

Fig. 3. Urban highways (left*) and Metro network (right) in Santiago.
*The star represents the central zone.
Sources: Figueroa (2012) (left), IDE OCUC (2019) (right) plus own elaboration.

3.2. Generation of relevant travel time data

For the purposes of this research, based on travel time comparisons, we want to obtain disaggregated information regarding travel times using cars and transit in Santiago including travel times under conditional circumstances, namely assuming highways cannot be used. To compute the traveling times across Santiago, we used the Google Maps API (GMA). To do this, we considered the zoning implemented by the transport authority for the last Origin-Destination Survey (SECTRA, 2012), which divided the Metropolitan Area of Santiago into 866 zones. The geographical coordinates of the centroids of these zones were calculated to be used as origins and destinations. The trip-time matrices built using GMA are the basis to construct adequate and simple - but quite useful - indices aimed at analyzing the overall impact of the new transport infrastructure in Santiago.

In essence, GMA requires three inputs for the calculation of travel times as the output: origin and destination coordinates, the time of departure, and the mode of transport. As said earlier this inputs-output process is a black box; however, we know (at least partially) the sources of information used to predict travel times by mode, origin-destination, and period. These include information from smartphones (through their GPS tracking devices), historical information, current or expected traffic conditions, and so on. Regarding public transport travel times, some information provided by local authorities is needed, such as transit routes, frequencies or timetables, and the location of transit stops and stations. This information exists for vehicles that are part of Transantiago but not for some peripheral locations that are served by external providers. GMA indicates that there are 146 zones not served by the transit system; additionally, 16 other zones exhibited at least ten destinations not reachable by public transport according to GMA. We discarded all 160 zones, ending up with a clean 726 × 726 matrix of public transport travel times, covering approximately the street network in the background of Fig. 1.

We discarded the use of the peak hour as travel time is subject to large variability due to exceptional situations introducing random noise in the answers provided by GMA; obtaining average trip times or describing their distribution within a period for each pair is simply out of the question because it would require the calculation of travel times repeatedly for each OD pair and mode; this is a limitation of the method. Thus we measured expected travel times at the off-peak period, asking for predicted travel times for trips beginning at 3 pm on a labor day about two weeks in the future (such that average conditions are considered by GMA). Three modes were considered: public transport, private transport letting tolled highways be part of the (best) route (car-highways), and private transport discarding the use of highways (car-streets). In this last case all urban highways that were built on pre-existent streets or avenues keep a parallel service road, usually with lower capacity than the replaced street or avenue; the resulting possible overestimation of car-streets times in some OD pairs is, however, mitigated by measuring travel times at the off-peak. GMA receives these inputs and gives the total time required as output. With this procedure, we were able to build three quite large OD travel time matrices. As we needed a little more than 2 million requests to obtain these matrices, the paid version of GMA was required (the free one puts a daily limit of 2500 requests). An automatic program in Matlab was created for this purpose. Due to the time imposed to connect with the web, it took us around three months to compute all the necessary output to construct the matrices; we estimate that a computer dedicated exclusively to this purpose would have needed some weeks.

GMA predictions for Transantiago can be compared with the publicly available database ADATRAP of estimated travel times of actual users (DTPM 2020), using the methodology proposed by Munizaga and Palma (2012). The ADATRAP method is built using smartcard information that shows location and time for users boarding the vehicles, considering the actual stop to stop operation (in-vehicle travel time); the stop where the individual alights is estimated. We sampled 85 random trips from ADATRAP and computed the travel time using GMA as well (i.e. inputting the coordinates of the stops and choosing transit as the mode). Times predicted by GMA result on average larger (by some 20%) due to the emergence of some walking time because of small mismatches with ADATRAP in the positions of the stops where passengers board, which could even imply that users have a choice regarding which bus stops to use. Fixing the mentioned mismatch goes beyond the scope of this paper. Details of the comparison are provided in the Appendix.

This procedure was applied between May and September 2018. Therefore, the public transport matrix considers the existence of new Metro line 6 and a suburban southern line (known as Metrotren Nos), which opened in 2017, but it excludes line 3, which opened in 2019. These matrices could be used for different purposes as presented in the next sub-section. Considering that the very purpose of obtaining reliable OD matrices is quite relevant, let us synthesize the virtues and difficulties of Google Maps-methods that we found:

a) **Virtues**: It is a method whose design is independent of the city characteristics. Online information is updated constantly, and its application is way easier and cheaper than traditional ones (such as OD surveys). Results are obtained at a very disaggregated level for each of the transport modes. Results are comparable across cities.
b) **Difficulties**: The time required to obtain a detailed matrix, although shorter than with other methods, is still quite long, such that it is not possible to update them easily. The estimation of travel times by public transport depends on local information that is not always available. Further, GMA provides only the information about total time, rather than distinguishing between access, waiting, and in-vehicle times, which are perceived in different ways by users. Being a black box, it cannot be adapted to inspect elements behind travel time estimates. The paid version of the GMA is required if many zones are considered.

Adding advantages and disadvantages, we assess that GMA is a very powerful novel tool to obtain travel times at a very disaggregated level.

