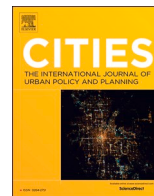

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Short run “rebound effect” of COVID on the transport carbon footprint

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ABSTRACT

The COVID-19 pandemic completely transformed the mobility of cities. The restrictions on movement led to “empty cities” throughout the world, with some environmental effects in terms of clean air and the reduction of CO₂ emissions. This research considers how COVID-19 mobility restrictions have affected the carbon footprint of four medium-sized Chilean cities (Coronel, Temuco, Valdivia, and Osorno) that have environmental problems and are highly dependent on motorized systems. The study uses data from 2400 household surveys at three distinct times: pre-pandemic - T0 (winter 2019), the time of implementation of restrictive mobility policies to contain the pandemic - T1 (winter 2020), and six months later when those restrictions were gradually lifted - T2 (summer 2021). The analysis suggests that CO₂ emissions actually went up, declining in the winter 2020, but then increasing with the greater use of cars in the summer 2021 due to the temporary effects of commuting to work, ultimately reaching levels higher than the pre-pandemic values, known as the “rebound effect.”

1. Introduction

In March 2020, mobility patterns in cities were transformed completely due to COVID-19. The restrictions on movement led to “empty cities” throughout the world. Some early research has focused on COVID-19's impact on the reduction of mobility in cities (Abu-Rayash & Dincer, 2020; Fatmi, 2020; Malik et al., 2020), with COVID-19 movement restrictions leading to an increase in telecommuting and online classes for students. At present, numerous research studies have addressed the impact of COVID-19 and confinement policies on CO₂ emissions (see Annex Table 1). Using data from 69 countries, 50 US states, and 30 Chinese provinces that together account for 97 % of the planet's CO₂ emissions, Le Quéré et al. (2020) estimate that the reduction in CO₂ emissions due to COVID-19 on a planetary scale during the first wave was 17 %. Pomponi et al. (2021) estimate a more limited reduction when comparing calendar years and using a sample of 129 countries. Their results indicate a reduction of between 1 and 3 %. Andreoni (2021) estimates that the reduction in emissions in Europe

between January and June 2020 was 12.1 %, with Spain, Italy, and France experiencing the greatest drop. Shulte-Fischedick et al. (2021) calculate that the drop in emissions associated with mobility in Europe reach 7.1 %. Other works also reflect a significant reduction in CO₂ emissions in countries such as India, France (Aruga et al., 2021), and Italy (Rugani and Caro, 2020).

Various studies have tried to measure the incidence of COVID-19 on CO₂ emissions at an urban scale. More than 55 % of the world's population lives in cities, dense areas that are conducive to the spread of the virus. The CO₂ emissions most affected by confinement policies are those of mobility. Marinello et al. (2021) calculate that during the confinement in Reggio Emilia (Italy), CO₂ emissions fell by 22 %. In San Francisco, Turner et al. (2020) estimate that 48 % of the drop in CO₂ emissions is also explained by the mobility restrictions. Velasco (2021) captures a reduction in the level of emissions at the neighborhood scale (Telok Kurau, Singapore) that reach 41 %. Du et al. (2021) show how confinement policies have significantly affected road traffic, congestion, and CO₂ emissions in the Washington DC-Baltimore area, Los Angeles

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(US), and Doha (Qatar).

The methodologies used to estimate the reduction in CO₂ levels associated with mobility in times of confinement can be divided into two categories. The first uses local data on mobility, traffic, and congestion to estimate CO₂ emissions (Du et al., 2021; Gensheimer et al., 2021; Velasco, 2021). The second method uses in situ gas concentration data (Lamprecht et al., 2021; Nicolini et al., 2022; Grivas et al., 2020; Venturi et al., 2021; Turner et al., 2020; Yadav et al., 2021). This second methodology cannot distinguish between CO₂ emissions associated with mobility and other sources of emissions, so they are usually based on prior information related to the distribution of CO₂ by sector (mobility, heating, industrial production, etc.). Another problem with this method is that local concentrations of CO₂ on an urban scale are difficult to measure given the tendency of CO₂ to rise towards the highest layers of the atmosphere following random patterns linked to climate conditions such as air temperature or the direction and strength of prevailing winds (Venturi et al., 2021; Gualtieri et al., 2021). Although local concentrations and fluxes of CO₂ are difficult to measure, the use of state-of-the-art technology, such as the cavity ring-down spectrometer (CRDS) (Grivas et al., 2020), three-dimensional nanometer open path infrared gas analyzer (Venturi et al., 2021), and other similar methods in numerous atmospheric stations and laboratories yield values similar to those obtained by indirect methods.

This research study considers how mobility restrictions due to COVID-19 have affected the carbon footprint of households in four medium-sized Chilean cities (Coronel, Temuco, Valdivia and Osorno) that have environmental problems and are highly dependent on motorized systems (Rojas et al., 2016). Using questionnaires distributed among 2400 families, data on mobility patterns for work and studies were obtained for each family member. This includes information on the decision to travel, telecommuting, distances traveled, and the modes of transport used. With these data, the carbon footprint is calculated for each family member by multiplying the distance traveled in each mode of transport by an emission factor that converts each kilometer traveled into kg of CO₂ equivalent. The surveys collect information from three periods: pre-pandemic - T0 (winter 2019), the time of implementation of restrictive mobility policies to contain the pandemic - T1 (winter 2020), and six months later when these restrictions were gradually lifted - T2 (summer 2021).

With the arrival of COVID-19 and the implementation of restrictive mobility policies, many cities in the world witnessed empty streets and clear blue skies for the first time in a while. One of the most obvious advantages of forced telecommuting was improved air quality and lower CO₂ emissions. However, this expectation of a reduction in emissions associated with mobility should be taken with caution, since COVID-19 has significantly increased the percentage of trips made by car. Traveling by car minimizes the chances of COVID-19 infection during the commute. The drop in the carbon footprint due to the reduction in the number of work commutes may actually be less than the increase in the carbon footprint due to greater car usage, such that emissions would first decrease, but then increase to levels higher than those seen in the pre-pandemic period. We call this the “rebound effect.” This research study aims to determine which of the two opposing forces (telecommuting/car use) tends to prevail.

The four cities studied are among the most air polluted in Chile, due simultaneously to industrial activities, motor vehicles, heating systems, and electricity generation (Rojas et al., 2022). It is important to note that air pollution is highly correlated with greenhouse gas (GHG) emissions, despite being two radically different gases. For example, motor vehicle combustion generates carbon monoxide (CO) and carbon dioxide (CO₂). The latter is a colorless and odorless greenhouse gas that accumulates for centuries in the upper layers of the atmosphere, while the former is a gas that is harmful to health and dissipates with normal atmospheric activity. They are both forms of waste generated from the same activity, such that the degree of air pollution in a city is a good indicator of its CO₂ emissions.

