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Cars in Latin America: An exploration of the urban landscape and street network correlates of motorization in 300 cities

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ABSTRACT

Car use creates significant externalities for urban residents worldwide. City characteristics such as the configuration of the urban landscape and street network likely influence the use and attractiveness of automobiles, especially in rapidly urbanizing areas such as Latin America. The understanding of factors associated with motorization can inform planning measures to reduce car usage, and to promote healthier, safer, and more sustainable urban lifestyles. We harmonized official passenger vehicle data from 300 cities with >100,000 inhabitants in Brazil, Chile, Colombia, and Mexico, and we calculated urban landscape metrics from satellite imagery and street network metrics from OpenStreetMaps. Analyzed cities had an average of 273.3 cars per 1,000 residents in 2015 and showed an average car rate increase of 30 % between 2010 and 2015. We used negative binomial regression to examine the association between car rates and urban landscape and street network characteristics, and linear regression to examine the association between the same characteristics and car rate increases. Car rates in the 300 cities analyzed showed a partial positive association with development fragmentation, and a consistent positive association with urban form complexity and circuity of the street network. In addition, the increase in car rates between 2010 and 2015 showed a negative association with population density. Implementing regional policies to reduce development fragmentation, to promote compact urban forms and less circuitous street networks may help reducing motorization in Latin American cities. Special attention needs to be paid to low density areas, where the increase in vehicle rates has been more pronounced.

1. Introduction

The emergence of car travel in the late 19th century initially allowed for high degree of human mobility and an increase in travel convenience (Hall, 1988; Sheller & Urry, 2000). As car use increased, however, automobile travel became a problem for many cities worldwide. Nowadays, car travel implies significant environmental costs, mainly due to high levels of energy consumption, emissions of air pollutants, increases in air temperature, and high levels of noise (Chapman, 2007; Eze et al., 2017; Gouveia et al., 2021; McAndrews et al., 2013). The presence of cars in cities also entails significant health risks for urban residents, both directly through the risk of crashes and pedestrian accidents, and indirectly when considering the various diseases associated with physical inactivity and exposure to air pollution (Bhalla, 2013; Mueller et al., 2017). At the same time, and despite significant purchase, fuel and parking subsidies, a car-dependent transportation system often implies significant financial burdens for households, such as those related to the acquisition, insuring, storage, maintenance, and use of vehicles (Miralles-Guasch & Cebollada, 2003). A similar financial strain applies to governments, from local to national, whose revenues often fail to keep up with multiple demands associated with automobile travel, including maintaining and expanding infrastructure, managing car-

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related pollution, and partially covering some of the health care costs of automobile externalities, such as road traffic collisions (Gössling et al., 2019). Lastly, the predominance of cars in the current mobility system also has a consequential impact on urban form, not only in relation to higher degrees of urban sprawl associated with the possibility of travelling farther, but also by requiring a tremendous amount of space for their use (roads) and storage (parking) which are often subsidized (directly and indirectly) and thus displacing more productive land uses (Litman, 2009; Shoup, 2015).

To address the challenges related to the dominance of cars in cities worldwide, many regional and local governments are aiming to progressively shift transportation systems away from cars towards options, such as public transportation, pedal cycling or walking, that are more environmentally friendly, healthier for urban residents, and come at lower individual and social costs (Elvik & Goel, 2019; Nieuwenhuijsen & Khreis, 2016). For example, a recent review found that there was a clear association between the reduction in traffic volume and safety of both cyclists and pedestrians (Elvik & Goel, 2019). Also, another recent study showed how that new public transit infrastructure could decrease the overall transportation health burden by 2.5 Disability Adjusted Life Years (DALYs) per 100,000 persons, resulting from the reduction of road traumas as well as gains in active transportation (Tétreault et al., 2018).

The shift towards a less auto-centered mobility system is particularly important, yet challenging, in areas where motorization rates are rising quickly. This is partly due to increased income-permissive car use policies, and cultural factors associated with car ownership. This is particularly the case of Latin America, where between 2005 and 2015 the number of registered cars grew almost by 80 %. This increase meant a 60 % rise in the motorization rate (cars per capita), which is only exceeded by Asian countries (OICA, 2015). At the same time, many cities in Latin America have invested in public transportation improvements such as bus rapid transit systems, rail systems, and bicycle facilities (Mejía-Dugand et al., 2013), while also complementing these improvements with policies to reduce car use in central urban areas, and encouraging active transportation such as walking and cycling (Mosquera Becerra et al., 2013; O. Sarmiento et al., 2010; Wang et al., 2021). Thus, to increase the effectiveness of these policies, and to identify other possible interventions, it is important to understand contextual factors shape everyday mobility patterns and thus to inform policies that aim to reduce car use at the city or the regional level.

