Abstract
Using a unique dataset containing gridded data on population densities, rents, housing sizes, and transportation in 192 cities worldwide, we investigate the empirical relevance of the monocentric standard urban model (SUM). Overall, the SUM seems surprisingly capable of capturing the inner structure of cities, both in developed and developing countries. As expected, cities spread out when they are richer, more populated, and when transportation or farmland is cheaper. Respectively 100% and 87% of the cities exhibit the expected negative density and rent gradients: on average, a 1% decrease in income net of transportation costs leads to a 21% decrease in densities and a 3% decrease in rents per m². We also investigate the heterogeneity between cities of different characteristics in terms of monocentricity, informality, and amenities.

Keywords: Urbanization, Standard Urban Model, Urban Spatial Structure, Between-country Comparisons

JEL: R14, R52, R10

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1. Introduction
Understanding urbanization patterns and modeling urban dynamics have been a subject of research for at least a century (Duranton and Puga, 2015). These questions have recently been brought back into the spotlight in the context of current environmental crises, as urban sprawl is a key driver of both climate change (IPCC, 2014) and biodiversity losses (IPBES, 2019; Seto et al., 2012).
A well-established framework to tackle these issues is the Standard Urban Model (SUM), widely used in theoretical and applied papers (Brueckner, 2001). The SUM, initially developed by Alonso (1964), Muth (1969), and Mills (1967), describes the relationship between land use, land value, and transportation costs in cities, and relies on the following mechanisms. Households trade off between housing size and transportation costs to employment centers, which, in a monocentric city, results in high bid-rents in city centers, where transportation costs are low, and low bid-rents in peripheries. Under the assumption of competitive land markets, private developers will provide a high housing supply in city centers and a low housing supply in peripheries, as inelastically supplied land and diminishing returns to factor inputs imply that taller buildings require higher floor space rents (Ahlfeldt and Barr, 2022). From these mechanisms, aggregated results can be derived at the city level. Wheaton (1974) showed that, under the assumptions of monocentricity and monetary commuting costs, large populations and high incomes lead to larger urbanized areas, while high transportation costs and high agricultural land prices lead to smaller urban areas.

An extensive literature investigates the validity of the SUM and empirically examines its main conclusions in terms of population densities, rents, and urbanized areas, with studies on density gradients starting even before the theory was formulated (Clark, 1951). However, this literature still suffers from some limitations. First, few studies simultaneously investigate the model’s predictions in terms of urbanized areas, population densities, and rent gradients in relation to transportation costs within cities. Indeed, while the literature on density gradients in cities is well developed (see, for instance, the review by McDonald, 1989), the literature on dwelling rents or prices is less developed due to data limitations, and most studies focus on one or two cities, preventing comparison between cities or generalization of results (Duranton and Puga, 2015; McMillen, 2006, 2010). In addition, most of the existing studies investigate developed countries. Exceptions include Deng et al. (2008), Ke et al. (2009), Angel et al. (2011), and Jedwab et al. (2021) for urbanized area sizes. Exceptions regarding density gradients are more numerous as the literature is larger but include only three large-scale studies comparing a large number of cities (Bertaud and Malpezzi, 2014; Mills and Tan, 1980; Ingram and Carroll, 1981) and a few single case studies, mainly in China (Chen, 2010; Feng et al., 2009; Wang and Zhou, 1999).

However, the recent increase in data availability offers an opportunity to deepen our understanding of urban forms and city structures globally. Satellite data can be used to compare urban shapes: for instance, Harari (2020) uses such data to demonstrate the impact of city compactness on accessibility and welfare. New datasets, such as night lights (Henderson et al., 2012) and Twitter data (Indaco, 2020) can also be used as proxies for economic activity at a disaggregated, e.g. city, level. Regarding transportation, big datasets, for instance from Google Maps, allow
detailed analysis of mobility and congestion for large samples of cities (Akbar et al., 2018; Hanna et al., 2017).

Using spatially-explicit data on population densities, rents, dwelling sizes, land cover, and transport time in 192 cities across all continents, this paper empirically assesses the ability of the SUM to represent cities throughout the world. We show that the SUM captures urban structures surprisingly well, both in developed and developing countries, with most cities exhibiting the expected negative rent and density gradients: on average, a 1% decrease in income net of transportation costs leads to a 21% decrease in densities and a 3% decrease in rents per m$^2$, and moving 1km farther from the city center decreases rents by 1.4% and population density by 8.5%. We structurally estimate that the median capital elasticity of housing production over the sample of cities is 0.87, and that the median percentage of housing expenses in households’ income net of transportation costs is 33%. Our sample also allows us to investigate heterogeneity between cities: we show that polycentricity, informality, and local amenities weaken the relationship between rents or densities and incomes net of transportation costs, flattening density and rent gradients in cities. Aggregated predictions of the model in terms of urbanized areas are also verified in our sample: cities spread out more when they are richer, more populated, and when transportation or farmland rents are less costly.

The remainder of the paper is organized as follows. Section 2 introduces the monocentric SUM and the extant evidence regarding its main predictions. Section 3 presents the data. Section 4 empirically tests the three main relationships derived from the model, and section 5 discusses the results.

2. Introducing the monocentric city model

2.1. Theory

This section describes the SUM of urban economics and derives expressions for three endogenous variables (rents within cities, population densities, and total urbanized area of each city) as a function of a set of exogenous variables (population, farmland rents, income, per-distance transport cost). We analyse a sample of cities indexed by $c$, with locations within cities indexed by $i$, in a closed-city framework assuming exogenous populations.

In the first step, we derive dwellings’ bid-rents per m$^2$ at location $i$ in city $c$, denoted $R_{i,c}$, as a function of transportation costs to the city center (where we assume for simplicity that all jobs are located) $T_{i,c}$ using the spatial equilibrium condition. We assume that households seek to maximise their Cobb-Douglas utilities:

$$\max \ U(z_{i,c}, q_{i,c}) = z_{i,c}^{\alpha_c} q_{i,c}^{\beta_c}$$

subject to:

$$z_{i,c} + q_{i,c} R_{i,c} + T_{i,c} \leq Y_c \quad (1)$$
with \( q_{i,c} \) the size of the dwellings in pixel \( i \) and city \( c \), \( Y_c \) the income in city \( c \) (assumed as constant over the city), \( z_{i,c} \) the consumption of a composite good (whose price is normalized to 1), and \( \alpha_c \) and \( \beta_c \) the Cobb-Douglas parameters (such that \( \alpha_c + \beta_c = 1 \)).

From equation 1, we find that:

\[
q_{i,c} = \beta_c (Y_c - T_{i,c}) / R_{i,c} \\
z_{i,c} = \alpha_c (Y_c - T_{i,c})
\]

(2)

Using the spatial equilibrium condition and writing \( u_c \) the uniform utility at equilibrium, we find:

\[
R_{i,c} = R_{0,c} \left( \frac{Y_c - T_{i,c}}{Y_c} \right)^{1/\beta_c} \quad \text{with} \quad R_{0,c} = \left( \frac{\alpha_c \beta_c Y_c}{u_c} \right)^{1/\beta_c}
\]

(3)

In the second step, we derive population density as a function of transportation costs. We assume that absentee private developers produce housing from capital \( K_{i,c} \) and urbanizable land \( L_{i,c} \) with the following Cobb-Douglas production function, with the parameters \( A_c \), \( a_c \) and \( b_c \) such that \( a_c + b_c = 1 \):

\[
H(K_{i,c}, L_{i,c}) = A_c L_{i,c}^{a_c} K_{i,c}^{b_c}
\]

(4)