In general, given the global context of reduction in CO₂ emissions associated with COVID-19 mobility restrictions, the carbon footprint of residential mobility patterns is associated with a greater incidence of telecommuting, i.e., around 50 % of the Canadian population is estimated to be working from home (Leger, 2020). However, these Chilean cities have been selected for three reasons. First, they are among the most air polluted in Chile (Rojas et al., 2022). Second, they are traditionally associated with a number of industrial sectors and regional universities, which implies a reduction in travel for study purposes. Third, they are highly dependent on private and public transport (Rojas et al., 2016).

One of the novel aspects of this study is the selection of cities. The cities chosen for this case study are: a) medium-sized, b) Latin American, and c) located in the southern hemisphere. The enormous size of megacities such as Mexico, Sao Paulo, Rio de Janeiro, Santiago, or Buenos Aires has attracted the interest of institutions and academics. There is abundant literature on Latin American megacities. However, it is the medium-sized and small ones that are expected to grow the most in the coming decades (Álvarez De la Torre, 2011; Montero et al., 2017; Da Cunha & Vignoli, 2009). The study of the dynamics of small- and medium-sized cities is essential to contextualize the transformation of regional and national urban systems. On the other hand, it is interesting to study the experience of cities in countries in the southern hemisphere, given the seasonal nature of the pandemic.

Finally, it is important to observe Chilean cities since the increase in motorized transport and poor quality of public transport in medium-sized cities could generate worse urban development conditions and exacerbate social inequality in access to transport. The pandemic is also an opportunity to reorganize transport systems in order to make them more sustainable. Muñoz (2020) proposes that Chilean cities rethink the spatial distribution of activities, improving the proximity of services and promoting active mobility modes (i.e. walking and bicycles). Changes in daily mobility habits could imply declines in gasoline/diesel fuel consumption and GHG emissions with greater expected positive effects on the environment.

2. Materials and methods

2.1. Case study

The study aims to assess the carbon footprint of mobility patterns in four medium-sized cities in south-central Chile (Fig. 1): Coronel, Temuco, Valdivia, and Osorno. These cities are all experiencing episodes of severe air pollution. Indeed, the four cities present annual average concentrations of breathable and fine particulate matter (PM₁₀ and PM_{2.5}, respectively) regularly exceeding the World Health Organization guidelines (Huneus et al., 2020; Jorquera et al., 2018). In 2020, according to data from Blommers Green and the NGO OpenAQ, Temuco was declared the most air polluted city in the world. The cities under study are located in the south-central zone of Chile. Coronel, in the Biobío Region, is the least populated city in the study, with 116,262 inhabitants. It is functionally integrated within the metropolitan area of Concepción, along with the neighboring cities of San Pedro de la Paz and Lota (Rojas et al., 2009). The city of Temuco, which is the most populated of the four, with 342,488 inhabitants, is a conurbation between the municipalities of Temuco and Padre las Casas and acts as a hub for work and study in the Araucanía Region (Salazar et al., 2017). The cities of Osorno and Valdivia present similar demographics, bringing together other smaller urban settlements in the Los Lagos and Los Ríos Regions, respectively.

The effects of the COVID-19 pandemic have implied periods of mobility restriction according to contagion rates. The four cities have seen an increase in confirmed cases, with differentiated peak and stabilization periods. The peak cases were seen from mid-June to October 2020. This increase was accompanied by the application of health measures, including restricted circulation for the four cities under study



Fig. 1. Location of case studies.

starting in September. All four cities were in lockdown during October and half of November 2020. It should be noted that the first round of surveys was applied during this period. During the summer 2021, there was a sharp increase in the number of cases per 100,000 inhabitants, particularly between January and February 2021, at which time the four cities were once again subject to total lockdown. In parallel, the second round of surveys was applied during this time. It must also be noted that during January and February 2021, residents had the possibility of requesting a vacation permit to travel to and from any municipality that was not in lockdown, and this measure led to a more dynamic inter-regional mobility in across the country.

2.2. Survey data

The assessment of the carbon footprint of household mobility was performed by processing surveys on mobility patterns and multiplying monetary units of consumption and distances by CO₂ equivalent emissions factors. The Carbon Footprint Survey conducted during the winter of 2020 (T1) and the summer of 2021 (T2) is a longitudinal survey that

seeks to monitor the same cohort and compare consumption patterns in the context of the pandemic between the winter of 2020 and the summer of 2021, as well as to inquire about prior situations in the winter of 2019 (T0). The survey was inspired by a previous study in the city of Concepción reported in [Muñiz and Rojas \(2019\)](#).

The survey was fielded by IPSOS to its nationally representative probability-based sample of Chilean households in the four cities of study, using a computer-assisted telephone interviewing (CATI) system. Panel recruitment used simple random selection of phone number and residential addresses within each of the city under study. Then, an equal sample of 300 households was selected in each city for comparative purposes. As the total sample over population yields a 2.8 % sampling error and a 95 % confidence level, the sample is found sufficient to provide a clear representation of the transport carbon footprint of households. Although we decided not to use stratified sampling, participant provided personal data, such as their highest level of education and the level of their current occupation based on the country's stratification categories, for weighting and to populate socio-economic level variables included with survey data. Two rounds of surveys were

fielded, one before the pandemic (T0-winter 2019) and the other one during the pandemic (T1-winter 2020, and T2-summer 2021) to the same sample of 1200 households (i.e. 300 households in each of the four cities under study).

Regarding commuters' work activities, the survey asks about the highest education level of the survey taker and the current job or occupation of the head of household, based on the country's stratification categories: (1) Occasional or minor labor (cleaning, janitorial services, occasional domestic services, sporadic jobs, informal street attendants, begging); (2) Minor trade, unqualified labor, day labor, domestic service on contract; (3) Qualified labor, foreman, micro business owner (kiosk, taxi, small store, street vendor); (4) Medium- to low-level administrative employee, sales assistant, secretary, head of area. Specialized technician. Independent professional in technical careers (accountant, systems analyst, designer, musician). Elementary or secondary school teacher; (5) Mid-level executive (manager, assistant manager), CEO of small or medium-sized company. Independent professional in traditional careers (lawyer, doctor, architect, engineer, agricultural engineer); and (6) High-level executive (CEO) of a large company. Directors of large companies. Medium to large business owners. Independent professionals of high prestige.