A socio-ecological framework (Stokols, 1992) can be used to describe the factors that explain individual's and household's decision to own a car, as well as the subsequent motorization rates in a particular geography. At the most proximate level, individuals and households have personal needs and preferences, financial considerations, and psychological and affective motives (Steg, 2005). At the neighborhood level, conditions such as safety, availability of parking or accessibility to public transport (Papu Carrone et al., 2021), are also likely to impact car ownership. Further upstream, at the city level, the configuration of the urban landscape and the characteristics of street network, as well as the socioeconomic conditions of the city, can affect households' decision to own a car. In this sense, the ecological approach is particularly useful for policies and interventions that aim to achieve large-scale changes in population behavior (Sallis et al., 2006).Urban landscape metrics refer to the extent and shape of developed land, which can be analyzed through density of urban development and the spatial distribution of resident population, as well as with measures of the footprint of developed land, such as the fragmentation and the shape complexity of built-up patches (i.e. the irregularity of the patch shape) (Huang et al., 2007; Sarmiento et al., 2021). For example, the association between lower built-up density and car-dependency has long been documented at the city-level (Cervero & Kockelman, 1997; Newman & Kenworthy, 1989). Similarly, higher degrees of development fragmentation (built-up patches per unit of land) have been found to be associated with higher motorization rates (Cárdenas Rodríguez et al., 2016; Huang et al., 2007). On the other hand, street network configuration metrics usually refer to the spatial distribution and connectivity of streets, as well as their actual shape. Specifically, denser street networks, characterized by a higher number of intersections, are generally inconvenient for automobile use (Litman, 2016). By contrast, street networks with longer distances between intersections, that are more circuitous, and that rely on high-capacity roads for mobility are generally associated with higher volumes of cars (Brown et al., 2009).

The link between urban landscape, street network characteristics and car use has been mostly explored in developed countries, as evidenced by the studies referenced in the previous paragraphs. Moreover, this is a particularly interesting topic of inquiry for developing countries worldwide where not only motorization rates are growing at a fast pace, but where rapid urbanization results in peripheral development, increasingly characterized by lower densities and by an increasingly dispersed growth (Sun et al., 2017). In the Latin American context in particular, previous evidence has shown how such expansive urbanization is resulting in higher degrees of isolation and fragmentation (Covarrubias, 2013; Duque et al., 2019), while maintaining relatively high levels of population density (Inostroza et al., 2013), and with urban forms that are relatively less complex in shape than in other regions in the world (Huang et al., 2007). At the same time, despite the considerable investment in public transportation systems in the past decades, there are still relevant challenges to overcome in terms of accessibility in the region (Hardoy & Romero Lankao, 2011). Along this line, one study focused found that commuters in 100 cities in Mexico were less likely to drive to work in dense urban areas, where jobs and population tended to concentrate, with better provision of public transit and less space allocated for roadways (Guerra et al., 2018). In addition, one previous study focusing on 77 cities worldwide, and including 12 cities in Latin America, had found a correlation between motorization rates and urban landscape with complex shapes (Huang et al., 2007). These results are understandable, since less dense, more fragmented, and more complexly shaped built-up areas increase day-to-day distances between people and economic activities, and thus increase the need of motorized and individual transport.

Thus, it is important to understand to what extent region-specific urban form characteristics are associated with growing motorization rates in Latin American cities (Hidalgo & Huizenga, 2013). This paper aims to contribute to the understanding of the relationship between urban landscape and street network characteristics and motorization in Latin America, which could help inform planning measures to reduce car usage, and to promote healthier, safer, and more sustainable urban lifestyles in the region. For this purpose, we first examined the association between a set of urban landscape and street network characteristics and car rates in 2015 in a large sample of 300 Latin American cities. Secondly, we explored the association between these same characteristics and car rate increases between 2010 and 2015. We hypothesize that car rates, as well as their growth, have a positive association with low population density, low population concentration, and with high levels of development fragmentation and urban form complexity. We also hypothesize that car rates and their growth are also associated with street networks that consist of low intersection density and high circuity.

2. Methods

2.1. Study area

This study is based on data from the SALURBAL project. The SALURBAL project compiles and harmonizes data on health as well as social and built environment for all cities with 100,000 or more residents in 11 countries: Argentina, Brazil, Chile, Colombia, Costa Rica, El Salvador, Guatemala, Mexico, Nicaragua, Panama, and Peru (Quistberg et al., 2019). Cities were defined in the project as a single administrative unit (e.g., municipality) or combination of adjacent administrative units (e.g., several municipalities) that are part of the contiguous built-up areas of the urban agglomeration, as determined from a visual examination of satellite imagery. Each "city" is defined based on its component administrative units (municipalities or similar depending on the country). In this study we focus on 300 cities in Brazil, Mexico, Chile, and Colombia, comprising 240 million residents, based on data availability. Cities included in the study are displayed in Fig. 1 and listed in **Supplementary Table S1**.

2.2. Outcomes

In this study we used vehicle registration data from official country-specific sources (**Supplementary Table S2**). Vehicle types reported by each country varied, with Brazil and Chile having more specific types of vehicles reported. In this paper we focus on passenger vehicles, which can be regarded broadly as referring to "cars," that included cars, sport utility vehicles, pick-up trucks, light trucks, vans, and similar vehicles.

The main outcome for this study is car rate, defined as the number of passenger vehicles per 1,000 inhabitants in 2015. The second outcome examined is the car rate change between 2010 and 2015, and is calculated as:

$$Carratechange = \frac{(carrate2015 - carrate2010)}{carrate2010}$$

2.2.1. The role of the urban landscape and street networks

The key independent variables refer to the urban landscape and the street network. Based on previous literature, the key urban landscape metrics include population density, development fragmentation, population concentration, and complexity of the urban footprint. Street network characteristics include intersection density and circuity of the network. Definitions and data sources are presented in Table 1, and stylized examples of scenarios in which low and high values for each metric arise are presented in Fig. 2.