With \( k_{i,c} = K_{i,c} / L_{i,c} \) (capital intensity per urbanizable land surface area) and \( h = H / L_{i,c} \) (housing density, i.e. number of m2 built upon per m2 of available ground), equation 4 can be rewritten:

\[
h(k_{i,c}) = A_c k_{i,c}^{b_c}
\]

(5)

Developers seek to maximize their profit per land surface area \( \pi_{i,c} = R_{i,c} h(k_{i,c}) - \rho k_{i,c} \) considering a capital cost \( \rho \). Thus, housing supply is written:

\[
H_{i,c} = A_c^{1/a_c} (b_c R_{i,c} / \rho)^{b_c/a_c} L_{i,c}
\]

(6)

and total population per pixel \( N_{i,c} \) is written:

\[
N_{i,c} = H_{i,c} / q_{i,c} = A_c^{1/a_c} (b_c R_{i,c} / \rho)^{b_c/a_c} L_{i,c} / q_{i,c}
\]

(7)

Replacing \( q_{i,c} \) by its expression in equation 2:

\[
N_{i,c} = A_c^{1/a_c} (b_c / \rho)^{b_c/a_c} L_{i,c} R_{i,c}^{1/a_c} \frac{1}{\beta_c (Y_c - T_{i,c})}
\]

(8)

The population density per pixel \( n_{i,c} = N_{i,c} / L_{i,c} \) can be expressed as:

\[
n_{i,c} = A_c^{1/a_c} (b_c / \rho)^{b_c/a_c} R_{i,c}^{1/a_c} \frac{1}{\beta_c (Y_c - T_{i,c})}
\]

(9)
Finally, replacing $R_{i,c}$ by its expression in equation 3:

$$n_{i,c} = A_1^{1/a_c} \left( \frac{b_c}{\beta_c} \right)^{b_c/a_c} \alpha_c \left( \frac{\alpha_c}{u} \right)^{1/(\beta_c a_c)} \beta_c^{b_c/a_c} \left( Y_c - T_{i,c} \right)^{(1 - \beta_c a_c)/\beta_c a_c}$$  \hspace{1cm} (10)$$

In the third step, we want to derive the total urban area as a function of city characteristics. We assume for simplicity that the city is circular, i.e. that the amount of urbanizable land per pixel is constant, with $L_{i,c} = 1$, and that transportation cost can be broken down as $T_{i,c} = d_{i,c} t_c$ with $d_{i,c}$ the distance from pixel $i$ to the city center of city $c$ and $t_c$ the constant per unit transportation cost.

We assume the following equilibrium conditions:

- from equation 3, we find that bid-rents decrease from city centers to peripheries. We assume that the bid-rent $R_{i,c}$ intersects with farmland rent $R_c$ at the fringe of the city $d_c$ and at a transport cost $T_c = d_c t_c$, such that:

$$R_c = R_0,c \left( 1 - \frac{T_c}{Y_c} \right)^{1/\beta_c} = R_0,c \left( 1 - \frac{t_c d_c}{Y_c} \right)^{1/\beta_c}$$ \hspace{1cm} (11)$$

- in a closed-city model, all the population of the city $N^*$ lives within the city, i.e.

$$N^*_c = \int n_{i,c} \, di$$ \hspace{1cm} (12)$$

Brueckner (1987, pp. 830-836 and 840-844) shows that, under the following hypotheses:

- preference of households for housing and composite good is represented by a quasi-concave utility function, as in equation 1;

- housing supply is represented by a concave production function with constant returns, as in equation 4;

we can derive the following relationships:

$$\frac{\partial d_c}{\partial N^*_c} > 0, \quad \frac{\partial d_c}{\partial Y_c} > 0, \quad \frac{\partial d_c}{\partial t_c} < 0, \quad \frac{\partial d_c}{\partial R_c} < 0,$$ \hspace{1cm} (13)$$

Therefore, urban areas are expected to decrease with transportation cost per unit of distance and farmland rent and increase with total population and income.

2.2. Extant evidence

This section reviews the extant literature and evidence regarding the three relationships derived from the SUM in the previous subsection: bid-rents expressed as a function of transportation costs (equation 3), population density as a function of transportation costs (equation 10), and urbanized area as a function of the total population, the average income, transportation costs, and farmland rents (equation 13).
2.2.1. Rent gradients

Studies beginning as far back as the 1970s have measured rent or land price gradients within cities. Most of them have found evidence of negative rent or land price gradients from city centers to the suburbs, mainly in the US (Coulson, 1991) and the UK (Cheshire and Sheppard, 1995), and more recently in Berlin (Ahlfeldt, 2011).

Nevertheless, flat or inverted rent or land price gradients have been measured in some cities. For instance, Yinger (1979) found the expected negative rent gradients in Madison, in the USA, but not in the more polycentric setting of St Louis. Working on Chicago, McDonald and Bowman (1979) found a negative land price gradient close to the Central Business District (CBD) but an inverted land price gradient farther away, which they explained by polycentrism, racial segregation, or disamenities such as air pollution or congestion in the city center. Also in Chicago, McMillen (1996) showed that the distance to the CBD could satisfactorily explain land values in the city between 1836 and 1928, but that it was no longer significant after 1960, as the development of O’Hare Airport made the city more polycentric.

Beyond accessibility, other variables have been shown to impact rents or land values, modifying the gradient. Cheshire and Sheppard (1995) found the expected negative land price gradient in Reading and Darlington, in the UK, but they use a fully hedonic model and show that, in addition to accessibility, location-specific and dwelling-specific amenities play a key role in determining rents. More recently, Ahlfeldt (2011) showed that the monocentric SUM performs satisfactorily if we account for structural and neighborhood characteristics such as distances to the nearest school or green space. He also showed that gravity employment accessibility measures perform better than the monocentric SUM in the polycentric setting of Berlin.

To summarize, despite the early literature on rent and land value gradients, the evidence for the negative relationship between rent and distance to CBD is mixed. Heterogeneity in rent gradients between cities can be explained by polycentricity (Yinger, 1979; McMillen, 1996) and location-based and dwelling-based amenities (Cheshire and Sheppard, 1995). A more systematic measure of rent gradients in various cities and an evaluation of the explanatory power of the hypotheses that have been proposed in the literature would usefully complement the existing studies.

2.2.2. Density gradients

The literature concerning population density gradients, summarized in McDonald (1989) and Duranton and Puga (2015), is wider, since data on population densities are easier to obtain than data on rents or land prices. An initial line of research, starting even before the formulation of the theory (Clark, 1951), sought to
empirically find regularities in population densities. Many studies support the negative exponential function (Berry et al., 1963; Weiss, 1961), theoretically grounded in Muth (1961). However, other functions have been proposed in the literature, including the addition of a quadratic component to the negative exponential function to describe the population crater near the city center (Newling, 1969; Latham and Yeates, 1970), the inverse square function (Stewart and Warntz, 1958; Batty and Sik Kim, 1992), and the Gaussian function (Ingram, 1971; Guy, 1983). A full review of these functional forms can be found in Martori and Suriñach Caralt (2002), and Qiang et al. (2020) performed a recent assessment of their explanatory power on American cities. Overall, all these studies agree that population densities decrease from the city center to the periphery, potentially attenuated by the city center population density crater, due to the concentration of economic activities.