Each fielding included questions targeted based on car dependence and obligatory mobility topics at different times (T), as in the following:

1. Car dependence
 - 1.1. Does the household own a car? (Yes/No)
 - 1.2. What is the fuel used to run the car? (Gasoline, Diesel, Gas and other)
 - 1.3. Did someone in the household buy a car since the start of the pandemic? (Yes/No)
 - 1.4. What was the car fuel expenditure in the last month?
2. Obligatory mobility
 - 2.1. How many people in the household worked or studied away from home last month? (N° Work/N° Study) (each person separately to respond to next questions)
 - 2.2. In which area or locality did they go to work/study? (Select area)
 - 2.3. What is the distance between the home and the place of work/study? (distance in kilometers)
 - 2.4. Going to the work place: Which main mode of transport did they use? (Select modes)
 - 2.5. Going to the study place: Which main mode of transport did they use? (Select modes)
 - 2.6. Did they have the possibility to work/study from home?(Yes/No)

2.3. Calculation of the carbon footprint

The *Carbon Footprint* is an indicator of the global environmental impact made by humans on the climate, which counts the greenhouse gases associated with the consumption of goods or services. It is an indicator oriented towards consumption (IPCC, 2014), which aims to correct the low *Direct CO₂ Emissions* of rich countries due to their ability to displace polluting activities outside their borders. The method adopted consists of assigning to the final consumer the total direct and indirect emissions originated to satisfy their consumption patterns. Another popular indicator of environmental impact aimed at consumption is the *Ecological Footprint* of Wackernagel and Rees (1998). An interesting aspect of the *Carbon Footprint* indicator, especially for the case at hand, is that, unlike the *Direct CO₂ Emissions* indicator, the emissions associated with the electricity used by electric vehicles are not assigned to the power plant that generates said electricity, but to the place of consumption: use of electric-powered public transport. Regarding internal combustion vehicles, there is no difference between *Direct CO₂ Emissions* and *Carbon Footprint* since the place of production of emissions and mobility consumption is the same.

Households were asked about the types of transportation they use for

work and study purposes, as well as their start and end points. Distance traveled was calculated using the Network Distance function of ArcMap software, which uses a network of graphs to calculate the distance between a given origin and destination. The IPCC database was used to indicate emissions factors for greenhouse gases produced from the combustion of each type of fuel. The estimated emissions factor considers the amount of CO₂, as well as the CO₂ equivalents of CH₄ and N₂O emitted during the combustion of each type of fuel.

The emissions factors shown in Table 1 were applied according to each of the transportation modes and/or combinations taken by users. While the survey asked about the type of fuel used in private transport (gasoline, diesel, gas, and other), where gas is not used (0 %) and others represent an average of less than 5 % of vehicles. In the case of other types of transportation, the most used fuel (gasoline and diesel) in medium-sized cities was considered according to information from the Chilean Ministry of Transport and Telecommunications. Electromobility is not yet present in the cities in our case studies, only in the capital city of Santiago de Chile, which has electric taxis and buses in the public transport network.

A high percentage of commutes used more than one type of transport, therefore mixed emissions factors were calculated, considering the average occupation of each type of transport. In concrete terms, 84 mixed emissions factors were calculated (Annex Table 2). It was surprising to find such a high number of combinations used by commuters, reflecting an extremely flexible use of the modes of transport available to students and workers, depending on their location with respect to the school/university or workplace, as well as other factors such as income or car ownership.

The mixed emissions factors were multiplied by the fuel consumption corresponding to the commuting distance declared by each *i* household member, for work or study purposes. This multiplication yields the carbon footprint (CF) expressed in kilograms of CO₂ equivalent (kg CO₂-eq).

$$CF_i = \text{Commuting distance}_i * \text{Conversion factor } z_i \quad (1)$$

where $z = (1, \dots, 84)$ is the conversion factor corresponding to the commuting mode combination employed (Annex Table 2).

Then, the carbon footprints for each of the *i* household member are added up to obtain the total carbon footprint for each of the *j* surveyed household (Eq. (2)).

$$\text{Household } CF_j = \sum_{i=1}^n CF_i \quad (2)$$

where n is the number of members constituting each *j* household.

Finally, the average household carbon footprint according to each *k* city is calculated using the following Eq. (3).

$$\overline{\text{Household } CF_k} = \frac{\sum_{j=1}^m \text{Household } CF_j}{m} \quad (3)$$

where m is the number of surveyed households in each *k* city.

Table 1
Emissions factors by transportation method.

Main transportation methods	Emissions factors (kg of CO ₂ -eq/km)	
	Gasoline	Diesel
Walking/Bicycle/Work from home	0.000	NA
Car	0.192	0.159
Share Taxi	0.058	NA
Microbus	0.058	NA
Taxi	0.192	NA
Train	0.020	NA
Other	0.058	NA

Source: IPCC (2014).

This calculation is performed for: a) mobility for work and study purposes; and b) before the pandemic (T0) and during the pandemic (T1 and T2). The results are presented on a monthly basis.

3. Results

The most remarkable result of this research is the detection of a rebound effect in the carbon footprint of work-related mobility as a result of COVID-19 and mobility restriction measures to curb the pandemic. Anti-COVID-19 policies reduced worker mobility, which resulted in a significant drop in the carbon footprint. However, six months later, mobility restrictions were relaxed, and the carbon footprint of work-related mobility exceeded pre-pandemic levels (Table 2).

In terms of work commutes, these cities are not highly associated with service jobs, innovation enterprises, or telecommuting, but rather activities tied to the primary sector, implying administrative or technical expertise that require in-person work (industries), where 40 % of workers are in occupation category 4. The lockdown never affected more than 50 % of workers. In this context, the highest reduction in emissions was seen in Coronel (45 %), followed by Valdivia with 34 %, Temuco with 31 %, and significantly lower in Osorno with a reduction of only 16 %. In the summer 2021 (T2), emissions begin to recover and even exceed pre-pandemic figures. The greatest rebound effect occurs in Osorno, where the carbon footprint in T2 more than doubles the pre-pandemic value. This trend does not occur in travel for study purposes (Table 2, Fig. 2).

3.1. How did the rebound effect occur?

In the cities surveyed before the pandemic (T0), 44 % of households had two members working outside the home, and 38 % had only one. In the winter 2020 (T1), 46 % of the 1200 households had one person working outside the home, and 19 % had two. In the summer (T2), 23 % of households had two member commuting to work, while 49 % had just one member (Annex Table 3). Before the pandemic (T0), 1880 people from the 1200 households commuted to work, versus only 1129 people during the winter 2020 (T1), representing a 36 % decrease. Winter 2020 (T1) data show a drastic reduction compared to T0, since the country was undergoing its first wave of the pandemic, which brought about stricter and longer measures such as lockdown, and many workers began to work from home. In the summer 2021 (T2), when there was greater flexibility, there were 1244 people commuting to work, representing a reduction of 33 % in comparison to pre-pandemic figs. (T0) and a slight increase over the winter data (T1) (Table 3).