The approach used to examine landscape metrics, and especially complexity of built-up land, warrant a specific mention. Traditionally, studies analyzing the shape and irregularity of urban form have mostly used fractal dimensions (Huang et al., 2007). However, the use of such metrics of irregularity can often lead to uncertainty in calculations, and the choice of a particular approach could significantly affect interpretation (Chen, 2019, 2020). Instead, and in order to be more easily interpreted and communicated through the lens of urban and transport planning, in this study we aimed to use metrics that were based on built-up patch geometries (e.g., areas and perimeters). Although such metrics were first used in landscape ecology (for example see Rahimi et al., 2021), a number of studies have applied them to complement and expand the understanding provided by more prevalent measures used among urban researchers (McCarty & Kaza, 2015; Wu et al., 2015), such as metrics of density, diversity, and design. Along these lines, a recent paper that shows how typologies of complexity are related to very specific geometric measures and configuration aspects that have a clear spatial interpretation, potentially helpful for non-experts and policy makers (Sarmiento et al., 2021).

2.2.2. City-level co-variates

We also included a set of variables that may be regarded as potential confounders of our main associations or may be important in interpreting other measures at the city level. We included percentage of built-up area to properly interpret patch density as fragmentation, and GDP per capita as a measure of economic prosperity, which can also explain patterns of urbanization and both car rates and motorization rate changes (Ingram & Liu, 1997; Ksenofontov & Milyakin, 2018; Schafer, 1998). Definitions and data sources of co-variates are also presented in

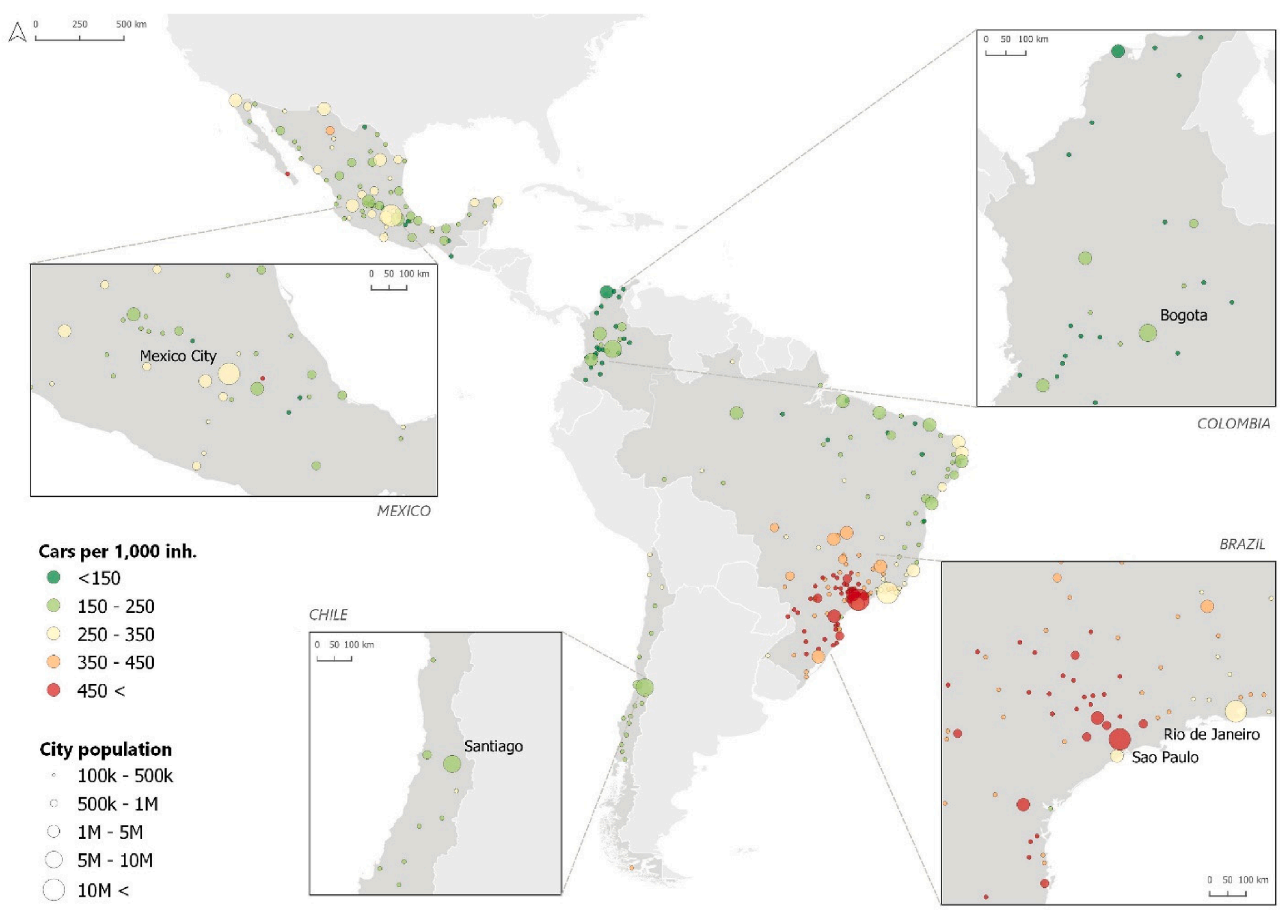

Fig. 1. Location of the analyzed cities (n = 300) by population size and car rate (2015).

Table 1
Description of selected urban landscape, street network characteristics, and key city-level co-variates.