A second line of research has compared density gradients, either in the same city across time or between cities. Two main results emerge from this literature. First, there is evidence of a flattening of density gradients over time in Latin America (Ingram and Carroll, 1981) and the US (Mills, 1970; Macauley, 1985; Kim, 2007), which might be due to an increase in incomes and a decrease in transportation costs (Mills, 1970). Second, this gradient depends on the characteristics of the cities. More populous cities tend to have flatter gradients (Muth, 1969; Guest, 1973; Edmonston and Davies, 1976; Glickman and Oguri, 1978; Johnson and Kau, 1980; Mills and Tan, 1980; Alperovich, 1983; Bertaud and Malpezzi, 2014): one explanation is that employment subcenters are more likely to emerge in large areas. Older urban areas tend to have steeper gradients, possibly because of the inertia in urban shapes: cities that developed when transportation costs were high are more likely to be compact (see the studies by Glickman and Oguri, 1978, in Japan and Johnson and Kau, 1980, in the US). Overall, income has been found to have a weak negative impact on the steepness of the gradient (Mills and Tan, 1980). Comparing developed and developing countries, Mills and Tan (1980) found that developed countries have flatter density functions than developing countries, as they have higher incomes and better urban transportation systems. Working on a diverse sample of 57 cities, Bertaud and Malpezzi (2014) found that cities subject to stringent regulations, such as Brasilia, or complex geographies, such as coastal cities, exhibit a flatter gradient.

Recently, the increase in data availability has allowed studies to be performed on large samples of cities (see for instance Lemoy and Caruso, 2020, working on 300 European cities) or with better proxies for transportation costs. Qiang et al. (2020), for instance, use transportation time data from Google Maps instead of distances to city centers. These data could allow empirical assessment, using larger samples and with increased accuracy, of the extant results relating to density gradient heterogeneity between cities of different sizes or degrees of monocentricity found in the literature.
2.2.3. Urban areas

Finally, the following relationship can be derived from the SUM with respect to urban areas: their sizes should depend positively on population and income and negatively on transportation costs and farmland rents (equation 13). Many papers have empirically verified these results in the US (Brueckner and Fansler, 1983; McGrath, 2005; Wassmer, 2006; Spivey, 2008; Paulsen, 2012), finding that population, income, and farmland rents have the expected impact on urban areas. An important exception is Spivey (2008), estimating a negative income elasticity, which she explains by the fact that the increase in incomes increases the demand for more affordable housing farther from the city center, but also raises the opportunity cost of time, the second effect outweighing the first. However, these studies struggled to find proxies for transportation costs, leading to mixed results. Spivey (2008) uses the fraction of households owning a car, which is not robust in her main specification, and the Texas Transportation Institute’s “time travel index” and “congestion cost index,” with which she finds mixed evidence. Paulsen (2012) does not include any commuting cost variables: the author considered the census average travel time to work, but finally dropped this variable.

Fewer studies exist in Europe. Oueslati et al. (2015) found conclusive results, with all variables being significant and of the expected sign. In particular, the authors found a high coefficient for farmland rents, which reflects the fact that in Europe, agriculture at the urban fringe is often highly intensive, offering relatively high yields and profits. In Germany, Schmidt et al. (2020) found a particularly low coefficient for income, which they explain by the fact that increased demand for housing is not realized due to growth management policies and restrictive land-use regulations. Their proxies for transportation costs were found to be unreliable, leading to insignificant estimates, or to estimates whose sign is opposite to that which is expected. They also found differences between east and west Germany and between growing and shrinking regions.

Few studies focused on developing countries. The existing studies on China (Deng et al., 2008; Ke et al., 2009) found that income growth played a significant role in determining urban sprawl. Recently, Jedwab et al. (2021) showed that cities in developing countries grow differently to those in developed countries, i.e. by crowding “in” instead of sprawling or growing “up”.

At a global level, analyzing both total urban land cover in 206 countries and urban land cover in 3646 large urban areas worldwide, Angel et al. (2011) found significant estimates of the expected sign, except for transportation costs. However, the authors do not analyze the heterogeneity of their results by world regions or development level.
3. Data

3.1. Spatially-explicit data

Our main dataset, described in detail in Lepetit et al. (2022), is a spatially-explicit dataset including population densities, rents, dwelling sizes, transportation times, and land cover in 192 cities worldwide. This dataset’s originality lies in the provision of data on cities’ internal structures at a 1km$^2$ resolution, in particular on rents and transportation times, while covering a large and diverse sample of 192 cities on five continents. By combining data on density, real estate, transportation, and land cover, this dataset allows us to run an integrated analysis of the validity of the SUM in the sample. The main data collection steps are summarized below.

The cities were chosen to obtain wide geographical coverage, and represent different cultural and historical backgrounds. However, data availability, in particular for real estate, has been a limiting criterion. The cities selected are medium to large cities: they all have more than 300,000 inhabitants, and together represent 800 million people, i.e. 19% of the global urban population, or 34% of the people living in cities of more than 300,000 inhabitants (Figure 1).

![Figure 1: Sample of cities for which data were collected.](image)

First, we divided each city into a georeferenced 1 km$^2$-resolution grid encompassing the whole urban area. Then, we combined data from different sources and aggregated them on these grids. For land use, we used the European Space Agency land cover data (ESA, 2017), available worldwide at a 300m spatial resolution on an annual basis from 1992 to 2015. We reclassified areas as “urbanizable” (e.g.,
farmlands) or “non-urbanizable” (e.g., water bodies) (Annex A). For population density, we used the European Commission GHSL data available for 1975, 1990, 2000, and 2015 at a 250m resolution worldwide (Schiavina et al., 2019).

Data on dwelling rents per m² and dwelling sizes were most difficult to obtain, as no global database exists. We obtained them by web-scraping real estate websites between 2017 and 2020. The websites were selected to meet four criteria: the website must have nationwide coverage to ensure consistent results in a given country, it must geolocalize the dwellings, have values for both rent or sale prices and dwelling size, and be written in the local language and give prices in local currency to limit real estate ads targeting expatriates. We aggregated the data at the grid cell level by taking mean rents per square meter. We computed two variables to assess rent data quality (Table 1): first, "Real estate data market cover" which corresponds to the average number of real estate ads that were scraped per grid cell in the city\textsuperscript{1} and second, "Real estate data spatial cover", the percentage of grid cells that have density data and for which we also have data on rents\textsuperscript{2}. In 109 cities out of 192, the spatial data cover of rent ads is above 10%, and in 153 cities out of 192, the spatial data cover is above 5%. In 95 cities out of 192, we scraped more than 1 rent ad per 1,000 inhabitants, and in 174 cities out of 192, we scraped more than 1 rent ad per 10,000 inhabitants.

\begin{table}[h]
\centering
\begin{tabular}{lcccccc}
\hline
 & Mean & Min. & Q1 & Med. & Q3 & Max. & Nb. of obs. \\
\hline
Market cover & 14168 & 98 & 550 & 1020 & 2281 & 810960 & 192 \\
Spatial cover & 11.81\% & 0.07\% & 5.79\% & 10.90\% & 15.41\% & 59.14\% & 192 \\
\hline
\end{tabular}
\caption{Real estate data quality.}
\end{table}

\textit{For 50\% of the cities, we scraped more than 1 real estate ad per 1,020 inhabitants, and we scraped real estate ads for more than 10.9\% of the inhabited pixels.}

Transport distances and durations from each grid cell to the city center have been estimated using Google Maps and Baidu Maps APIs (Application Programming Interfaces). Different definitions of city centers exist in the urban economics literature. Most rely on job density data, which are unfortunately not consistently available for the cities in the database. Therefore, this study defined city centers on the basis of a compromise between five qualitative criteria: the geographical center of the data, the historical center of the city, the location of the public transport hub, the official central business district, and the city hall location. When available, both driving and public transport data were collected for typical afternoon rush hours\textsuperscript{3}.

\textsuperscript{1}This is given by (population/number of ads).
\textsuperscript{2}This is given by (number of pixels with real estate data)/(number of pixels with population > 0).
\textsuperscript{3}We have identified rush hours for each city by extracting a sample of transportation data at
It was not possible to collect transport data from each grid cell, so 10% of all cells were collected\(^4\) and then performed bivariate interpolation using the R package AKIMA, allowing us to approximate transportation times for the whole grid.