These data indicate that the rebound effect in the mobility footprint is not due to the fact that there were fewer workers telecommuting in T2 than before the pandemic. A certain degree of telecommuting seems to have consolidated for some professions, and it is unlikely to disappear

Table 2

Monthly carbon footprint (kgCO₂-eq/home) corresponding to mobility (T0: Average month before the pandemic, winter 2019; T1: average winter month 2020; T2: average summer month 2021).

City	Work			Study		
	T0	T1 (change over T0)	T2 (change over T0)	T0	T1 (change over T0)	T2 (change over T0)
Coronel	173	95 (−45 %)	176 (+2 %)	37	0 (−100 %)	6 (−84 %)
Temuco	86	59 (−31 %)	108 (+26 %)	40	4 (−90 %)	2 (−94 %)
Valdivia	105	69 (−34 %)	170 (+62 %)	50	4 (−91 %)	30 (−40 %)
Osorno	82	69 (−16 %)	183 (+122 %)	67	0 (−100 %)	16 (−76 %)
Total	446	293 (−34 %)	637 (+43 %)	194	8 (−96 %)	55 (−72 %)

after the pandemic.

Data clearly indicate that the rebound effect is due to increased car use. Before the pandemic (T0), 55 % of trips to work were made by car. With the first mobility restrictions (T1), this percentage grew to 62 %, and six months later (T2), it grew to 64 % (see percentages and flows in Fig. 3). Public transportation by bus has been the most affected by the pandemic, considerably reducing its share in cities. This trend is fairly consistent with what has been reported in large cities across the world by press reports and research (The New York Times, 2021). Faced with the perception of a high probability of contagion in public transport, the population has responded by preferring private transport, making this a prophylactic trend to reduce the probability of contracting the coronavirus.

The commuting distances used to calculate the carbon footprints averaged 23 km for both purposes (Table 4). In the winter, work commutes dropped by an average of 13 km and recovered in the summer up to 24 km. Study-related commutes dropped considerably to 2 km, with a peak of 2.8 km.

Fig. 4 shows how, in the four cities, the percentage of car use in T2 exceeds the pre-pandemic values (T0) at the cost of a decrease in more sustainable transportation methods, such as bicycles, walking, or public transport.

For the average worker and student, Fig. 5 shows the evolution of the carbon footprint per capita between T0 and T2 for each mode of transport. If we look at work-related mobility, we see a rebound effect in the carbon footprint of private car travel, regardless of whether the car is gasoline- or diesel-powered. Beyond a doubt, these results demonstrate that the rebound effect is due to the increase in the percentage of trips made by car.

Results clearly show the existence of a rebound effect in the carbon footprint of work-related mobility. The existence of a possible rebound effect on the volume of emissions has also been suggested very recently by Li and Li (2021). In their study, they show how extreme events only reduce emissions in the short term. In the long term, emissions continue to grow once the extreme event ends, returning to a previous situation characterized by lower energy efficiency and lower energy prices. In the case of study-related mobility, it does not seem that there is a rebound effect since classes remained virtual at the time of the survey.

The results obtained are consistent with the hypothesis proposed in Li and Li (2021), but with significant differences. First, we capture a rebound effect, not in the long term, but in the short term. The lower emissions due to the reduction in the number of trips are quickly neutralized due to greater car use. There is no need to go long-term to see the rebound effect since this is already taking place. The long-term expectations are even worse in terms of an increase in the carbon footprint, since the fear of COVID-19 contagion and confined living conditions have led many families to leave the city and the public transport and move to nearby rural areas, a decision that takes more time than buying a car, for instance. This increasing suburbanization would further increase the volume of emissions, given the dependence on cars that living in rural areas would imply.

4. Discussion

4.1. Principal findings

The main result obtained in this study is the detection of a rebound effect in the carbon footprint associated with commuter mobility due to COVID-19 and the restrictive mobility measures adopted. With the first mobility restrictions, the carbon footprint was reduced, but in a few months, it began to grow and even exceed pre-pandemic levels. This result largely coincides with that obtained in Li and Li (2021) and Schulte-Fischer et al. (2021). Commuter mobility has been affected by the pandemic, and a review of recent empirical evidence on how mobility restrictions in cities have affected CO₂ emissions indicates that the impact has been strong. Grivas et al. (2020), Lamprecht et al. (2021),

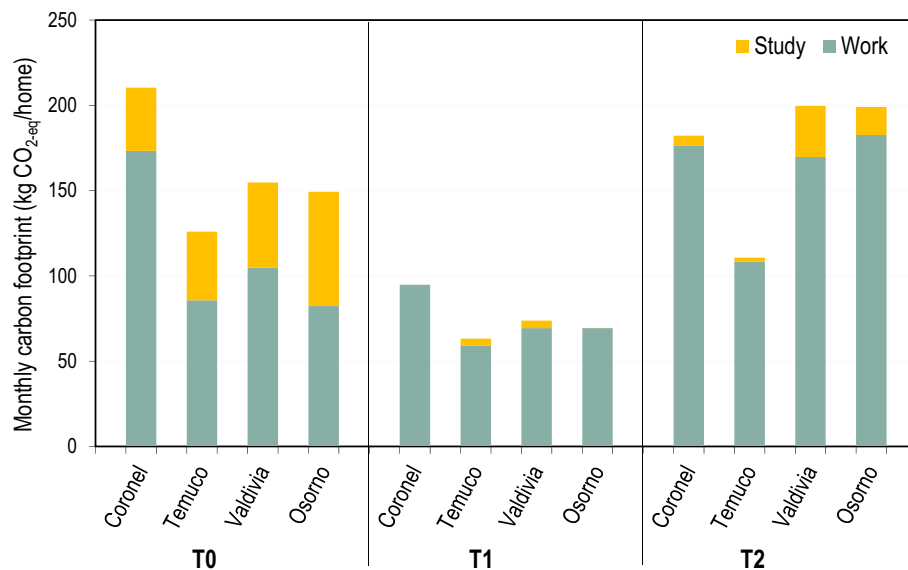


Fig. 2. Carbon footprint from work & study transportation (monthly average per home). Monthly carbon footprint corresponding to mobility (T0: Average month before the pandemic, winter 2019; T1: average winter month 2020; T2: average summer month 2021).