Urban landscape metrics	
Population density (persons per hectare)	We divided the city population by the total built-up area in the administrative city. Population was from 2018 and was extracted from national statistics agencies. In the case of Mexico, 2018 data was obtained from official population projections from the Consejo Nacional de Población. Built-up area was extracted from 30x30m grid cells classified as urbanized in the Global Urban Footprint dataset (Esch et al., 2011, 2017, 2018). GUF measured urban footprint at a native 12-meter resolution between 2011 and 2012, and we resampled GUF to 30 m resolution so that we could calculate other landscape metrics over large geographies.
Population concentration (%)	Measures how evenly distributed the population is over the population over the city's urban extent (McCarty & Kaza, 2015). It is calculated as the Gini coefficient of population within the urban footprint, as defined in the SALURBAL project (Quistberg et al., 2018). Higher values indicate an uneven distribution of the population across the defined geographic area, whereas lower values indicate a more even distribution of the population across the urban footprint. This variable is calculated using the Matlab 2017 package "gini()" (Lengwiler, 2021).
Urban development fragmentation (number of built-up patches per 100 ha)	We use built-up patch density as a measure of fragmentation of urban development (Irwin & Bockstael, 2007), calculated as the number of built-up patches divided by the total land area of the city. Patches were defined based on GUF, and we grouped connected urban pixels into urban patches using the Moore Neighborhood rule (Weisstein, n.d.). We derived the patches and calculated fragmentation using the FRAGSTATS 4.2 software package (McGarigal et al., 2012).
Complexity of built-up patches (meters per hectare)	We used area-weighted edge density as a measure of complexity of the urban form (i.e., the irregularity of the built-up patch shape)The metric was calculated as the total perimeter of all built-up patches divided by the total land area of the city. In addition, the perimeter of each patch is weighted by its patch size. When used together with urban patch density, edge density can be interpreted as measure of the complexity of the shape of the urban form. We used an area-weighted measure to give more prominence to larger patches of urban development. This variable was calculated using the FRAGSTATS 4.2 software package.
Street network metrics	
Intersection density (number of intersections per square km)	Measures street connectivity and is calculated as the number of intersections (excluding dead ends) divided by the total city built-up footprint. Number of intersections were collected and processed using the OSMnx python library (Boeing, 2017), which is based on OpenStreetMaps data.
Average circuity (ratio)	Measures the ratio between the network distances between every pair of nodes in the street network and the Euclidean distance between them. It describes the directness of the network. Values close to 100 indicate that the network distance is close to air-line distance, which is the shortest possible distance. As values increase, the connection between a pair of points becomes less direct. Overall, this metric is an indicator of the extent to which a given street network resembles a grid (which has high directness) or, conversely, if it presents more irregular layouts (low directness). Calculations were also conducted using the OSMnx python library.
City-level covariates	
Percentage of built-up area (%)	Measures total built-up area divided by the total land area of the geographic unit and multiplied by 100. Built-up area was calculated from GUF.
GDP per capita (USD)	GDP per capita (purchasing power parity) in constant 2011 international USD. The GDP dataset was described in (Kummu et al., 2018).

Table 1 (*continued*)
Urban landscape metrics
Population density (persons per hectare) We divided the city population by the total built-up area in the administrative city. Population was from 2018 and was extracted from national statistics agencies. In the case of Mexico, 2018 data was obtained from official population projections from the Consejo Nacional de Población. Built-up area was extracted from 30x30m grid cells classified as urbanized in the Global Urban Footprint dataset (Esch et al., 2011, 2017, 2018). GUF measured urban footprint at a native 12-meter resolution between 2011 and 2012, and we resampled GUF to 30 m resolution so that we could calculate other landscape metrics over large geographies.

Table 1.

2.3. Statistical analysis

First, we examined the bivariate associations between motorization rate and motorization rate change and city characteristics, by using ANOVA. Second, we performed a cross-sectional analysis of the association between motorization rate and the key urban landscape and street network characteristics, while adjusting for other city-level covariates. We used a negative binomial model with passenger vehicle counts (cars) as the outcome and the natural log of population as the offset to model rates. We selected a negative binomial model instead of a Poisson model because overdispersion was observed in the outcome variable (see **Supplementary** Table S3 for descriptive statistics). We did not observe significant cases of multicollinearity among the independent variables, and we only observed significant correlations between percent built-up area and the two urban landscape metrics (patch and edge density), as expected (see **Supplementary** Table S5 for Pearson correlations among independent variables and **Supplementary** Table S6 for Variance Inflation Factors).

We examined the association between all the urban landscape characteristics and the outcome in a first model, and then we added the two street network characteristics in a second model. Both models were adjusted by the percentage of the area that is built-up, and city GDP per capita. As sensitivity analysis we included 5- and a 10-year lags in population density. Coefficients from the negative binomial model were exponentiated and are interpretable as Motorization Rate Ratios (MRR) and 95 % Confidence Intervals (CIs). Third, we examined the association between the change in car rate between 2010 and 2015 and the same