### 3.2. Aggregated data at the city level

To complement the spatially-explicit dataset, we use data relating to characteristics of the whole cities, detailed below.

City populations are derived from the spatially explicit dataset and correspond to the sum of the densities over the grid. Similarly, urbanized areas correspond to the sum of the urbanized area data over the grid. We are aware that this definition of city limits is likely to overestimate population and urbanized area, but it allows the extent of "urban area" to be identical for the two variables and independent of city administrative or legally-defined boundaries. Indeed, the extent of functional urban areas may differ substantially from cities’ administrative limits: administrative or legally-defined city boundaries tend to adapt slowly to rapid changes in population and economic activities and are highly inconsistent between countries (Moreno-Monroy et al., 2021).

Incomes are approximated using World Bank GDP per capita data at the country level. We also use World bank data on gasoline prices and International Energy Agency (2012) data on fuel efficiency to compute the cost of travel by car. We estimate farmland rents with data from the FAO, dividing agricultural GDP by the total agricultural area in the country.

We measure monocentricity using a qualitative index that shows the extent to which the geographical center, the historical center, the public transport hub, the official CBD, and the town hall are located in the same place. The higher this index, the more monocentric the city. For instance, in Paris, the historical center (Notre Dame), the transport hub (Châtelet - Les Halles), and the town hall (Hôtel de Ville) are very close to each other: only the official CBD (la Défense) is located further away, at 8km from the city center. This is a rough proxy compared to the approach used in other studies (see, for instance, Ahlfeldt et al., 2020), but no consistent database of employment centers is available for all the sampled cities.

We use data on the percentage of informal housing per country and Gini indices per country from the World Bank. We have also designed a categorical variable for the regulatory environment. This variable, based on Bertaud and Malpezzi (2014), is equal to 2 for “stringently planned cities in violation of market principles” (such

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\(^{16h, 16h30, 17h, 17h30, 18h, 18h30, 19h, 19h30, \text{and 20h, by comparing the average delay due to congestion, and by defining rush hours as the moment when the average delay is highest.}}\)

\(^{4}\text{With a method close to Saiz and Wang (2021), we defined a star shape with 8 branches, centered on the city center, and we collected data from the grid cells at a regular distance along each star branch so that the number of grid cells for which data were collected equals 10% of the total number of grid cells.}\)
as Moscow and Brasilia), to 1 for cities, like Warsaw or Sofia, that have imposed stringent planning onto a market-oriented base and to 0 for market-oriented (though still planned) cities. This variable has been taken from Bertaud and Malpezzi (2014) for the 45 cities in common between their sample and ours. For the remaining cities, we used our own judgement to allocate this variable: we looked at whether the Internet-based information available for each city, relying mainly on Wikipedia, mentions a widespread, stringent planning approach. The table showing this variable can be found in Annex C.

4. Testing the monocentric city model

4.1. Rent gradients

4.1.1. Empirical strategy

This subsection empirically assesses the relationship between rents per m² and transportation times. Building on equation 3, we run the following regression on the cities in the database:

\[
\ln(R_i,c) = e_c + f_c \ln(Y_c - T_{i,c}) + \varepsilon_{i,c}
\]  

We run this regression 191 times to individually estimate \(e_c\) and \(f_c\) for all the sampled cities. \(e_c\) is a constant, and \(f_c\) can be interpreted structurally as \(1/\beta_c\), drawing on equation 3. Finally, the error term \(\varepsilon_{i,c}\) accounts for the fact that, in reality, locations within cities differ in attributes other than transportation costs, such as neighborhood-based or dwelling-based amenities (Cheshire and Sheppard, 1995; Ahlfeldt, 2011).

Our empirical approach, theoretically grounded, differs from the existing studies by using a measure of income net of transportation costs instead of transportation costs alone. In practice, we assume that incomes are constant within cities so that incomes net of transportation costs only vary with transportation costs. This approach is equivalent to the majority of the existing literature, which directly regresses rents on a proxy of transportation costs, except that it allows us to interpret parameter \(f_c\) as \(1/\beta_c\). However, a monetary measure of transportation cost is required to compute \(Y_c - T_{i,c}\): we thus cannot simply measure transportation costs as the Euclidean distance to the city center, as in most existing studies.

Like Qiang et al. (2020), we use commuting times and distances from Google Maps data. We go two steps further by considering two transportation modes and accounting for both opportunity and monetary costs. We compute transportation costs as follows:

\[5\] In this section, the city of Sfax is excluded from the sample because of insufficient real estate data quality.
• We assume that households choose the cheaper transportation mode between private cars and public transport;

• For each transportation mode, we derive the opportunity cost of time from Google Maps’ transportation time data assuming that workers value it at the hourly wage rate;

• We compute the monetary cost of private cars as the product of the commuting distance, vehicle efficiency, and fuel prices;

• We assume that the monetary cost of public transport is a fixed cost per trip, thus independent of distance: this varies between cities and has been obtained from various sources.

However, this measure of transportation costs might be endogenous. Indeed, it is based on real-world speeds, which depend on congestion and infrastructure and might capture negative externalities of transport infrastructures such as noise or barrier effects. To overcome this limitation, we use the logarithm of the Euclidean distance to the city center as an instrumental variable (2SLS approach). Indeed, changes in distances to the city center are likely to impact transportation costs, but they have little impact on transportation-infrastructure-related amenities or disamenities.

4.1.2. Results

We start by analyzing the sign of parameter $f_c$. Based on the theory, we expect that rents will increase with income net of transportation costs, leading to a positive estimate of $f_c$. However, the existing literature has found mixed evidence regarding the relationship between rents and transportation costs (see subsection 2.2.1).

Figure 2 shows, for each city, based on the 2SLS specification, whether the estimate for parameter $f_c$ is positive and significantly different from 0 at the 10% level, negative and significant at the 10% level, or non-significant at the 10% level. We find, as expected, that the parameter is positive and significant at the 10% level in the vast majority of the cities (167 with 2SLS). However, we find that it is non-significantly different from 0 in 23 cities with 2SLS, including cities where our data are of low quality (Isfahan, Mashhad, Fez), cities with a large percentage of informal housing (Addis Ababa, Abidjan, Manaus), and coastal cities where coastal amenities are likely to impact rent gradients (Nice, Patras). It is negative in one city, Riga.
Figure 2: Map of the direction and significance of parameter \( f_c \) (rent elasticity with respect to income net of transportation costs), estimated with 2SLS. *This parameter is positive and significant in 167 cities, negative and significant in one city, and non-significant in 23 cities.*

To understand whether the relationship between accessibility and rents theorized in the SUM is verified, we also compute the \( R^2 \) of regression (Table 2), which can be interpreted as the percentage of the variance in rents per m\(^2\) that is due to the variance in transportation costs. We find that the mean \( R^2 \) is 0.20 and that \( R^2 \) can be up to 0.66 in some cities (OLS), supporting the postulate that rents strongly depend on transportation costs to the city center but showing significant heterogeneity between cities.

|         | Mean | Min. | Q1  | Med. | Q3  | Max. | Nb. of obs. |
|---------|------|------|-----|------|-----|------|-------------|
| OLS     | 0.20 | 0.00 | 0.06| 0.18 | 0.31| 0.66 | 191         |
| 2SLS    | 0.19 | -0.17| 0.04| 0.16 | 0.30| 0.66 | 191         |

Table 2: Distribution of the \( R^2 \) of equation 14.

Then, we analyze the value of the estimate of \( f_c \). Figure 3 shows the distribution of these estimates. Despite a few negative or very high values (above 8), most estimates are between 0 and 6, with a median estimate of 2.71 and a mean of 3.10 (2SLS): on average for our sample of cities, when income net of transportation costs increases by 1%, rents increase by 3.1%. This can be interpreted as \( \beta_c \) being around 1/3 in most cities, meaning that households spend around one-third of their income net of transportation costs on housing, which is consistent with the data available for the OECD countries\(^6\).