Table 3

Number of people working outside the home (T0: Average month before the pandemic, winter 2019; T1: average winter month 2020; T2: average summer month 2021).

City	T0	T1	T2
Coronel	463	280	328
Osorno	466	287	317
Temuco	476	281	296
Valdivia	475	281	303
Total	1880	1129	1244

Venturi et al. (2021), and Turner et al. (2020) estimated reductions of 58 %, 38 %, between 37 % and 43 % and 48 % respectively, while Yadav et al. (2021) detected drops of more than 30 %. The estimated drop in emissions strictly associated with mobility offers values between 7 and 12 % (Gensheimer et al. (2021), 41 % (Velasco, 2021), reaching nearly 90 % during the week in which a higher level of confinement is applied. Of course, the number of trips has been reduced (with an increase in telecommuting), but, and perhaps less obviously, car use has increased. Traveling by car avoids the possibility of contagion that occurs when using public transport. In terms of carbon footprint, the two elements act in opposition to each other. Telecommuting reduces the carbon footprint, while greater car use increases it. Our results indicate that the “telecommuting effect” is less than the “car use effect”, hence the rebound effect.

First, commuting mobility drops, which reduces the carbon footprint. But as the mobility restriction measures are relaxed and telecommuting decreases, the footprint increases due to greater car use, which goes from 55 % in pre-pandemic to 64 %. The increased car use is concerning because: a) it is the mode of transport with the largest associated footprint per km traveled; b) it is the only possible means of transport in many peri-urban areas, medium-sized cities being especially dependent on this mode of transport; and c) it entails a relevant cost (about USD100 per month) that is difficult to assume for the families most affected at work by COVID-19 and lower income groups in general. Regarding mobility for study purposes, a different pattern is seen. Mobility restrictions have been more demanding, and the footprint falls steadily during the pandemic period studied. Indeed, 97 % of students stayed at home during that period, demonstrating the effectiveness of the closure of educational centers nationwide.

In order to explain the differences in carbon footprint obtained by households between cities, it is important to delve deeper into urban form and modes of transport. It bears noting that the presence of the urban train favors the use of public transportation, as its share remains above 30 % in Coronel. In the case of Temuco, recent improvements in the public transport system also contributed to maintain a 30 % share. Such figures are a clear indication of a fairly good distribution of employment places and denser occupation of neighborhoods or compact city. From the urbanism theory, there is a consensus that “compact cities” or “dense cities” are more energy efficient and have a lower environmental impact, and therefore, a negative correlation with the carbon footprint (Muñoz et al., 2013). In fact, Coronel (55 inhabitant/ha) and Temuco (59 inhabitant/ha) are relatively denser than Valdivia (41 inhabitant/ha) and Osorno (40 inhabitant/ha), which explain why the rebound effects in the summer 2021 are smaller in Coronel (+2 %) and Temuco (+26 %) than in Valdivia (+62 %) and Osorno (+122 %).

Despite using a novel method to estimate the drop in CO₂ emissions due to confinement, our results are in the same order of magnitude as other works that pursue the same objective using other methods. The drop in emissions associated with home-to-work mobility during confinement is estimated between 16 % (Osorno) and 45 % (Coronel). The drop in CO₂ emissions due to reduced student mobility reached 100 % in some cases. Regarding the rebound effect, our work obtains results in line with those obtained in Schulte-Fischer et al. (2021), although the rebound effect that we have estimated is significantly greater.

We are not aware of any previous study that has estimated the drop in CO₂ emissions due to confinement policies through a representative survey of households that provides information on their mobility patterns before, during, and after confinement. This methodology, when used in other studies (Høyer & Holden, 2003; Muñoz et al., 2013; Muñoz et al., 2016; Muñoz & Rojas, 2019), has not been employed to study the effect of COVID-19 on household mobility. Its main advantage here is that we can be precise about the drop in CO₂ emissions strictly associated with obligatory mobility (for work and study purposes). Another advantage is that we can cross-reference information on mobility with household characteristics (number of members, family structure, car ownership, distance to the city center, distance to the place of work/study, etc.), which allows for the detection of certain patterns.