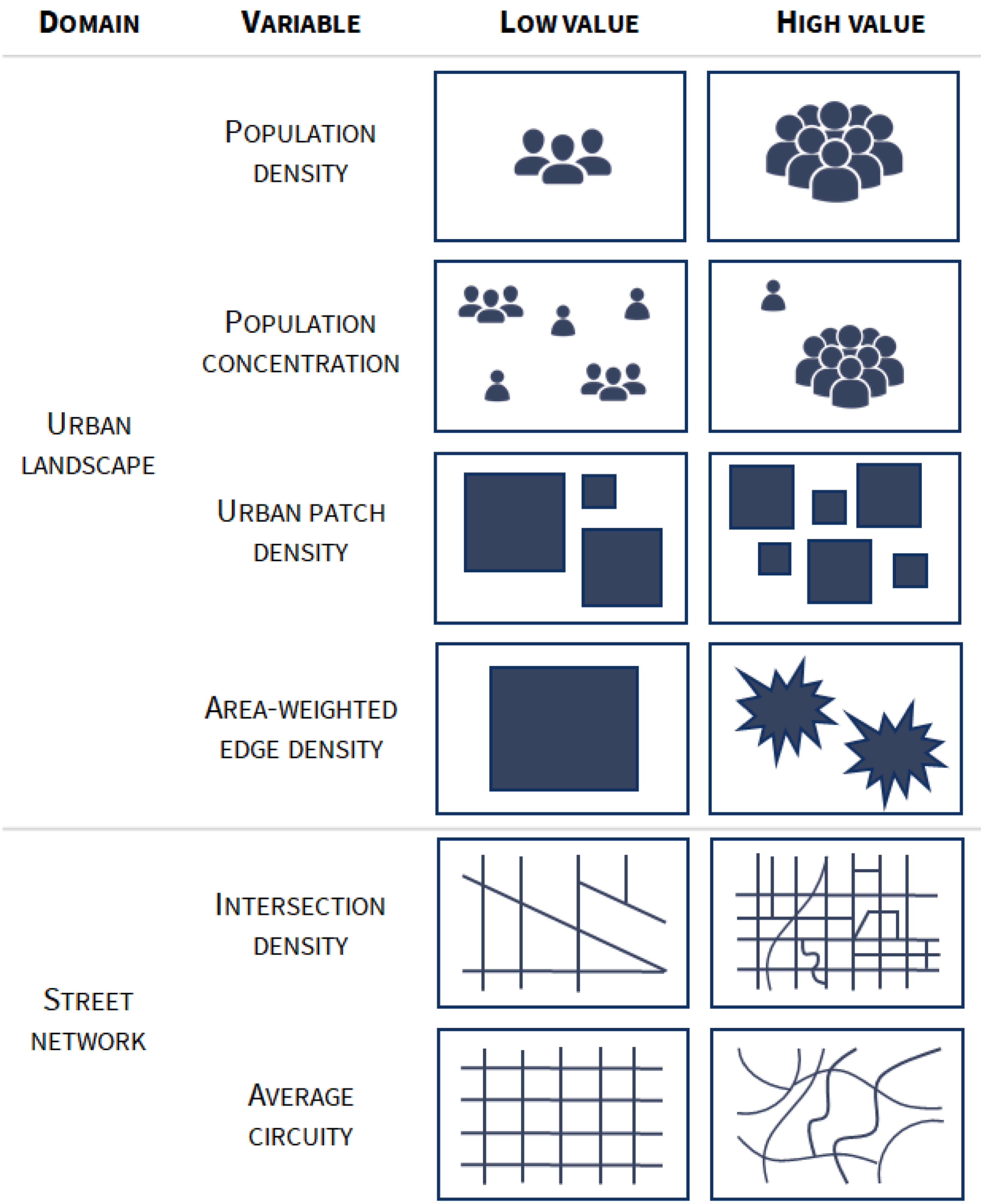

Fig. 2. Stylized examples of scenarios with low and high values of the key exposure variables.

key independent variables. In this case, we used a linear regression with car rate change 2010–2015 as the outcome, and thus we report standardized coefficients for each of the independent variables. All models included country as fixed effects to adjust for possible country-specific urbanization patterns as well as country-based policies that could be related to different levels of motorization.

Data processing and analyses were conducted using 'pandas' and 'TableOne' Python libraries for the descriptive analyses and SPSS version 26 (IBM Corp. Released 2012. IBM SPSS Statistics for Windows, Version 26.0. Armonk, NY, USA) for the models.

3. Results

The analysis included 300 cities from Brazil (N = 152), Chile (N = 21), Colombia (N = 35), and Mexico (N = 92). Table 2 contains descriptive characteristics of the cities, overall and stratifying by tertiles of motorization rate (2015) and motorization rate change (2010–2015). City characteristics by country are presented in **Supplementary Table S4**. Cities in the analysis had an average of 210.2 cars per 1,000 inhabitants in 2010 and 273.3 cars per 1,000 inhabitants in 2015; the resulting change in car rate between 2010 and 2015 was a 30 %

Table 2
Description of city characteristics overall and by categories of car rate (2015) and car rate change (2010–2015).