\(^6\)OECD affordable housing database, [https://www.oecd.org/housing/data/affordable-housing-database/housing-conditions.htm](https://www.oecd.org/housing/data/affordable-housing-database/housing-conditions.htm), accessed on May 17, 2022
4.1.3. Second-step regressions

This section further examines heterogeneity in the estimates of parameter $f_c$. We aim to understand why rents are highly dependent on transportation costs to the city center in some cities, leading to high rent gradients, while this is not the case in others, leading to low or even inverted gradients. For that purpose, we regress our estimates of parameter $f_c$ on a set of city characteristics based on the literature and on the intuitions derived from Figure 2 (Table 3).

In the literature, transportation costs to the city center have been found to be good predictors of rents, but their explanatory power can be mitigated by polycentrism and local amenities (see section 2.2). Therefore, in specification (1), we regress estimates of parameter $f_c$ on monocentricity and on a dummy indicating whether the city is coastal, since the sea is in general associated with strong locational amenities that are likely to impact the real estate market. We also control for rent data quality and for population, as subcenters are more likely to emerge in more populous cities. We find that the relationship between income net of transportation costs and rents is stronger in non-coastal cities. Transportation costs to the city center are also a better predictor of rents in monocentric cities, but this coefficient is non-significant. Finally, as expected, we find a stronger relationship between rents and income net of transportation costs when our real
estate data are of better quality.

In specification (2), we add three variables: the Gini index, the percentage of informal housing, and the stringency of the regulatory environment. The first two are based on our observation that the estimate of $f_c$ seems to be non-significant in some cities with high inequalities and levels of informal housing. The third is based on Bertaud and Malpezzi (2014), who observe that the regulatory environment might affect the city's structure. We find that the estimate of parameter $f_c$ is lower in cities with a large percentage of informal housing. We also find higher estimates in cities for which we have good-quality data. The dummy for coastal cities is no longer significant. The categorical variable coding for stringent regulations is also non-significant at the 10% level: an explanation might be that, even in a stringently regulated city such as Moscow with a population density pattern that departs from the monocentric SUM pattern, housing prices may have initially been random, but over time consumers tend to value accessibility and housing prices tend to follow the negative density gradient, similarly to market economies (Bertaud and Malpezzi, 2014; Bertaud and Renaud, 1997).

Specification (3) includes continental fixed effects, taking Europe as the reference. In this specification, the percentage of informal housing is significant at the 1% level; we also find that the relationship between transportation costs and rents is stronger in Asian cities. Overall, in these three specifications, $R^2$ values vary between 0.073 and 0.227: we are only able to provide limited explanations of the heterogeneity in rent gradients between cities. This might be due to unobserved variables: for instance, the only amenity we account for is that provided by a coastal location, and we cannot account for other location-based or dwelling-based amenities. Another explanation might be quality of variables. The "regulatory environment" dummy, for instance, is based in some cases on the authors' judgement and might lack accuracy. Finally, some of the explanatory variables might be correlated, such as the quality of real estate data and the percentage of informal housing.
| Dependent variable: rent gradients $f_c$ | (1)     | (2)     | (3)     |
|---------------------------------------|--------|--------|--------|
| Coastal city                         | -0.700*| -0.602 | -0.395 |
|                                      | (0.408) | (0.408) | (0.409) |
| Monocentricity index                 | 0.196  | -0.318 | 0.567  |
|                                      | (0.426) | (0.479) | (0.487) |
| log(population)                      | -0.132 | 0.161  | -0.255 |
|                                      | (0.183) | (0.221) | (0.236) |
| Market data cover                    | -0.000 | -0.000 | -0.000**|
|                                      | (0.000) | (0.000) | (0.000) |
| Spatial data cover                   | 7.474***| 6.707**| 3.196  |
|                                      | (2.625) | (2.657) | (2.593) |
| Gini index                           | -0.045 | -0.037 |        |
|                                      | (0.030) | (0.044) |        |
| Percentage of informal housing       | -0.035*| -0.091***|
|                                      | (0.021) | (0.026) |        |
| Regulatory environment               | 0.265  | 0.374  |        |
|                                      | (0.413) | (0.404) |        |
| Asia                                 | 4.065***|
|                                      | (0.919) |        |        |
| Africa                               | 0.329  |        |        |
|                                      | (1.213) |        |        |
| Oceania                              | -1.275 |        |        |
|                                      | (0.994) |        |        |
| North America                        | -0.060 |        |        |
|                                      | (0.946) |        |        |
| South America                        | 1.429  |        |        |
|                                      | (0.987) |        |        |
| Constant                             | 4.035  | 2.955  | 6.576**|
|                                      | (2.868) | (3.029) | (3.213) |

| Observations                        | 191    | 191    | 191    |
|                                     |        |        |        |
| $R^2$                                | 0.073  | 0.104  | 0.227  |
|                                     |        |        |        |
| Adjusted $R^2$                       | 0.048  | 0.065  | 0.170  |
|                                     |        |        |        |
| F Statistic                         | 2.904**| 2.647***| 4.002***|

Note: * p<0.1; ** p<0.05; *** p<0.01

Table 3: Second-step regression of the estimates of rent gradients $f_c$ against city characteristics.
4.1.4. Robustness checks

We run some robustness checks for alternative specifications of equation 14. In particular, we regress the logarithm of rents per m$^2$ on the Euclidean distance from the city center, instead of considering the logarithm of the income net of transportation costs. On average, in the sample of cities, we find a gradient of -0.014, meaning that going 1km farther from the city center decreases rents per sqm by 1.4% (Annex B, Figure B.5). We also find heterogeneity in the estimates of this gradient between cities: the interquartile range is -0.019 - -0.006, and the results of the second-step regression show that this gradient is steeper in Asia and South America, and flatter in cities with a large percentage of informal housing.

We run some additional robustness checks, including regressing the logarithm of rents per m$^2$ on the logarithms of transportation costs or transportation times instead of regressing them on the logarithm of incomes net of transportation costs. Full details and results are in Annex B. Overall, our results are robust to alternative specifications. Depending on the robustness check performed, a rent gradient of the expected direction is found in between 157 and 167 cities. The percentage of informal housing, the data quality, and the continental fixed-effects are found to impact the value of the rent gradient in all robustness checks.

To summarize this subsection, despite the rent gradient having rarely been studied in the literature, in particular in developing countries, we found a gradient of the expected direction in most of the cities in our sample, with a mean elasticity of around 3 that can structurally be interpreted as households spending on average one-third of their income net of transportation costs on housing. However, low data quality or a high percentage of informal housing make the rent gradient flatter, so that an important direction for future research should be to adapt the monocentric SUM to such local contexts.

4.2. Density gradients

4.2.1. Empirical strategy

This subsection examines a second relationship derived from the SUM: the negative population density gradient from the city center to the periphery. We expect population density to decrease with transportation costs or increase with income net of transportation costs. Building on equation 10, we run the following regression on the sampled cities:

$$ln(n_{i,c}) = g_c + h_c ln(Y_{c} - T_{i,c}) + u_{i,c}$$

(15)

We run this regression 192 times to individually estimate $g_c$ and $h_c$ for all the sampled cities. The error term $u_{i,c}$ accounts for the fact that locations within cities differ in attributes other than transportation costs. We can structurally interpret parameters $h_c$ as $(1/\beta_c a_c) - 1$. 