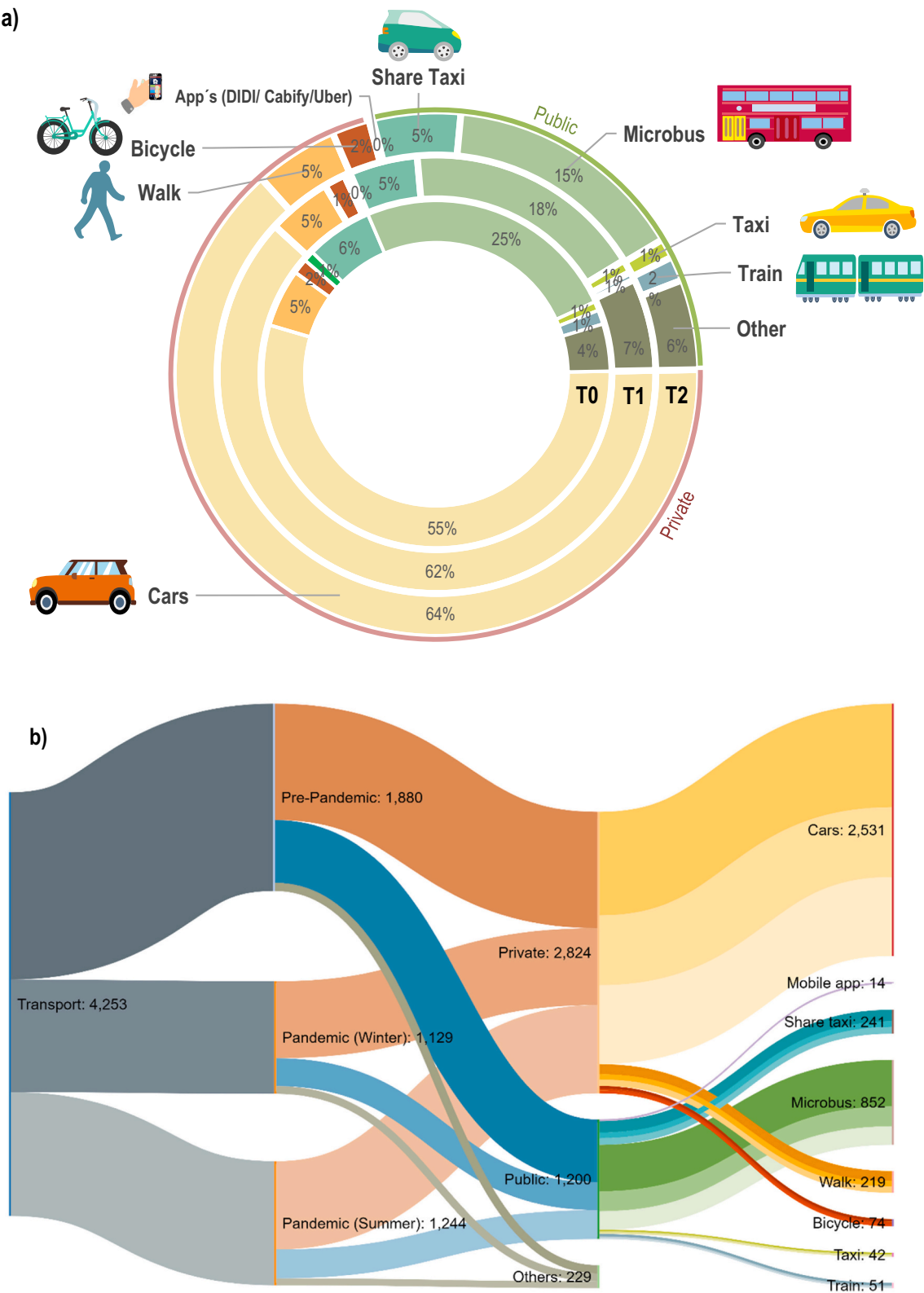


Fig. 3. Transportation modes used in the three periods evaluated.
a) Transportation Modes in %. This shows how the percentage of car use in T2 exceeds the pre-pandemic values (T0) at the cost of a decrease in more sustainable transportation methods, such as bicycles, walking, or public transport. b) Flows of Transportation Modes. This shows the flows of workers by transport mode, where cars increase in T2 (Summer).

Table 4
Average distance traveled (km).

	School			Work		
	T0	T1	T2	T0	T1	T2
All	23.46	2.16	2.81	23.73	13.68	23.99
Only commuters	23.46	55.17	48.17	23.73	22.62	34.39

4.2. Limitations

The main limitation of the method introduced here is that it does not factor in traffic congestion. Indeed, in order to calculate CO₂ emissions, we solely use the distance traveled and the emission factor associated to the mode/combination of transport used. The reason for not including the congestion factor in the calculation is the lack of information on traffic congestion in the medium-sized cities under study. Although traffic congestion levels in these medium-sized cities may be similar to those of large cities in some sectors, valid information is only available for large Latin American metropolises (Banco Iberoamericano de Desarrollo, 2021). For instance, unlike in the capital city of Santiago,

there is no real time traffic data collection of the public transport in the cities under study (Ministry of Transport – https://datos.gob.cl/organizacion/subsecretaria_de_transporte). Various studies confirm that incorporating information on traffic congestion levels significantly increases emissions per kilometer traveled (Du et al., 2021; Gensheimer et al., 2021; Velasco, 2021). It is therefore important to note that we systematically underestimate the real drop in CO₂ emissions.

4.3. Policy implications

As part of its pledge to reach carbon neutrality by 2050, Chile has established an electromobility strategy for its transport sector. Thus far, the focus has been on increasing the fleet of electric cars, taxis, and city buses and the presence of public charging stations, but most of the efforts were done in the capital city of Santiago, while cities in regions have received much less attention. For instance, as of October 2021, more than 92 % of the total fleet of public electric buses are circulating in Santiago metropolitan and 65 % of the total number of public charging stations have been installed in the capital (Gobierno de Chile, 2021). By the end of 2022, the Ministry of Transport expects the

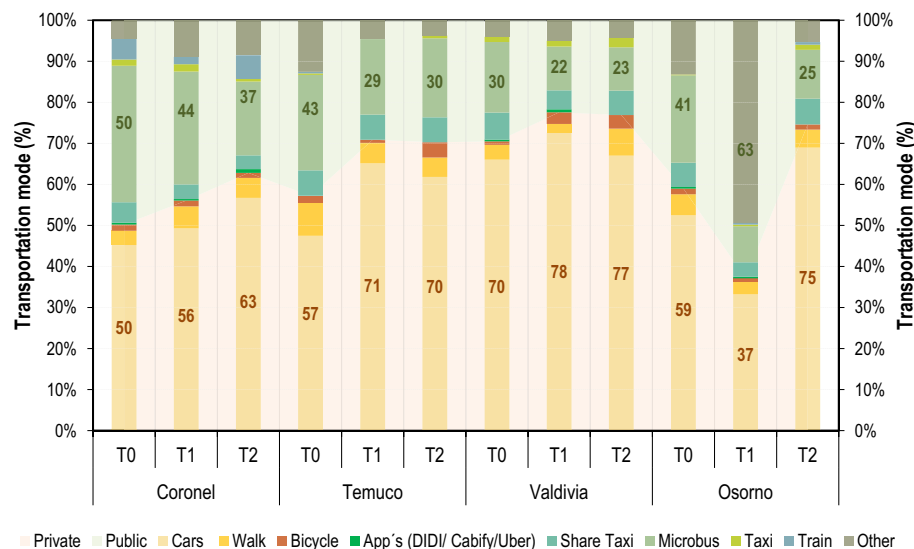


Fig. 4. Transportation modes used by city.

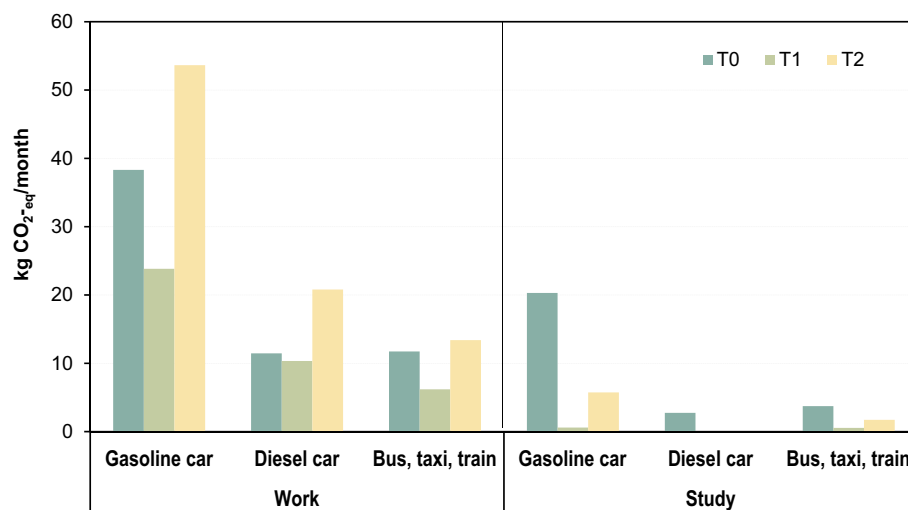


Fig. 5. Per Capita carbon footprint from transportation. Carbon footprint for mobility (T1: average winter month 2020, T2: average summer month 2021) according to the type of transport used.