	Total	Car rate (2015)			p-value*	Car rate change (2010–2015)			p-value*
		Low (4.9, 205.9]	Middle (205.9, 320.9]	High (320.9, 687.1]		Low (−0.27, 0.24]	Middle (0.24, 0.33]	High (0.33, 1.54]	
n	300	100	100	100		100	100	100	
Outcomes									
Car rate (2015)	273.3 (134.9)	134.8 (53.6)	249.9 (31.8)	435.2 (68.2)	<0.001	267.6 (138.0)	334.1 (124.2)	218.2 (116.8)	<0.001
Car rate change (2010–15)	0.30 (0.21)	0.36 (0.31)	0.27 (0.16)	0.28 (0.08)	0.007	0.12 (0.11)	0.29 (0.03)	0.50 (0.22)	<0.001
Urban landscape characteristics									
Population density (pop. /ha)	78.65 (42.00)	104.62 (55.97)	72.40 (24.18)	58.95 (22.33)	<0.001	69.57 (33.26)	75.42 (41.45)	90.97 (47.51)	0.001
Population concentration (%)	30.58 (9.08)	26.25 (9.63)	30.78 (8.90)	34.72 (6.39)	<0.001	30.59 (8.33)	32.79 (8.37)	28.36 (9.99)	0.002
Patch density (n/100 ha)	0.38 (0.29)	0.31 (0.24)	0.38 (0.30)	0.45 (0.32)	0.002	0.39 (0.28)	0.44 (0.32)	0.31 (0.27)	0.009
Area-weighted edge density (m/ha)	0.93 (0.80)	0.81 (0.81)	0.82 (0.70)	1.15 (0.85)	0.003	0.96 (0.86)	1.03 (0.76)	0.80 (0.78)	0.137
Street network characteristics									
Intersection density (n/km^2)	93.62 (25.90)	102.18 (27.78)	98.16 (26.03)	80.53 (17.57)	<0.001	92.98 (24.84)	87.38 (23.68)	100.51 (27.58)	0.001
Average circuity (ratio)	103.80 (2.03)	103.53 (1.65)	104.06 (1.85)	103.81 (2.49)	0.184	103.74 (1.47)	104.18 (2.53)	103.47 (1.92)	0.043
City-level covariates									
Percentage of built-up area (%)	5.02 (4.95)	3.72 (3.82)	5.60 (5.82)	5.76 (4.79)	0.005	5.75 (5.59)	5.53 (4.88)	3.80 (4.09)	0.009
GDP per capita (10,000 USD)	1.58 (1.19)	1.24 (1.19)	1.67 (1.47)	1.84 (0.71)	0.001	1.93 (1.62)	1.68 (0.94)	1.14 (0.65)	<0.001

All values correspond to means (SD). *One-way ANOVA.

increase. In terms of the key urban landscape metrics, cities had an average population density of 78.65 persons per hectare, an average population concentration value of 30.6 %, an average urban fragmentation of 0.38 built-up patches per 100 ha and had an average of 0.93 m of built-up area patch edge per hectare. Cities in the study also had approximately 94 intersections per square km and an average street network circuity of 103.8. In terms of city covariates, cities in the study showed an average 5 % of developed land and an average GDP per capita of 15,800 USD.

By stratifying city characteristics by car rate tertiles, we observed a negative association between car rate and population and intersection density, and a positive association between car rate and population concentration, patch density, percent of the city area that is built, area-weighted edge density and city GDP per capita (Table 2). When we stratified city characteristics by car rate change tertiles, we observed different associations. We found a negative association between car rate increase and percent of the city area that is built, a non-linear association between car rate increase and population concentration, patch density, intersection density and average circuity, and we observed a positive association between car rate increase and population density.

Table 3
Motorization Rate Ratios (2015) associated with urban form and street network characteristics.

	Model 1	Model 2
	MRR (95 % CI)	MRR (95 % CI)
Urban landscape characteristics		
Population density (pop. /ha)	0.999 (0.997, 1.001)	0.997 (0.995, 1.000)
Population concentration (%)	1.002 (0.996, 1.009)	1.001 (0.994, 1.007)
Patch density (n/100 ha)	1.198 (1.011, 1.420) *	1.118 (0.908, 1.375)
Area-weighted edge density (m/ha)	1.068 (0.997, 1.144)	1.082 (1.006, 1.163) *
Street network characteristics		
Intersection density (n/km^2)		1.002 (0.999, 1.005)
Average circuity (ratio)		1.044 (1.014, 1.076) *

Both models are adjusted by % of built-up area, city GDP per capita and country fixed effects. *p-value < 0.05. 95 % confidence intervals are in the brackets.

In the first model (Table 3), we observed that car rates were 20 % higher per unit increase in patch density (MRR 1.20, 95 % CI 1.01 to 1.42). When adding the street network variables in the second model, we observed only a positive association between car rate and area-weighted edge density (MRR of 1.08, 95 % CI 1.01 to 1.16). In addition, we also observed a MRR of 1.04 (95 % CI 1.01 to 1.08) for the average circuity of the street network. The magnitude and direction of these associations remained consistent when we included 5-year lag in population density, but patch density showed a significant and positive association with car rates in the model that included a 10-year lag in population density (MRR of 1.26, 95 % CI 1.01 to 1.56) (**Supplementary Table S7**).

The results of the adjusted linear regression model of the association between car rate change and urban landscape and street network metrics are presented in Table 4**.** In both models we observe a consistent negative association between car rate increase and city population density, with a standardized coefficient of −0.205 (95 % CI −0.344 to

Table 4
Standardized coefficients for car rate change (2010–2015) associated with urban form and street network characteristics.

	Model 3	Model 4
	Std. Coeff. (95 % CI)	Std. Coeff. (95 % CI)
Urban landscape characteristics		
Population density (pop. /ha)	−0.205 (−0.344, −0.066)*	−0.191 (−0.361, −0.021)*
Population concentration (%)	0.034 (−0.105, 0.173)	0.041 (−0.101, 0.183)
Patch density (n/100 ha)	−0.003 (−0.138, 0.131)	0.011 (−0.132, 0.153)
Area-weighted edge density (m/ha)	−0.048 (−0.187, 0.090)	−0.055 (−0.195, 0.086)
Street network characteristics		
Intersection density (n/km^2)		0.015 (−0.106, 0.136)
Average circuity (ratio)		−0.025 (−0.139, 0.090)

Both models are adjusted by % of built-up area, city GDP per capita, country fixed effects, and passenger vehicle rate for the baseline year (2010). *p-value < 0.05. 95 % confidence intervals are in the brackets.