18
We empirically measure the income net of transportation costs as in the previous subsection and use the Euclidean distance to the city center as an instrumental variable. Population density in city $c$ and pixel $i$ is measured as $n_{i,c} = \frac{N_{i,c}}{L_{i,c}}$ with $N_{i,c}$ the total population in the pixel derived from the GHSL data and $L_{i,c}$ the amount of urbanizable land in the pixel derived from ESA CCI land cover data.

4.2.2. Results

We start by analyzing the sign of parameter $h_c$. Based on the theory, we expect this parameter to be positive: population density should decrease when transportation costs increase, or when income net of transportation costs decreases. Empirically estimating this parameter in our sample, we find that it is significantly positive at the 10% level in all the cities.

Table 4 shows the distribution of the $R^2$ of regression 15 in the sampled cities, which can be interpreted as the percentage of the variance in population densities explained by accessibility. We find a median $R^2$ of 0.17 and a maximum of 0.46, meaning that accessibility is a strong determinant of population densities in a large number of cities in our sample. These $R^2$ figures are not as high as in some existing studies (such as Bertaud and Malpezzi (2014)): an explanation is that we analyze our data at a highly disaggregated level, not grouping them by rings for instance (Duranton and Puga, 2015).

|       | Mean | Min. | Q1  | Med. | Q3  | Max. | Nb. of obs. |
|-------|------|------|-----|------|-----|------|-------------|
| OLS   | 0.19 | 0.02 | 0.12| 0.17 | 0.24| 0.46 | 192         |
| 2SLS  | 0.15 | -1.12| 0.09| 0.15 | 0.23| 0.46 | 192         |

Table 4: Distribution of the $R^2$ of equation 15.

Figure 4 shows the distribution of the estimates of parameter $h_c$ in the sampled cities. The mean estimate is 21.17, meaning that, on average, in our sample, when income net of transportation costs decreases by 1%, population density decreases by 21.17%. However, despite being always positive, estimates are highly heterogeneous between cities. The minimum is 2.5, the maximum 58.7, and the interquartile range 13.2 - 27.5 (2SLS).

We can structurally derive the elasticity of housing production with respect to land and capital (parameters $a_c$ and $b_c$ from equation 4). From equation 10, $h_c = \frac{1-\beta_c a_c}{\beta_c a_c}$, and from equation 3, $f_c = \frac{1}{\beta_c}$, meaning that we can derive $a_c$ as $f_c \frac{1}{1+h_c}$. Using the estimates of $f_c$ from subsection 4.1 and the estimates of $h_c$ from this subsection, we find that the median estimate of the elasticity of housing production

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7Running the same regressions, aggregating the data into 1km rings, leads to a median $R^2$ of 0.71 and a mean $R^2$ of 0.73 (OLS).
with respect to land $a_c$ over the sample of cities is 0.13 (interquartile range of 0.08-0.21) and that the median estimate of the elasticity of housing production with respect to capital $b_c$ over the sample of cities is 0.87 (interquartile range of 0.79 - 0.92). Our results are in line with Epple et al. (2010), who estimate a land elasticity of 0.14, but slightly differ from Combes et al. (2021), who estimate a capital elasticity of 0.65 for France.

![Histogram of parameter $h_c$.](image)

**Figure 4:** Distribution of the estimates of parameter $h_c$ (elasticity of population density with respect to the income net of transportation costs) in the 192 cities.

### 4.2.3. Second-step regressions

This section further investigates the heterogeneity in density gradients by regressing our estimates of $h_c$ against city characteristics (Table 5).

Specification (1) is based on the density gradient literature, which suggests that polycentrism leads to flatter density gradients. Some studies show that larger populations lead to flatter gradients, an explanation being that employment subcenters are more likely to emerge in larger urban areas (see subsection 2.2.1). Incomes and transportation costs have also been found to play a role in explaining density gradients (see subsection 2.2.1). However, they are already accounted for in our first step empirical regressions (equation 15), and therefore we do not need to include them in this second-step regression.
Empirically testing these hypotheses, we find that larger (in terms of population) and more polycentric urban areas tend to have flatter density gradients. The $R^2$ of this first specification is 0.38, meaning that population and polycentricity explain a large percentage of the variance in density gradients across urban areas. Since, here, population is included in the second-step regression as an indicator of polycentricity, it may be surprising that population and monocentricity are both significant. We attribute this to the quality of our monocentricity index: it indicates whether the historical, geographical, transportation, administrative, and business centers are all located in the same place, but it does not indicate whether the city has a large number of subcenters, which is proxied by the city’s population. Thus, the total population and the monocentricity index correspond to two different definitions of monocentricity.

In specification (2), we add four explanatory variables: the level of inequalities, the percentage of informal housing, and two categorical variables indicating whether the city is coastal and whether there is a stringent regulatory environment. The first two variables are based on our observation that rent gradients seem to be flattened in cities with a large percentage of informal housing or inequalities (Figure 2). The two categorical variables are based on Bertaud and Malpezzi (2014), who find that complex geographies or stringent regulatory environments flatten the density gradient. We find that a large percentage of informal housing and high inequality levels tend to flatten the population density gradient, the two variables being significant at the 1% level. Monocentricity and population remain significant as well.

Specification (3) adds continent fixed effects, taking Europe as the reference. Population, monocentricity, and informal housing remain significantly different from 0 at the 1%, 1%, and 5% levels respectively: cities with larger populations, more subcenters, and more informal housing tend to have flatter density gradients. Surprisingly, the dummy for stringent regulatory environments is positive and significant at the 10% level, meaning that cities with strong regulations tend to have steeper density gradients, which contrasts with Bertaud and Malpezzi (2014). However, as Bertaud (2004) has observed, some cities subject to stringent regulations developed before the implementation of the latter, and have kept an urban form that is to some extent similar to market-oriented cities. For instance, Central and Eastern European cities, such as Cracow, were stringently regulated during the socialist era, but these cities had a large historical center established many centuries before socialism so that they have remained largely monocentric. Finally, African and Oceanian cities tend to have flatter density gradients.
|                         | (1)          | (2)          | (3)          |
|-------------------------|--------------|--------------|--------------|
| log(population)         | -5.895***    | -4.192***    | -5.428***    |
|                         | (0.626)      | (0.690)      | (0.856)      |
| Monocentricity index    | 6.525***     | 3.148**      | 4.346***     |
|                         | (1.314)      | (1.463)      | (1.591)      |
| Gini index              | -0.263***    | -0.104       |              |
|                         | (0.087)      | (0.147)      |              |
| Percentage of informal housing | -0.218*** | -0.176**     |              |
|                         | (0.053)      | (0.070)      |              |
| Coastal city            | 0.386        | 1.583        |              |
|                         | (1.362)      | (1.508)      |              |
| Regulatory environment  | 2.512        | 3.119*       |              |
|                         | (1.584)      | (1.749)      |              |
| Asia                    | 2.602        |              |              |
|                         | (3.939)      |              |              |
| Africa                  | -8.157***    |              |              |
|                         | (2.968)      |              |              |
| Oceania                 | -9.958***    |              |              |
|                         | (2.442)      |              |              |
| North America           | 2.598        |              |              |
|                         | (3.429)      |              |              |
| South America           | -3.264       |              |              |
|                         | (3.801)      |              |              |
| Constant                | 92.486***    | 86.716***    | 95.918***    |
|                         | (10.650)     | (11.113)     | (12.958)     |

|                         |             |              |              |
| Observations            | 192         | 192          | 192          |
| $R^2$                   | 0.375       | 0.448        | 0.508        |
| Adjusted $R^2$          | 0.368       | 0.430        | 0.478        |
| F Statistic             | 70.21***    | 40.15***     | 29.49***     |

*Note:* $^* p<0.1; ^{**} p<0.05; ^{***} p<0.01$

Table 5: Second-step regression of population density gradient estimates $h_c$ against city characteristics.
We run some robustness checks for alternative specifications of equation 15. In particular, we regress the logarithm of population density on the Euclidean distance from the city center, instead of considering the logarithm of the income net of transportation costs. On average, in the sample of cities, we find a gradient of -0.085, meaning that going 1km farther from the city center decreases population density by 8.5% (Annex B, Figure B.6). We find some heterogeneity in the estimates of this gradient between cities: the interquartile range is -0.102 - -0.060, and results of the second-step regression show that this gradient is flatter in North America, Oceania, and when the city is larger in terms of population, and steeper when the city is coastal or has a large percentage of informal housing.