addition of 1000 new electric buses in the public transport network of Santiago, 170 in Arica, 100 in Copiapó, 40 in Antofagasta, 30 in Valparaíso, 25 in Concepción, 20 in La Serena-Coquimbo, 20 in Rancagua-Machali, 11 in Talca, 10 in Temuco and 10 in Puerto Montt (Ministry of Transport, 2022). This is a typical example of the large disparity that exists between Santiago and the rest of the country, since the Chilean state features a highly centralized organization of economic and political life in the capital city of Santiago (Atienza et al., 2021). This disparity has historically affected the development of regions in comparison with the capital, and that is why it is important to include medium-sized cities in studies, in order to collect information data, diagnose their needs and increase their visibility at the national level.

In this context, it is important to plan post-pandemic medium-sized cities, with a series of public policies to keep the transport and vehicular congestion situation from having a greater impact than before the pandemic in those regions. For this reason, the research team has met with local and regional policy makers in a collaborative workshop to elaborate 21 public policy proposals aimed at reducing CO₂ emissions in the medium-sized cities under study (Rojas et al., 2021). Specifically, the proposals related to transport and mobility are: (1) Cycle-inclusion and non-motorized program; (2) Clean transport enhancement fund; (3) Better connectivity and investment in cycle networks; (4) Strategy for the use of electric vehicles, including two-wheeled vehicles; and (5) Tax exemptions for electric and hydrogen-powered cars. The local authorities validated these public policy proposals on the basis of the results obtained for their respective city in the study. Since different carbon footprint results between cities were obtained, the order of priority of these measures may be different depending on the city particular characteristics and needs.

We are convinced that the Chilean cities studied urgently require reactivation of their public transport system and the prioritization of routes for more sustainable modes such as walking, cycling, and electric vehicles, including taxis, e-bikes, and public transport that is less dependent on fossil fuels. Otherwise, there is a risk of accelerated motorization, whose effect on increased emissions will not be temporary but long-term and affect the country's climate goals.

5. Conclusion

The positive environmental effects of COVID-19 restrictions have not shown up as expected. The drop in the carbon footprint due to the reduction in the number of work and study commutes is less than the increase in the footprint due to greater car use in summer, such that emissions first decreased, but then increased up to levels higher than pre-pandemic values, generating a clear rebound effect.

There is empirical evidence of a rebound effect in different countries

and cities, but the rebound effect detected in this study is significantly more pronounced. The main explanation would be that, during the pandemic, these cities have seen a greater use of individually-owned cars over public transport, as a prophylactic strategy against the spread of the COVID-19 virus. The question that arises is whether this result can be extended to other cities or if it is unique to the area. If the changes detected in our study are reflected in other countries and cities, COVID-19 could lead to a higher level of CO₂ emissions associated with household mobility in the medium and long term.

When the cities experienced total restriction of movement, they failed to fully take advantage of the chance to plan for more sustainable cities and non-motorized transport methods, also supported by environmentally positive synergies between urban development, air quality, and CO₂ emissions. On the contrary, the 2400 household surveys showed that in the summer 2021, when cities began to recover activity, the rebound effect was greater due to the larger dependence on cars for commuting to work and the poor quality of public transportation, thus increasing the carbon footprint of households. This is particularly concerning since cities have not yet seen a reactivation of student mobility. Therefore, the post-pandemic scenario is projected to have a greater environmental impact despite the country's decarbonization efforts.

CRediT authorship contribution statement

Carolina Rojas: Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Supervision, Project administration, Funding acquisition. **Iván Muñoz:** Conceptualization, Methodology, Validation, Formal analysis, Investigation, Resources, Writing – original draft, Writing – review & editing, Supervision. **Marc Quintana:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft. **Francois Simon:** Methodology, Validation, Formal analysis, Investigation, Data curation, Writing – original draft. **Bryan Castillo:** Methodology, Software. **Helen de la Fuente:** Methodology, Software. **Joaquín Rivera:** Methodology, Software. **Michael Widener:** Investigation, Supervision.

Declaration of competing interest

This study does not involve any conflict of interests.

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Appendix A

Annex Table 1

Selection of recent studies on CO₂ reduction in cities during mobility restrictions period.

	Neighborhood/city/ Region	Period	Raw data	Data Transformation	Mobility and/ or other CO ₂ sources	CO ₂ reduction due to mobility restrictions	Rebound effect
Gensheimer et al. (2021)	Munich Cape Town Oslo	March 13–March 26, 2020 Compared with previous years	Apple Inc. Google LLC, Local government traffic data		Mobility	7–12 %	No
Velasco (2021)	San Francisco Singapore (Telok Kurau neighborhood)	2020 vs 2019	Apple Inc. Google LLC, Local government traffic data	Eddy Covariance	Mobility and other sources	41 % (mobility)	Yes
Lamprecht et al. (2021)	Tyrol (Austria)	March 11, April 9, 2019 March 16, May 1, 2020	Innsbruck Atmospheric Observatory (IAO)	Eddy Covariance + Real data on traffic and other energy uses	Mobility and other sources	38 %	No

(continued on next page)

Annex Table 1 (continued)

	Neighborhood/city/ Region	Period	Raw data	Data Transformation	Mobility and/ or other CO ₂ sources	CO ₂ reduction due to mobility restrictions	Rebound effect
Nicolini et al. (2022)	Innsbruck Vienna Basel Berlin Helsinki Heraklion Florence Pesaro Sassari Amsterdam London	Compared with previous years Oct 2020 Feb 5, May 6, 2020 Compared with previous years	Several Institutes CO ₂ local detection		Mobility and other sources	CO ₂ reduction in all cities	No
Grivas et al. (2020)	Athens	March 23, May 10, 2020 compared with previous years	Picarro2401 cavity ring- down spectrometer (CRDS)		Mobility and other sources	Total CO ₂ reduction at city level 58 %	Yes
Venturi et al. (2021)	Florence	Feb 17, June 4, 2020 Compares with previous years	Three dimensional sonic nanometer and open path infrared gas analyzer	Eddy Covariance +local data traffic	Mobility and other sources	Total CO ₂ reduction at city level 37–43 %	Yes
Turner et al. (2020)	San Francisco	Feb 2, May 14 Compared with previous years	Local network of CO ₂ observations	Bayesian inference to obtain hourly CO ₂ emissions	Mobility and other sources	Total CO ₂ reduction at city level 48 %	No
Yadav et al. (2021)	Los Angeles Washington DC/ Baltimore Metro Area	April 2020 Compared to 2018 and 2019 previous data	High accuracy measurement stations	Bayesian inference to obtain hourly CO ₂ emissions	Mobility and other sources	Total CO ₂ reduction at city level between 3 y 34 %	Yes
Du et al. (2021)	Los Angeles Doha	Feb 6, April 10 Compared with previous years	Traffic local data	Simulations traffic demand networks	Mobility	55 % reduction in traffic reduces CO ₂ emissions by 90 %	No

Annex Table 2

Average emissions factor for 84 combinations of modes of transport declared in the survey.