−0.066) in the model that only includes urban landscape metrics (Model 3) and of −0.191 (95 % CI −0.361 to −0.021) in the saturated model that also includes street network characteristics (Model 4). This means that for every standard deviation (SD) increase in population density, car rate change decreases in 0.191 SD.

4. Discussion

We examined the association between urban landscape and street network characteristics and car rates in 300 Latin American cities in Brazil, Chile, Colombia, and Mexico. We observed a strong, positive association between car rates in 2015 and shape complexity of developed land, and the directness of the street network. In addition, we observed a partial positive association between car rates and patch density, an indicator of urban fragmentation. These associations were generally consistent with our expectations and indicate that car rates are sensitive both to the complexity of urban landscape configuration and to road infrastructural factors promoting the ease of vehicle movement such as directness. In addition, we also observed a strong, negative association between increases in car rates between 2010 and 2015 and city population density.

In two models we observed a positive association between urban fragmentation, measured as built-up patch density, and car rates (in the model with only urban form metrics and the also in the model that included a 10-year lag in population density). If true, this would confirm that to some extent higher levels of development fragmentation can contribute to larger distances between daily destinations, which hinders active forms of travel (i.e., walking or cycling) and thus increases the dependency on motorized transportation (Ewing & Cervero, 2010). This result would be consistent with previous evidence. For example, one study focused on 10 Latin American cities found that the low efficiency in the use of infill areas, a different measure of development fragmentation, was correlated with the rate of vehicles per 1,000 inhabitants (Inostroza et al., 2013). Other studies found that urban fragmentation was associated with higher concentration of pollutants such as NO_2, PM_{10} and O_3 produced by road transportation (Cárdenas Rodríguez et al., 2016; McCarty & Kaza, 2015). However, this association was not statistically significant in the main model, which suggests that to some extent the interaction between different metrics of the urban form may present temporal lags that need to be explored further.

We also found an association between car rates and area-weighted edge density, an indicator the complexity of the shape of urban areas. Complex urban shapes are especially related to higher automobile use since public transportation accessibility is related to the compacity of urban form (Lee et al., 2015; Stevenson et al., 2016). This is consistent with studies conducted in other parts of the world. For example, city shape in 114 urban areas in the United States showed a significant effect on household car use (Bento et al., 2005). Further downstream, metropolitan areas that exhibited more complex morphologies were also associated with higher concentrations and emissions of air pollution related to road transportation. Specifically, edge density of built-up areas showed a positive correlation with PM_{10} and noise pollution (Liu et al., 2018; Weber et al., 2014).

We also observed a strong, positive association between average circuity of the street network and car rates, suggesting that motorization is promoted by lower network efficiency. In broad terms, grid-like networks tend to be more efficient patterns to ingest large volumes of pedestrians or vehicles at slow speeds (Yen et al., 2021). Circuitous street networks are more prevalent in environments with less development, in informal settings, and in areas where topographic conditions may limit a more connected street network (Boeing, 2020). Furthermore, low density, peripheral development that is disconnected from existing development is likely to increase street network circuity, considering that it is rather common that the design of suburban residential areas aims to resemble or replicate rural settings and lifestyles (Mayo, 1979; Southworth & Ben-Joseph, 1995). In the United States, the progressive adoption of more dendritic and hierarchical road networks, partly to protect residential areas from high traffic volumes, has caused the general increase in circuity over the past few decades (Giacomin & Levinson, 2015). These two pathways leading to higher levels of street circuity could also be particularly relevant in the Latin American context. While the street network of cities in the region can be generally regarded as highly stable, a small increasing trend is observed in circuity index values from 1996 to 2010 (Duque et al., 2019). This is possibly related to the fact that rapid urbanization is reflected in both a larger area of informal settlements and suburban-type low-density developments (Inostroza, 2017).

We did not observe statistically significant associations between car rates and population density, concentration, or intersection density, after adjusting for other city characteristics. We had expected a negative association between population density and car rates, as suggested by studies that focused on household car ownership, car use and motorization rates (Des Rosiers et al., 2017; Ewing & Cervero, 2010; Giuliano & Dargay, 2006; Schwanen et al., 2004). Similarly, higher values of population concentration were expected to be associated with lower car rates, considering that geographical concentration of people has been found to facilitate public transportation services as well as to favor travelling by bicycle or on foot (Lee et al., 2015; Mendiola et al., 2015). Lastly, higher intersection densities were expected to be negatively associated with car rates, since street connectivity is a measure of walkability and is associated with larger pedestrian and bicycle flows (Frank et al., 2010; Le et al., 2018). The lack of such associations in our study could be explained by the fact that motorization rates in cities in Latin America may be still low compared to high income settings, and thus factors associated with the current rates may be different from such contexts. For example, GDP per capita could still be the major driver of motorization rates in the selected cities. In addition, cities in the region are experiencing unprecedented urbanization rates that could also be resulting in development patterns different from other geographic contexts, for instance with levels of density and street connectivity that are significantly higher than in such contexts (Cervero, 2013), which in turn could have different implications in terms of their association with passenger vehicle rates.