3.3. Using data to create relevant indices

The three time-matrices built as described above resulted almost symmetrical, with more than 97% of the OD pairs exhibiting less than 20% difference when switching the origin and the destination (which might not hold during peak hours). This makes the choice of looking at each zone as origin or destination relatively irrelevant for the analysis, and we have chosen to look at zones as origins (rather than destinations) to facilitate the association with socio-economic variables at a later stage in the analysis. The absolute value of each element in a matrix is in itself an index of how "difficult" (time-consuming) it is to go from a given origin to a given destination using a given mode: transit (P), car-highway (H), car-streets (S). By looking at the numbers in a row of the matrices (a zone as origin) one can get a first idea of how well-connected a zone is, but this procedure will assign lower connectivity to the zones that are on the border of the city. Instead, we will look at the travel time ratios taking as reference the car-streets times, such that the resulting numbers will represent a relative index of how different is to move by public transport, and what is the gain in time induced by the highways. Car-streets is taken as a reference because it naturally takes the absolute distances and the geographical characteristics of the city into account.

Let us define $T_m(i,j)$the time index from zone i to zone j using mode m. Formally, we define for each OD pair

$$\lambda_m(i,j) = \frac{T_m(i,j)}{T_S(i,j)}, m = P, H \quad (1)$$

The index for $m = P$represents the ratio between time using transit and time using car-streets, such that the larger the index the more attractive the car-street is to go from i to j. The index $\lambda_H(i,j)$is the ratio between the two time-indices involving car, with $\lambda_H(i,j) \leq 1$ because car-

street routes are a subset of the car-highway routes set; the smaller the index the more attractive the use of highways is.

The next step is to define origin-specific indicators. For this, we will first consider trip times to the main destination area c, the center in Fig. 1 (Santiago's CBD). Let us define the "trip-time-ratio-to-the-center using mode m" index as

$$\lambda_{m,C}(i) = \lambda_m(i,c) \tag{2}$$

The representative zone for the CBD will be the one that contains Plaza de la Constitución and the presidential palace, La Moneda, which lies in the heart of Santiago (black star in Fig. 3 left). It is worth mentioning that Santiago's center has been expanding towards the east, although the historical center still attracts the largest amount of trips. This indicator synthesizes how well-connected is each zone to the most relevant destination in the city by mode m relative to car-streets. When $m = P$the larger this ratio is the larger the willingness to use the car instead of the public transport network by an individual departing from i; when $m = H$, the ratio indicates how useful are the highways to reduce times from each origin to arrive at the CBD.

To have a measure of the city-wide connectivity of a zone, the index in eq. (3) is defined as the simple average of the time ratios across all possible destinations, yielding a multizone index by mode:

$$\lambda_{m,MZ}(i) = \frac{1}{N}\sum_{j=1}^{N}\lambda_m(i,j) \tag{3}$$

Indices (2) and (3) reflect *potential* relative connectivity by mode only, as they do not take into account observed OD flows nor car ownership. Indices (4), (6) and (8) below include information from the last available OD survey (SECTRA, 2012). Let Y_{ij}^{PT}, Y_{ij}^{C} be the number of users traveling from zone i to zone j by public transport and by car, respectively, and Y_i the total number of users departing from i in one of those two modes (we exclude the other modes for this analysis, as they are not directly affected by highways). We define the average "time saved by highways" by users departing from zone i as

$$\Delta T(i) = \sum_j \beta_{ij}(T_S(i,j) - T_H(i,j)), \tag{4}$$

where $\beta_{ij} = Y_{ij}^{C}/Y_i$. Defining $\alpha_{ij} = Y_{ij}^{PT}/Y_i$ (such that $\alpha_{ij} + \beta_{ij} = \frac{Y_{ij}}{Y_i}$, and $\sum_j(\alpha_{ij} + \beta_{ij}) = 1$), $\Delta T(i)$ can be trivially rewritten as:

$$\Delta T(i) = \sum_j \beta_{ij}(T_S(i,j) - T_H(i,j)) + \sum_j \alpha_{ij}\cdot 0, \tag{5}$$

which confirms that this index can be seen as an average among all users departing from zone i, with transit users exhibiting zero savings. Therefore, $\Delta T(i)$ is measuring the direct savings due to the highways for all users, accounting for those users that do not travel by car so are not directly benefited. Note that $\Delta T(i)$ condenses the information regarding car usage and the impact of the highways, i.e., a large value of $\Delta T(i)$ implies that users from zone i travel intensively by car and their trip times have diminished considerably with the highways, meaning that it is a zone that was much favored by the highways.

The perceptions of transit users are also affected by the time savings induced by highways. Indeed, the decision of switching from public transport to private vehicles depends, among other things (such as highways' tolls), on how much faster is the private mode. We can define the "time-advantage to switch from public transport to car" (with or without highways) as

$$W_k(i) = \sum_j \alpha_{ij}(T_P(i,j) - T_k(i,j)) \quad (k = H, S), \tag{6}$$

which can also be seen as an average in which car users exhibit no advantage because they are not using transit:

$$W_k(i) = \sum_j \alpha_{ij}(T_P(i,j) - T_k(i,j)) + \sum_j \beta_{ij}\cdot 0 \quad (k = H, S) \tag{7}$$

Then the *change* in the time-advantage to switch to car induced by urban highways on transit users is

$$\begin{aligned}\Delta W(i) &= W_S(i) - W_H(i)\\ &= \sum_j \alpha_{ij}(T_P(i,j) - T_H(i,j)) - \sum_j \alpha_{ij}(T_P(i,j) - T_S(i,j))\\ &= \sum_j \alpha_{ij}(T_S(i,j) - T_H(i,j))\end{aligned} \tag{8}$$

Large values for $\Delta W(i)$ imply that zone i presents many transit users, whose time savings induced by a modal shift would be significantly increased due to highways. That is to say, the higher this index, the larger the expected impact on modal share in the zone under analysis in the medium run.