We run some additional robustness checks, including regressing the logarithm of population densities on the logarithm of transportation costs or transportation times instead of regressing them on the logarithm of incomes nets of transportation costs. Full details and results are in Annex B. Overall, our results are robust to alternative specifications. A density gradient of the expected direction is found in all of the cities and with all robustness checks. The population of the city, its monocentricity, and continent-fixed effects are found to impact the value of the density gradient in most of the robustness checks. The percentage of informal housing has an impact on density gradients in some of the robustness checks performed.

To summarize this subsection, we find that the expected negative population density gradient is observed in all of the cities in our sample. In addition, in line with the literature, we found flatter density gradients in larger, and more polycentric, cities. A direction for future research should be incorporating informality into urban models, as we also observed flatter density gradients in cities with large percentages of informal housing.

This subsection examines whether the size of urban areas increases with population and income and decreases with farmland rents and transportation costs, as suggested by the SUM (equation 13).

In the first specification (“all cities”) of Table 6, we regress urbanized areas on a range of city characteristics derived from the theory (subsection 2.1), including populations, incomes, and farmland rents. We add two commuting cost variables: fuel price and "commuting speed", which is the density-weighted average speed when traveling to the city center during the evening rush hour using the fastest transportation mode (car or public transport). We also include the monocentricity index, as many studies argue that polycentricity impacts the size of urban areas. Spivey (2008) finds that more sub-centers are associated with a smaller land area in
the United States, which she interprets as the fact that sub-centers are more likely to develop in dense areas or that increased density associated with sub-centers mitigates sprawl. Paulsen (2012) confirms this result. In contrast, Burchfield et al. (2006) find that decentralized employment increases sprawl in the US. Schmidt et al. (2020) find non-significant estimates of the impact of polycentricity on the size of urban areas in Germany.

We find an $R^2$ of 0.86, meaning that city characteristics explain a large percentage of the variance in the size of urbanized areas among the sampled cities. In addition, all the coefficients of the explanatory variables are significant and of the expected sign, except for fuel price. For instance, a 1% increase in population leads to a 0.86% increase in the urban area, in line with Spivey (2008), which finds an elasticity of 0.91, and slightly higher than Paulsen (2012), which finds elasticities of between 0.56 and 0.64. We also find that a 1% increase in incomes leads to a 0.40% increase in the urban area. An increase in farmland rents tends to decrease urban areas, and an increase in commuting speed, corresponding to a decrease in the opportunity cost of transportation, increases urban areas. The non-significant estimate for fuel price might be caused by cities’ inertia when compared to the relative volatility of fuel prices. Finally, for monocentricity, we find a positive coefficient significant at the 10% level, in line with Spivey (2008).
### Table 6: Regression of urbanized areas against city characteristics.

To further investigate the heterogeneity in the determinants of urbanized areas between cities, we slice the result by income levels. “High income” cities are those located in high-income countries, according to the World Bank classification. “Upper-middle income to low income” corresponds to the cities located in upper-middle, lower-middle, or low income countries according to the World Bank classification. In our sample, all North American and Oceanian cities are classified as high-income, as well as 2 Asian cities (Hong Kong and Singapore), 4 South American cities (in Uruguay and Chile), and most European cities (83/97). The remaining cities are all African cities, most Asian cities (30/32), and most South American cities (30/34). This classification allows us to split our sample into:

| Dependent variable: log(urbanized area) | All cities | High income | Upper-middle income to low income |
|----------------------------------------|------------|-------------|----------------------------------|
| log(population)                        | 0.856***   | 0.913***    | 0.778***                         |
|                                        | (0.040)    | (0.067)     | (0.047)                          |
| log(income)                            | 0.397***   | 0.277**     | 0.436***                         |
|                                        | (0.038)    | (0.125)     | (0.055)                          |
| log(farmland rents)                   | -0.220***  | -0.311***   | -0.076                           |
|                                        | (0.043)    | (0.056)     | (0.047)                          |
| log(fuel price)                       | -0.061     | 0.125       | -0.153                           |
|                                        | (0.101)    | (0.213)     | (0.136)                          |
| log(commuting speed)                  | 0.466***   | 0.434**     | 0.563***                         |
|                                        | (0.100)    | (0.168)     | (0.132)                          |
| Monocentricity index                  | 0.146*     | 0.101       | 0.199**                          |
|                                        | (0.082)    | (0.172)     | (0.085)                          |
| Constant                               | -12.876*** | -12.413***  | -12.070***                       |
|                                        | (0.624)    | (0.998)     | (0.847)                          |

Observations | 192 | 108 | 84  
$R^2$         | 0.858 | 0.866 | 0.878  
Adjusted $R^2$ | 0.853 | 0.858 | 0.869  
F Statistic | 225.7*** | 184.9*** | 96.78***  

Note: *p<0.1; **p<0.05; ***p<0.01

Table 6: Regression of urbanized areas against city characteristics.
two groups each containing a similar number of cities, with each group broadly corresponding to three continents. Unfortunately, we cannot slice the results by continent due to data limitations: we do not have enough cities for some continents (we only have 8 cities for Oceania and 10 cities for Africa) or enough heterogeneity within continents (the fact that all of the North American cities of the sample are located in the USA is problematic because we only have data at the country level for some explanatory variables).

We run a Chow test to check whether we need separate models for these two groups of cities. The test is significant at the 5% level, meaning that the differences in estimated coefficients across the two sub-samples are not the result of sampling error.

We find that an increase in population has a larger impact on the size of urbanized areas in high-income cities than in other cities, whereas income has a larger impact on the size of urbanized areas in middle and low-income cities. The latter result is in line with the studies that find that income growth is a large driver of urban sprawl in developing countries (Deng et al., 2008; Ke et al., 2009). It is also in line with Schmidt et al. (2020): they find that income has a low impact on urban sprawl in Germany, which they explain by the growth management policies that eliminate the impact of income in Germany. Farmland rents have a large negative impact on urban sprawl in high-income countries, in line with the findings of Oueslati et al. (2015): they found a high coefficient for farmland rents, which, according to the authors, reflects the fact that in Europe, agriculture on the urban fringe is often highly intensive, offering relatively high yields and profits. Commuting speed has a smaller impact on high-income countries. Finally, monocentricity is non-significant in high-income countries, whereas it is significant for middle-income and low-income countries.

5. Conclusion

Exploiting a new spatially-explicit dataset on population densities, land cover, but also real estate and transportation costs, we are able to empirically assess the main relationships derived from the SUM in a large and diverse sample of cities. In particular, we can assess the SUM’s predictions in terms of internal city structures, evaluating density and rent gradients in 192 global cities.

Although the SUM is an old, simple model, we show that its main predictions are verified for our sample of cities. We find the expected declining rent gradient from city centers to suburbs in 167 out of 192 cities and the expected declining density gradient from city centers to suburbs in all the sampled cities. In addition, we find that the total urbanized area of a city tends to increase with population and income and decrease with farmland rents and transportation costs, as expected from the theory.
Our dataset also allows us to investigate heterogeneity in the internal structures of cities. Large or polycentric cities are more likely to have flat density gradients, as are cities with a higher percentage of informal housing. Cities are more likely to have flat or inverted rent gradients if they have a large percentage of informal housing or if the quality of our rent data is lower. Overall, urban sprawl in high-income cities is largely driven by population and farmland rents, whereas income plays a key role in developing countries.