We did, however, observe a negative association between population density and the increase in car rates between 2010 and 2015, which suggests that low density areas have been experiencing a larger increase in car rates in the cities examined. Given that the current urbanization process in Latin America is projected to continue to embody low-density and peripheral areas (Inostroza et al., 2013) and that most of the strategies to reduce car use to this date have targeted central urban areas (Mosquera Becerra et al., 2013; O. Sarmiento et al., 2010), special policy attention should be directed at slowing the growth of vehicle ownership in low-density areas. Such policies should aim to facilitate multimodal travelling, for example by enhancing travel alternatives such as high level-of-service bus systems and rail, or by increasing the cost of using and parking automobiles through pricing or the creation of urban tolls.

To the best of our knowledge, this is the largest study evaluating associations between passenger vehicle rates and urban landscape and street network characteristics in Latin American cities at an ecological level. The study is strengthened by its use of harmonized official datasets on vehicle registration from 300 cities in four countries. In addition, we measured consistently urban landscape and street network characteristics using metrics that can be replicated for cities and regions elsewhere. However, this study also has limitations that could inform future research. First, we used a cross-sectional design, and therefore no causality can be interpreted from the associations identified, especially considering that there is a potential effect of reverse causality between motorization rates and urban landscape and street network characteristics. Along this line, the difficulties in obtaining a clear causal relationship has also been acknowledged in studies exploring the land use-transportation link, a relationship that can be regarded as circular (Waddell et al., 2007). Second, the hypothesized effect of urban characteristics on car rates might have a lagged effect, meaning that changes in the urban landscape could translate into changes in mobility decisions and habits later in time. However, sensitivity analyses with lagged population density, for example, did not show any significant changes in the associations observed. Furthermore, the urban landscape metrics were developed based on satellite imagery dating from 2011 to 2012 and thus are technically lagged compared to the passenger vehicle rates analyzed. In any case, future studies could explicitly examine the longitudinal relationship between urban landscape and street network metrics and present-day motorization levels. Third, since the focus of this study was on the attributes of the urban landscape and the street network, we only included city GDP per capita as a control of for socioeconomic development due to data availability. However, while economic prosperity and motorization rates have been highly correlated (Ksenofontov & Milyakin, 2018; Schafer, 1998), this relationship might no longer be as straightforward considering that the relationship between income and motorization is not linear (Kutzbach, 2009). For example, cities and regions with more economic resources are more likely to take actions to limit private car use (G. Chen & Kauppila, 2017). Similarly, motorization rates are not only related to urban landscape and street network metrics, but also are a clear function of the underlying economic activity, land-use spatial configuration and transport alternatives (Guerra et al., 2018), aspects that were beyond the scope of this paper due to data limitations. In this line, the results presented in our study as well as the conclusions drawn from them should be interpreted considering that there might be other variables that could be mediating or nuancing the associations found in this study. Variables such as the presence and characteristics of public transit facilities, the specific characteristics of transportation infrastructure and even the effect of local, regional, and country-level transportation policies could also be further explored in future studies.

5. Conclusion

We found that higher car rates were associated with higher levels of urban form complexity and circuity of the street network in a sample of 300 Latin American cities of more than 100,000 inhabitants. In addition, we observed that car rates could be related also to urban fragmentation when considering temporal lags in population density, and also that these were more likely to have increased between 2010 and 2015 in urban areas with low population densities. These results provide evidence that features of the urban landscape and street network are associated with passenger vehicle rates in Latin America, and thus suggest that such features should be considered in policy efforts that aim to reduce the negative environmental, social, and health-related impacts of the high motorization levels projected for the region.

Current trends from other countries indicate that car use will continue growing if no action is taken to reduce motorization and if no alternative modes of transportation are provided. However, coupled with the necessary investment in public transportation that is already taken place in the four countries of this study (Hidalgo & Huizenga, 2013) and the rise of new shared mobility alternatives, the increasing motorization rates in Latin America could be further curbed by policies that address the urban spatial structure. These include policies to reduce urban fragmentation, encourage compact urban development, and enhance street connectivity, in order to reduce the need for private vehicle travel and support active forms of mobility such as walking, cycling or public transportation. Examples of such measures could be to incorporate density and contiguity requirements in new developments, or to prioritize vertical growth in already urbanized areas. In the Latin American context in particular, in addition, some authors have also suggested that tackling informal urban development should be another crucial aspect of urban planning and management, considering that such forms of development can increase fragmentation and isolation (Inostroza, 2017), and thus increasing motorized mobility needs. In terms of the characteristics of the street network, there are now increasing examples of how cities in other world regions are progressively reducing the presence of car-oriented infrastructure by avoiding the construction of new highways and reducing area allocated to parking (Shoup, 2015), and instead promoting not only the construction of infrastructure for public transport and active transport (e.g., cycleways, pedestrianized areas), but also to invest in increasing and improving public spaces in order to increase accessibility and economic activity and thus reduce the need for car travel (Rye & Hrelja, 2020).

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CRediT authorship contribution statement

Xavier Delclòs-Alió: Conceptualization, Formal analysis, Writing – original draft. **Claudio Kanai:** Data curation, Writing – review & editing. **Lucas Soriano:** Data curation, Writing – review & editing. **D. Alex Quistberg:** Data curation, Methodology, Writing – review & editing. **Iryna Dronova:** Data curation, Writing – review & editing. **Nelson Gouveia:** Supervision, Writing – review & editing. **Daniel A. Rodríguez:** Conceptualization, Supervision, Writing – review & editing.

Declaration of Competing Interest

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

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.tbs.2022.09.005.

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