As noted above, to construct the indices synthesized by Eqs. (4)–(8) the data coming from the OD survey is necessary to obtain α_{ij} and β_{ij}. As the last survey was applied to 30,000 users only, there are several OD pairs with just a few observations (including zero). Discarding those zones that exhibit less than 30 originated trips in the survey, we end up with 571 zones when constructing these indices.

Before using the indices defined here for the empirical analysis it is useful to stress the differences between $\lambda_{m,C}$, $\lambda_{m,MZ}$, and the indices that take the modal share into account $\Delta T$and ΔW. The λ's look at the direct ratio between the times required by each mode, that is to say, they describe for an individual departing from a zone the comparison between the three modes. On the other hand, the Δ indices take all the users departing from such a zone into account. For a specific traveler, the λ indices are the most informative regarding the attractiveness of each mode irrespective of car ownership. But when we aim at understanding which zones are most favored by the highways $\Delta T$is the best index, whileΔW is the index to look at if we want to detect in which zones the modal shift is being pushed forward by the highways (as predicted by the Down-Thompson paradox).

4. Empirical effects of infrastructure investment

4.1. Aggregate analysis of results

The time figures $T_m(i,j)$contained in the original modal matrices are synthesized in Table 1, that shows average times to go from any point of the city to the CBD (row 1) and to all destinations (row 2) if the corresponding mode was used. Total figures do not seem surprising; differences among modes are very significant, though. Traveling to the center of the city by car using highways would take on average less than half the time it takes by public transport and considering all destinations make things even worse for transit, which is bad news if trying to stimulate the use of public transport is a relevant target. Note that as we are looking at the off-peak, the relative advantages of metro or special lanes for buses (transit segregation) diminish which explains, in part, the differences between public and private modes.

Let us now provide an aggregate view of the indices defined in Section 2. In Fig. 4 we show the cumulative distribution of all six λindices. The ratios in Eq. (1) $\lambda_k(i,j) = \frac{T_k(i,j)}{T_S(i,j)}$, are shown in the first two graphs for $k = P, H$. The results for public transport indicate its disadvantage regarding traveling by car using streets, while the results for highways reveal the contrary. When the representative center zone is used as destination (Eq. 2) the curve representing public transport, $\lambda_{P,C}$, shows that it can be as high as 3.4; numbers lower than 1 are usually achieved when the origin is also located at the Centre because walking

Table 1
Average time by mode (min).

	Car-highways	Car- streets	Public transport
Destination CBD	20.9	28	50.5
Multizone	25	35	70

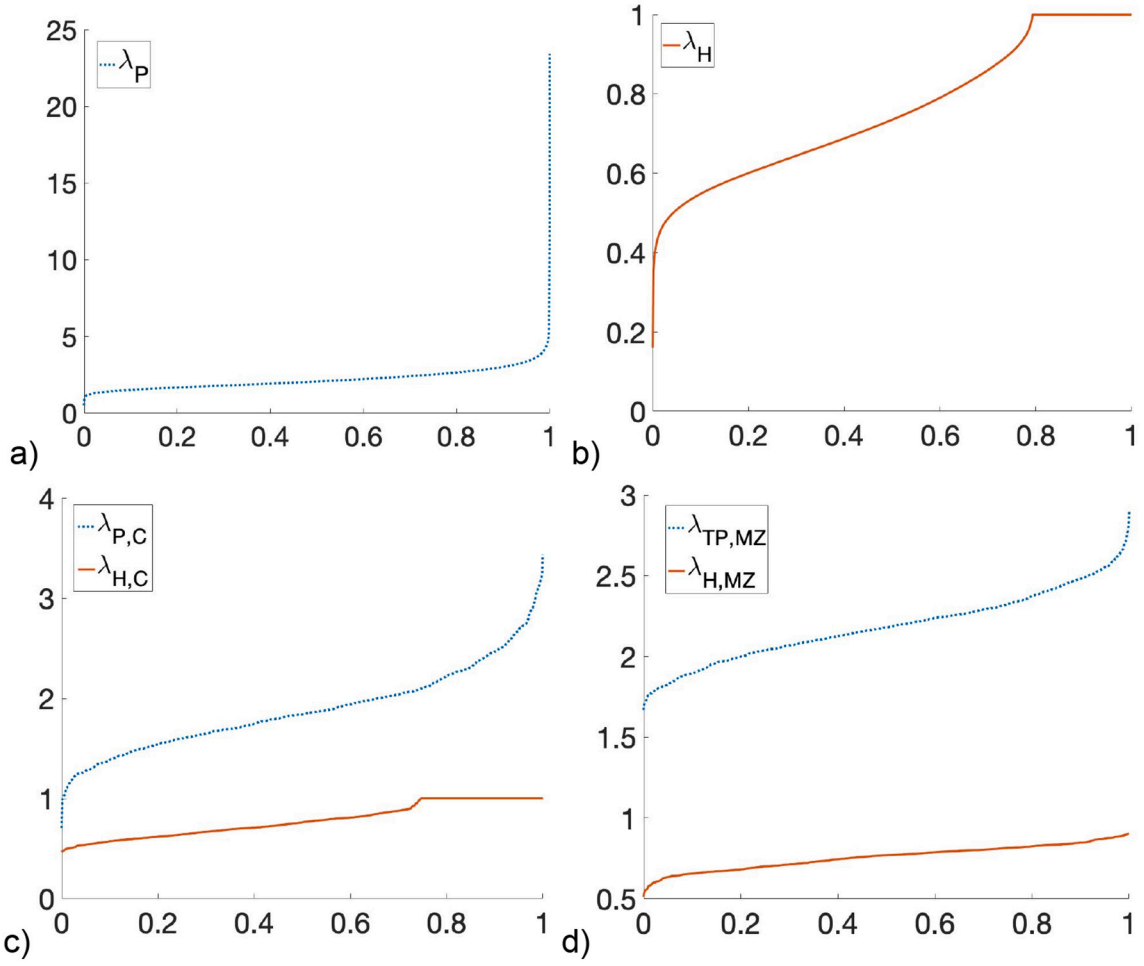

Fig. 4. Distribution of time indices.