Type(s) of commuting mode combination	Emissions factors (kg CO ₂ -eq/km)	
	Gas	Diesel
Walking	0.000	NA
Walking, Transport App (DIDI/ Cabify/Uber)	0.096	NA
Walking, Collective Taxi	0.029	NA
Walking, Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.083	NA
Walking, Other	0.029	NA
Walking, Taxi	0.096	NA
Transport App (DIDI/ Cabify/Uber)	0.192	NA
Auto	0.192	0.159
Car, Walking	0.096	0.080
Car, Walking, Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.110	0.102
Car, Walking, Other	0.083	0.072
Car, Transport App (DIDI/ Cabify/Uber)	0.192	0.176
Car, Bicycle	0.096	0.080
Car, Bicycle, Walking	0.064	0.053
Car, Bicycle, Taxi	0.128	0.117
Car, Bicycle, Taxi, Transport App (DIDI/ Cabify/Uber)	0.144	0.136
Car, Collective Taxi	0.125	0.108
Car, Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.147	0.136
Car, Bus / Bus	0.125	0.109
Car, Bus / Bus, Walking	0.083	0.072
Car, Bus / Bus, Walking, Collective Taxi	0.077	0.069
Car, Bus / Bus, Transport App (DIDI/ Cabify/Uber)	0.147	0.136
Car, Bus / Bus, Bicycle	0.083	0.072
Car, Bus / Bus, Collective Taxi	0.103	0.092
Car, Bus / Bus, Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.125	0.117
Car, Bus / Bus, Other	0.103	0.092
Car, Bus / Bus, Taxi	0.147	0.136
Car, Bus / Bus, Taxi, Transport App (DIDI/ Cabify/Uber)	0.159	0.150
Car, Bus / Bus, Taxi, Collective Taxi	0.125	0.117
Car, Bus / Bus, Taxi, Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.138	0.132
Car, Bus / Bus, Train	0.090	0.079
Car, Other	0.125	0.108
Car, Taxi	0.192	0.176

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Annex Table 2 (continued)

Type(s) of commuting mode combination	Emissions factors (kg CO ₂ -eq/km)	
	Gas	Diesel
Car, Taxi, Collective Taxi	0.147	0.136
Car, Train	0.106	0.090
Car, Train, Collective Taxi	0.090	0.079
Bicycle	0.000	NA
Bicycle, Walking	0.000	NA
Bicycle, Collective Taxi	0.029	NA
Bicycle, Other	0.029	NA
Bicycle, Taxi, Collective Taxi	0.083	NA
Collective Taxi	0.058	NA
Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.125	NA
Collective Taxi, Other	0.058	NA
Bus / Bus	0.058	NA
Bus / Bus, Walking	0.029	NA
Bus / Bus, Walking, Transport App (DIDI/ Cabify/Uber)	0.083	NA
Bus / Bus, Walking, Collective Taxi	0.039	NA
Bus / Bus, Walking, Taxi	0.083	NA
Bus / Bus, Walking, Taxi, Collective Taxi	0.077	NA
Bus / Bus, Transport App (DIDI/ Cabify/Uber)	0.125	NA
Bus / Bus, Transport App (DIDI/ Cabify/Uber),Other	0.103	NA
Bus / Bus, Bicycle	0.029	NA
Bus / Bus, Bicycle, Walking	0.831	NA
Bus / Bus, Bicycle, Transport App (DIDI/ Cabify/Uber)	0.083	NA
Bus / Bus, Bicycle, Collective Taxi	0.039	NA
Bus / Bus, Bicycle, Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.083	NA
Bus / Bus, Collective Taxi	0.058	NA
Bus / Bus, Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.103	NA
Bus / Bus, Collective Taxi, Other	0.058	NA
Bus / Bus, Other	0.058	NA
Bus / Bus, Taxi	0.125	NA
Bus / Bus, Taxi, Transport App (DIDI/ Cabify/Uber)	0.147	NA
Bus / Bus, Taxi, Collective Taxi	0.103	NA
Bus / Bus, Taxi, Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.125	NA
Bus / Bus, Taxi, Collective Taxi, Other	0.091	NA
Bus / Bus, Train	0.039	NA
Bus / Bus, Train, Bicycle, Walking	0.020	NA
Bus / Bus, Train, Collective Taxi	0.045	NA
Bus / Bus, Train, Other	0.045	NA
Bus / Bus, Train, Taxi	0.090	NA
Bus / Bus, Train, Taxi, Collective Taxi	0.082	NA
None (Work from home)	0.000	NA
Other	0.058	NA
Taxi	0.192	NA
Taxi, Transport App (DIDI/ Cabify/Uber)	0.192	NA
Taxi, Collective Taxi	0.125	NA
Taxi, Collective Taxi, Transport App (DIDI/ Cabify/Uber)	0.147	NA
Train	0.020	NA
Train, Transport App (DIDI/ Cabify/Uber)	0.106	NA
Train, Collective Taxi	0.039	NA
Train, Other	0.039	NA
Train, Taxi	0.106	NA

Annex Table 3

Number of persons commuting to work per household.

Number of persons per household	Coronel (Bío-Bío)			Temuco / Padre Las Casas (La Araucanía)			Valdivia (Los Rios)			Osorno (Los Lagos)		
	T0	T1	T2	T0	T1	T2	T0	T1	T2	T0	T1	T2
0	8 %	29 %	20 %	8 %	34 %	31 %	9 %	33 %	25 %	8 %	31 %	26 %
1	43 %	51 %	55 %	36 %	42 %	45 %	36 %	44 %	51 %	39 %	46 %	46 %
2	39 %	16 %	23 %	47 %	20 %	21 %	44 %	20 %	22 %	44 %	19 %	26 %
3	7 %	3 %	3 %	9 %	3 %	3 %	9 %	2 %	2 %	7 %	3 %	2 %
4	3 %	0 %	0 %	1 %	1 %	1 %	1 %	0 %	0 %	2 %	1 %	0 %

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