(recognized as public transport by GMA) can be more convenient than the car. By definition, $\lambda_{H,C}$ is always lower or equal than 1, and at its minimum is slightly lower than 0.5. The distance between the curves representing the multizonal indices from Eq. (3) is larger than between the ones that consider the CBD only because the transit network serves the CBD particularly well; as it is the preferred destination, scale effects induce more frequent, dense, and more direct services (Fielbaum et al. 2020). See, for example, Fig. 3 right that shows that most of the Metro lines arrive there. When multiple destinations are considered, this does not hold everywhere and the differences between modes are more pronounced; note that the CBD is neither well nor badly served by the highways.

All three indices related to public transport present a sudden and sharp increase by the end of the distribution, meaning that there are a few zones whose connection by public transport is particularly weak. On the other hand, indices dealing with highways are much more stable, although when looking at all OD pairs (Fig. 4.d) there are a few that take particular advantage of the highways. About one-fifth of the OD pairs do

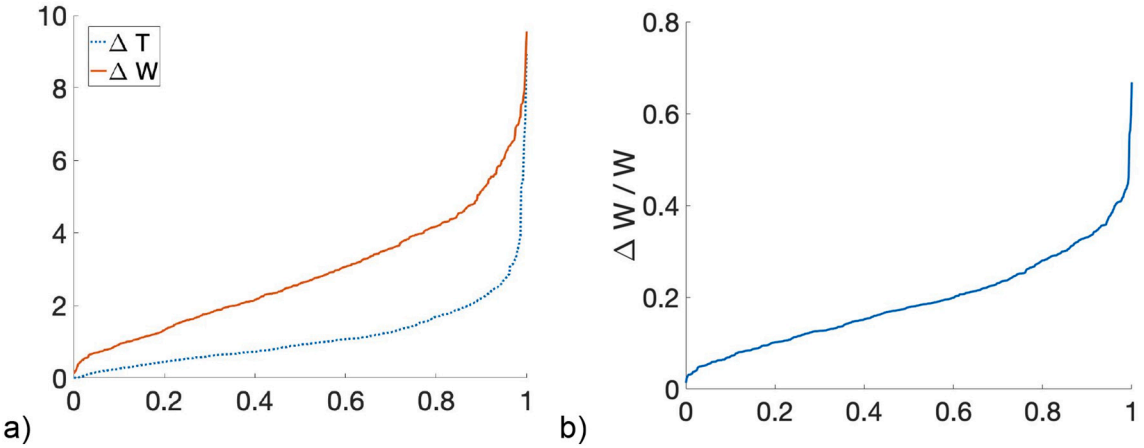

Fig. 5. Cumulative distribution of a)$\Delta T$and ΔW(minutes), and b) $\Delta W/W_S$.

not use highways in their shortest paths (reaching $\lambda_H = 1$in Fig. 4.b).

In Fig. 5 we present the cumulative distribution of the indices that consider observed usage of the system along with the time matrices. The index ΔTin Fig. 5a, that represents how much favored by the highways a zone is, is extremely concentrated in a few zones. This means that in most zones within the city, either travelers do not use car (for whom the highways are useless) or highways are not useful for car routes. This reveals that the large amount of resources assigned to build these highways, noted in the Introduction, have favored a very small fraction of the population. The impact on transit users ΔW is not so concentrated, and it reaches higher numbers than ΔT, i.e., there are more savings for prospective car users (presently transit users) than for actual car users. This suggests that, at least from the time savings point of view, the impact on modal share can be more relevant than the gains allocated to the (few) favored zones.

To analyze Fig. 5b, recall that ΔWacts on top of W_S, as it is the extra savings induced by highways. In Fig. 5b we compare these two quantities, to see if highways can really make a difference in the modal share within a given zone. The answer depends on the zone: although there is always some effect ($\Delta W > 0$), the relative effect can be almost nil or quite large. Two facts are noteworthy: in more than half of the zones, the average savings for transit users increases by more than 20%, and for a few zones this difference can be larger than 50%. In all, and as anticipated by Table 1, the difference between public transport and car-streets is already high, and this difference is enlarged by a significant amount because of the highways in most zones.

4.2. Spatial representation

How do these indices distribute in space? The access-to-the-center indices from Fig. 4c are represented in detail in Fig. 6, which shows in colors the size of the $\lambda_{m,\,C}$ index for each zone in Santiago, with $\lambda_{P,\,C}$in Fig. 6a and $\lambda_{H,\,C}$ in Fig. 6b. The bluer the point, the lower the indicator, i.e. better served by either public transport (Fig. 6a) or highways (Fig. 6b). The cloud of points replicates the shape of the street network in the background of Fig. 1.

Fig. 6a shows that public transport is quite evenly distributed in space regarding access to the center, although there is a set of zones - located towards the west of the city - that is very poorly served; the bluest zones (best served) are evidently located along some metro lines. Noteworthy is that both extreme points - the bluest and the most yellow - are located very close to the CBD. This happens because, as explained earlier, walking is considered public transport; so pedestrian streets in the heart of the city make walking much faster than car-streets, while walking from a point that is not that close to the center could still be the best transit option but time is much higher. On the other hand, from Fig. 6b it is evident that highways are potentially much more useful for those living in the peripheries if users had a car; the intense yellow stain that extends East-West represents those origins for which highways are not used to go downtown by car (the index is equal to one).

Relative travel time to all zones by different modes is represented in Fig. 7 that shows the spatial distribution of the multizonal index defined in eq. (3); public transport in Fig. 7a and highways in Fig. 7b. They present some important differences with respect to Fig. 6.

In the case of the transit index, Fig. 7a shows that the bad "yellow zone" still exists but somewhat displaced to the south, indicating where the transit network should be improved, a useful result of the method from a policy standpoint. In the case of this multizonal transit index, the influence of the Metro lines is more evident than in Fig. 6a. Fig. 7b shows a remarkable result: the location of the highways does not translate directly into the darkest colors, which suggests that some of these highways are not so useful to reduce travel times. The potential advantage of highways goes to a few peripheral zones only, particularly in the north, which complements what Fig. 6b showed regarding peripheral zones being favored if the destination is the center.

So far we have analyzed relative travel times as if all users had a car. Let us move to the representation taking into account the observed flows introduced through the α_{ij} and β_{ij} figures defined earlier. We begin by studying ΔT(Eq. 4), which shows the average time per zone that would be saved if all car trips originated in each zone were switched from streets to highways. Recall that this index can be seen as how favored each zone is thanks to the highways. This indicator is distributed across the city according to Fig. 8 where, again, yellow means large (in this case, more time saved); we use $log(\Delta T)$ to allow for a better representation of the differences, as a few zones are much more benefited than the rest. As shown in Fig. 8a, the richest zones of the city (located at the northeast) are dominated by yellow dots, which are also present in other zones, mostly in the north and peripheries, showing that passengers

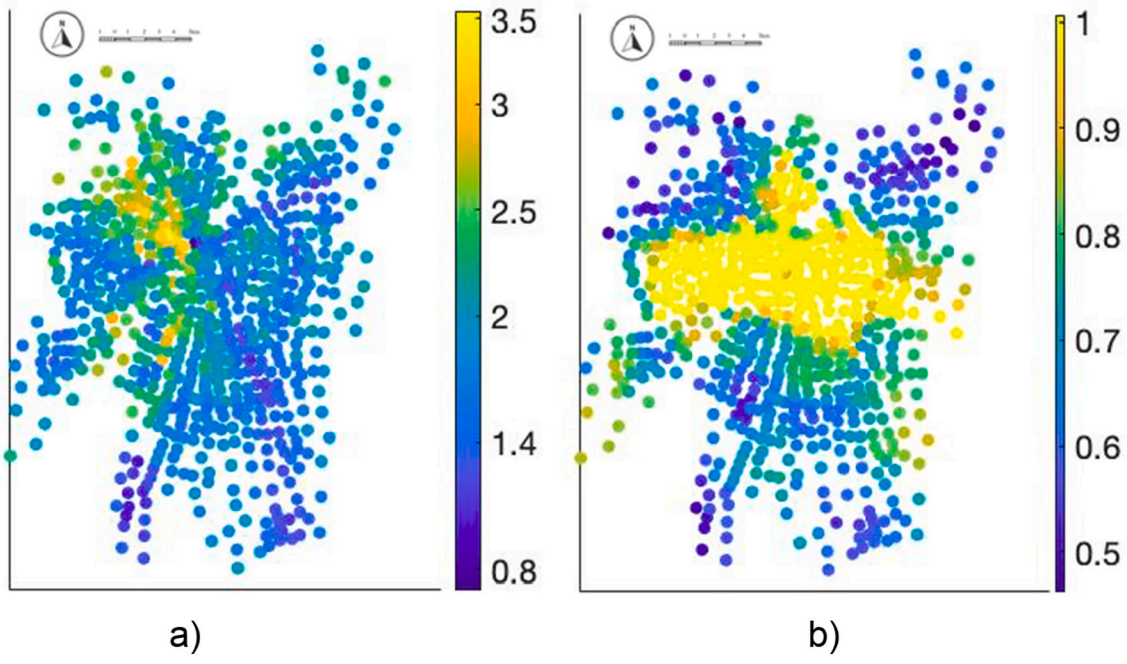

Fig. 6. Relative time-to-center index: public transport (a) and car-highways (b).

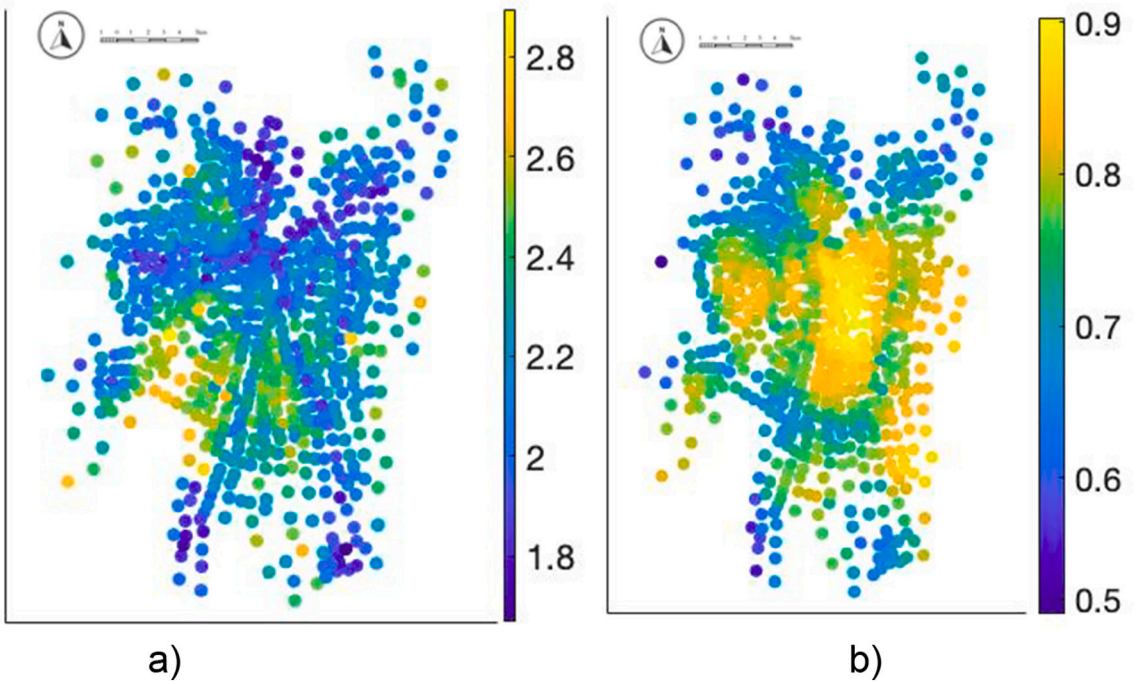

Fig. 7. Multizonal time index by public transport (a) and car-highways (b).

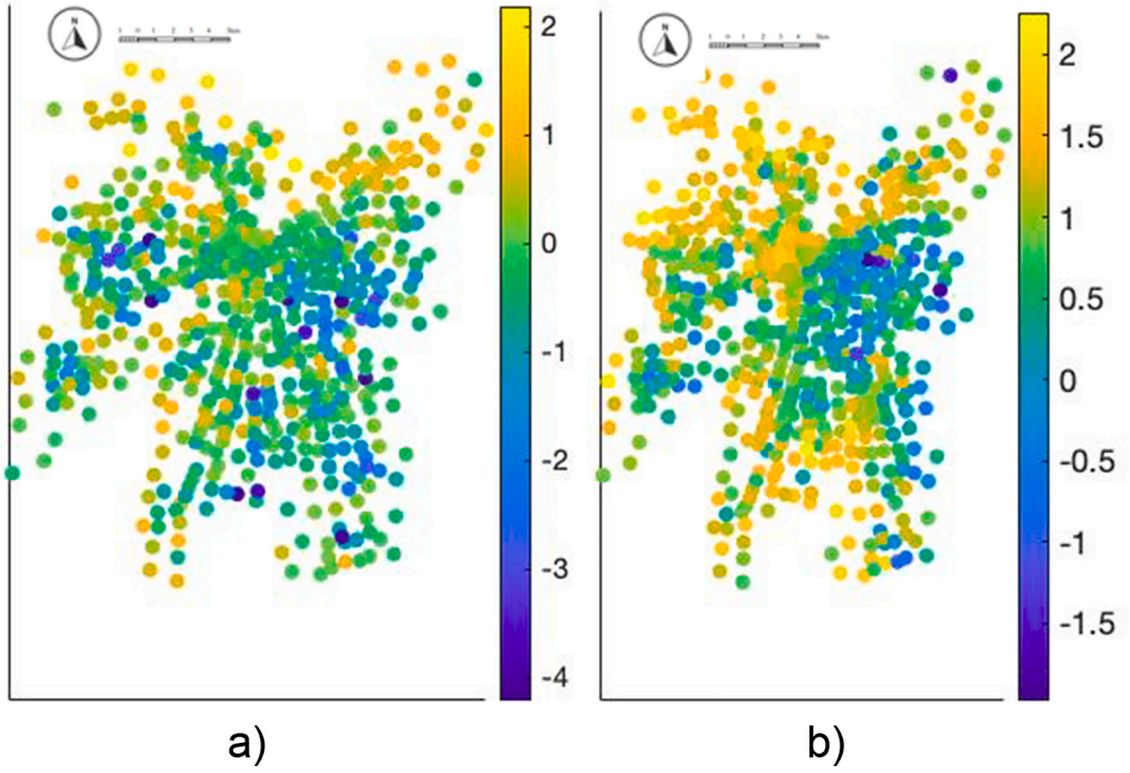

Fig. 8. a) Time saved by cars using highways instead of streets (ΔT in Logs) b) Time savings using cars induced by the highways as perceived by transit users (ΔWin Logs).

departing there take good advantage of the highways because they exhibit high car usage and the highways are effectively reducing their travel times.

Fig. 8b shows the spatial distribution of ΔW (in logs), i.e., which zones might lose more transit users due to the highways. We already know (Fig. 5) that this quantity is positive everywhere; Fig. 8b suggests that this increase is rather homogenous from a spatial point of view, although the peripheries are more affected in general; but it also shows another interesting result. Fig. 6a shows that when public transportation is seen as a means to go to the center, it does badly in a relatively large

area to the north-west of the city (the yellow zone). Fig. 7a shows that when all zones are considered as destinations, public transportation does badly in an area at the south-west. Fig. 8b shows that in this whole western zone the variation in travel time in favor of the car due to the highways is quite large, which increases car attractiveness.

4.3. Spatial analysis with socio-economic characteristics

We have seen the spatial variation of the indices that reflect the impact of infrastructure investment, noting that there seems to be a relation between those indices and a) the relative location of the zones, and b) the socio-economic characterization of the aggregate zones represented in Fig. 1. Let us link the results with these two zonal variables. For location we will use distance to the center. For the characterization of a zone, we will use the socio-economic level index (SEL) constructed by the Observatorio de Ciudades PUC (Cities Observatory of the Pontificia Universidad Católica de Chile). The SEL index ranks each block in the city with a score between 200 and 1000, depending on the earnings, on the educational level, and on the possession of certain representative goods (IDEOCUC, 2012). This information was obtained from the 2012 census that, despite its limitations (Pavez, 2020), was the most recent information available by the time this analysis was done and has been used for research in many studies such as Mateo Piñones and Valenzuela Carvallo (2017), Vásquez et al. (2016), Aguirre et al. (2018), Grande and García González (2019), and Rotarou and Sakellariou (2017). As SEL is reported at a very detailed spatial level, we took the simple average across all the blocks that compose a zone. As there were six zones with no census information this statistical analysis is done over the 720 remaining zones.

Fig. 9 suggests that SEL is directly correlated with car ownership and inversely correlated with transit usage, summarizing many socioeconomic characteristics: first, the spatial distribution of SEL across the city (Fig. 9a) confirms Santiago's segregation shown in Fig. 1, with affluent families living in the Northeast; second, the share of public transport users by zone (Fig. 9b) looks like the photographic negative of Fig. 9a, i.e. modal share is closely related to SEL; third, car ownership (Fig. 9c) has a 0.72 correlation with SEL (mostly explained by income as seen in Fig. 2), with the largest figures located on the borders of the city such that this variable is fully explained by SEL and distance to the center.

SEL and distance to the center summarize quite well all the elements that seem to influence the indices built to capture the impact of infrastructure in Santiago, and are nearly uncorrelated (0.02); we run linear regressions of each index on SEL and distance to the center (divided by their respective standard deviations to have them adimensional), including an interaction term that captures the variation of the effect of one variable over the corresponding index as the other variable grows. Table 2 contains the estimated coefficients.

As the attractiveness of mode i to travel to either the center ($j = C$) or all other zones ($j = MZ$) is inversely related with the values of the $\lambda_{i,j}$'s, the first two rows show that when traveling to any destination public transport serves better the wealthy zones and those that are far from the center, while the coefficients in the third and fourth rows indicate that the contrary happens with highways. In both cases ($P$and H) the direct effects soften as the other variable increases. If observed modal split at the zonal level is taken into account (final two rows), the results show that the zones that have been mostly favored by the construction of the highways are those that are at the same time wealthy and peripheral, which fits intuition as therein most people use a car and some of the highways connect specifically those places with the rest of the city. The change in the time-related car's attraction induced by the urban highways (ΔW) increases towards the poverty levels (decreases with SEL) and the peripheries.

For synthesis, highways have indeed favored affluent persons that live far from the center. Individuals with a low socio-economic index living far from the CBD cannot take advantage of the (potential) reduction in travel times due to the highways because most of them do not own a car. Finally, for those inhabitants of the peripheries of

Table 2
The role of socioeconomic level and location on the different indices.

Index\coeff	β_{SEL}	$\beta_{Distance\ Center}$	$\beta_{Distance\ Center \cdot SEL}$
$\lambda_{P,C}$	−0.061	−0.013*	0.0035
$\lambda_{P,MZ}$	−0.13	−0.15	0.031
$\lambda_{H,C}$	0.1	0.26	−0.051
$\lambda_{H,MZ}$	0.048	0.052	−0.015
ΔT	−0.33	−0.98	0.21
ΔW	−0.36	0.23	−0.067*

* Not significant at a 5% level.

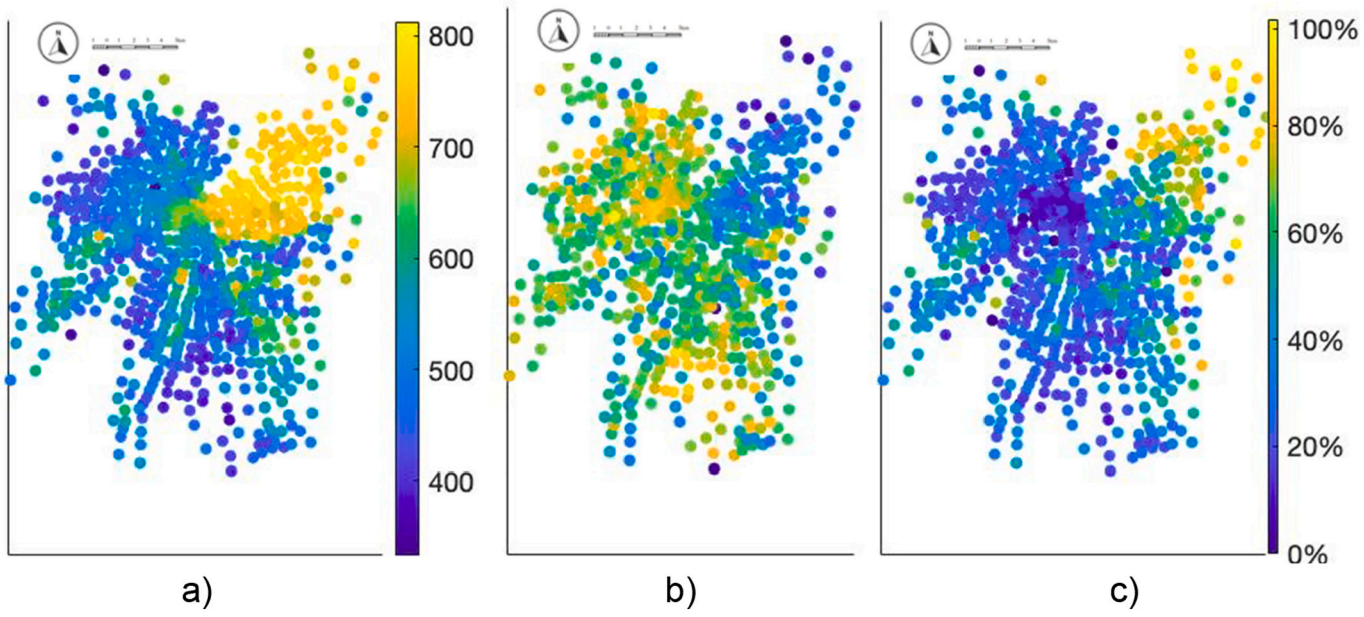

Fig. 9. Socio Economic Level (a), share of transit users (b), and car ownership (c). Sources: (a) and (c) IDE OCUC (2012); (b) SECTRA (2014).

Santiago that presently use public transportation the introduction of highways has translated into an increase in the perceived attractiveness of using cars. These results contribute to explain the tendency observed in Santiago, where the share of private transport trips increases while transit share decreases: those who live in the peripheries switch to a car as soon as they can. As new highways are constantly being built, the situation might worsen in the near future.

5. Synthesis and conclusions

In this paper, we have intensively used the tools provided by Google Maps (Google Maps API, GMA) to study the effects on mobility of urban highways built during the first decade of the XXI century in Santiago, Chile, something that has not yet been analyzed due to the lack of data. We introduced a novel use of GMA by calculating travel times not only by public transport and car but also for car trips assuming the highways were not built (unavailable); this required more than 2 million requests to GMA. We constructed travel time matrices and defined and employed trip time-related indices. The way these matrices were conceived and built is one contribution of this paper: they contain information at a very disaggregated level, they were obtained using these online tools, and they may be used for different purposes.

We first studied the ratios between the time needed using public transport or highways, and the time needed using car without highways (streets) calculated for each OD pair, which helps revealing which parts of the city should be prioritized for future public interventions; in particular, as designing better transit lines for a zone can be done in a relatively short period, this tool shows where some of those new lines should be allocated. Considering travel to all destinations, we concluded that transit offers better service to the wealthy zones and to those users located in the peripheries (far from the center), and the contrary happens with highways; we showed later that in both cases the effect of socio-economic level and distance softens as the other variable increases. We then compared for each zone the total time spent by travelers that depart from every origin if all car-users avoided highways, against the same scheme but considering the highways. The distribution of these indices show that the time-advantages provided by the highways are concentrated in only a few zones.

All indices were analyzed as functions of a socio-economic indicator by zone (correlated with Income and car ownership) and distance to the center (uncorrelated with income), revealing that wealthier households located far from the center are the most favored by the highways, which is explained by their more intense usage of the car. On the other hand, the time-related advantage to switch from transit to car, measured as the potential time saved by all the transit users, increases in most zones within the city due to the highways, but this increase is more relevant in the peripheries. These results help to explain the present dynamics in Santiago, where the share of auto trips is permanently increasing. These empirical conclusions are the other important contribution of the paper.

The approach presented and applied here was intended as a feasible proxy for a comparison of travel times before and after the highway construction, for which there is no data; in spite of the limitations, similar tools could be developed for studying changes across different periods of a day. They can also be used to evaluate some public policies that are supposed to affect travel times: how do these indices evolve over time? As presented here, this approach does not touch on important local design issues such as pedestrian routes, urban segregation, and/or community severance. These are questions for future research. Finally, Google Maps API is a paid and very time-consuming device but permits the analysis of interesting (non-existent) conditions as shown here, while other tools such as OTP are open source but limited to what can be observed. So developing flexible open-access tools that can be freely used is also another relevant future task that will permit good policy analysis based on very disaggregated information in space and time.

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Appendix A. Appendix. Comparison between GMA and ADATRAP estimates of transit total travel time

The available data from ADATRAP considers connections between transit stops whereas GMA connects centroids of the city zones, so walking times to access the transit network are quite different in both cases. In order to have a fair comparison between the times estimated by the two platforms, we computed new calculations using GMA, taking as origins and destinations the geographical coordinates of the stops for 85 trips from the most recent ADATRAP matrix (March 2020). On average, GMA predicts travel times that are 20% larger than ADATRAP, and the differences are more meaningful for shorter trips. An inspection analysis using the common version of Google Maps suggests that the main differences relate to small mismatches between the two platforms regarding the geographical coordinates of the bus stops, which implies that GMA is likely considering some extra walking time (note that GMA outputs total times only) to the same stops, or even computing routes that begin or end in a different nearby stop. The distribution of the results is detailed in Fig. A1. ADATRAP predicts shorter times for 80% of the trips.

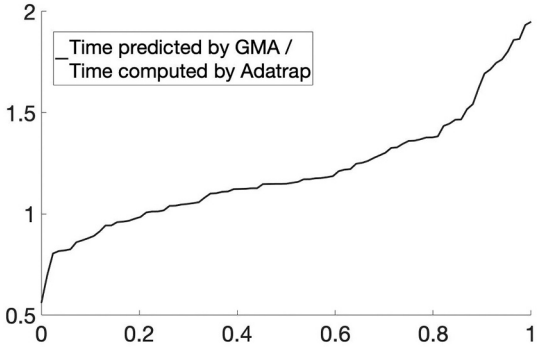

Fig. A1. Distribution of the ratio between times predicted by GMA and by ADATRAP.

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