This result implies that the SUM does not perfectly fit all cities. Coastal amenities, polycentricity, and informal housing can lead to flatter, and sometimes inverted, rents and density gradients, so that modelling cities more accurately requires more complex models that account for these dimensions, in particular beyond the SUM’s traditional application area (North America, Europe).

A first limitation of this study is that it only assesses the simplest version of the SUM. Indeed, data were missing that would have enabled systematic study of more advanced urban models. Gathering data on employment subcenters and transportation costs to these employment centers is, for instance, outside the scope of this study. However, the development of new big data approaches will allow this gap to be filled in future research (Barzin et al., 2022).

Another limitation is that the SUM is mostly a static model, whereas there is inertia in cities’ development. Densities and built environment are changing slowly (as are transport times, to some extent), whereas rents and land prices can change quickly. Obtaining panel data on cities would be necessary in order to study changes in city structures over time.

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### Annex A. Land cover classification

| ESA CCI land cover category | Reclassification |
|----------------------------|------------------|
| 10 Cropland, rainfed       | Urbanizable      |
| 11 Herbaceous cover        | Urbanizable      |
| 12 Tree or shrub cover     | Urbanizable      |
| 20 Cropland, irrigated or post-flooding | Urbanizable |
| 30 Mosaic cropland (>50%) / natural vegetation (<50%) | Urbanizable |
| 40 Mosaic natural vegetation (>50%) / cropland (<50%) | Urbanizable |
| 50 Tree cover, broadleaved, evergreen, closed to open (>15%) | Urbanizable |
| 60 Tree cover, broadleaved, deciduous, closed to open (>15%) | Urbanizable |
| 61 Tree cover, broadleaved, deciduous, closed (>40%) | Urbanizable |
| 62 Tree cover, broadleaved, deciduous, open (15–40%) | Urbanizable |
| 70 Tree cover, needleleaved, evergreen, closed to open (>15%) | Urbanizable |
| 71 Tree cover, needleleaved, evergreen, closed (>40%) | Urbanizable |
| 72 Tree cover, needleleaved, evergreen, open (15–40%) | Urbanizable |
| 80 Tree cover, needleleaved, deciduous, closed to open (>15%) | Urbanizable |
| 81 Tree cover, needleleaved, deciduous, closed (>40%) | Urbanizable |
| 82 Tree cover, needleleaved, deciduous, open (15–40%) | Urbanizable |
| 90 Tree cover, mixed leaf type (broadleaved and needleleaved) | Urbanizable |
| 100 Mosaic tree and shrub (>50%) / herbaceous cover (<50%) | Urbanizable |
| 110 Mosaic herbaceous cover (>50%) / tree and shrub (<50%) | Urbanizable |
| 120 Shrubland              | Urbanizable      |
| 121 Evergreen shrubland    | Urbanizable      |
| 122 Deciduous shrubland    | Urbanizable      |
| 130 Grassland             | Urbanizable      |
| 140 Lichens and mosses     | Urbanizable      |
| 150 Sparse vegetation (tree, shrub, herbaceous cover) (<15%) | Urbanizable |
| 160 Tree cover, flooded, fresh or brackish water | Non urbanizable |
| 170 Tree cover, flooded, saline water | Non urbanizable |
| 180 Shrub or herbaceous cover, flooded, fresh/saline/brackish water | Non urbanizable |
| 190 Urban areas            | Urbanizable      |
| 200 Bare areas             | Urbanizable      |
| 201 Consolidated bare areas | Urbanizable   |
| 202 Unconsolidated bare areas | Urbanizable |
| 210 Water bodies           | Non urbanizable  |
| 220 Permanent snow and ice | Non urbanizable  |

Table A.7: Reclassification of the ESA CCI land cover categories into "urbanizable" and "non urbanizable"

### Annex B. Robustness checks

#### Annex B.1. Description of the robustness checks

We run five robustness checks, detailed below, for subsections 4.1 and 4.2. In robustness check 1, our variable of interest is the Euclidean distance to the city center $d_{i,c}$ instead of the income net of transportation costs $Y_c - T_{i,c}$. Our theoretical model is similar to subsection 2.1, except that households seek to maximize the following utilities:
max \( U(z_{i,c}, q_{i,c}, d_{i,c}) = z_{i,c}^\alpha \beta_{c}^{\beta_{c}} l(d_{i,c}) \) s.t. \( z_{i,c} + q_{i,c} R_{i,c} \leq Y_{c} \) (B.1)

with \( l \) an amenity that depends on the Euclidean distance to the city center \( d_{i,c} \).

From equation B.1, we find that:

\[
q_{i,c} = \beta_{c} Y_{c} / R_{i,c} \\
z_{i,c} = \alpha_{c} Y_{c}
\] (B.2)

Using the spatial equilibrium condition and writing \( u_{c} \) the utility at equilibrium:

\[
R_{i,c} = R_{0,c} l(d_{i,c})^{1/\beta_{c}} \quad \text{with} \quad R_{0,c} = (\alpha_{c} \beta_{c}^{\beta_{c}} Y_{c} / u_{c})^{1/\beta_{c}}
\] (B.3)

The housing production function remains unchanged from section 2.1:

\[
H(K_{i,c}, L_{i,c}) = A_{c} L_{i,c}^{a_{c}} K_{i,c}^{b_{c}}
\] (B.4)

As in subsection 2.1, from the profit maximization of private developers, we can derive the total population per pixel \( N_{i,c} \):

\[
N_{i,c} = H_{i,c} / q_{i,c} = A_{c}^{1/a_{c}} (b_{c} R_{i,c} / \rho)^{b_{c}/a_{c}} L_{i,c} / q_{i,c}
\] (B.5)

Replacing \( q_{i,c} \) and \( R_{i,c} \) by their expressions in equations B.2 and B.3, the population density per pixel \( n_{i,c} \) can be expressed as:

\[
n_{i,c} = A_{c}^{1/a_{c}} \rho^{b_{c}/a_{c}} (\alpha_{c}^{a_{c}} \epsilon_{c}^{\beta_{c}} Y_{c}^{1-\alpha_{c}^{a_{c}}} / \alpha_{c}^{a_{c}} u_{c})^{1/\alpha_{c}^{a_{c}}} l(d_{i,c})^{1/a_{c}^{a_{c}}}
\] (B.6)

Our empirical strategy is then as follows: assuming that \( l(d_{i,c}) = \kappa e^{-\theta d_{i,c}} \) and building on equations B.3 and B.6, we run the following regressions on the cities in the database:

\[
\ln(R_{i,c}) = \epsilon_{c}^{\prime} + f_{c}^{\prime} d_{i,c} + \varepsilon_{i,c}^{\prime}
\] (B.7)

\[
\ln(n_{i,c}) = g_{c}^{\prime} + h_{c}^{\prime} d_{i,c} + \eta_{i,c}^{\prime}
\] (B.8)

\( \epsilon_{c}^{\prime} \) and \( g_{c}^{\prime} \) are constants, \( \epsilon_{c}^{\prime} \) and \( \eta_{i,c}^{\prime} \) are error terms, and \( f_{c}^{\prime} \) and \( h_{c}^{\prime} \) can be structurally interpreted as \(-\theta / \beta_{c}\) and \( -\theta / a_{c}^{a_{c}} \beta_{c} \) respectively.

In addition to robustness check 1, we run four additional robustness checks:
• Robustness check 2: We regress the logarithm of population densities and rents on the logarithm of transportation costs, instead of the logarithm of income net of transportation costs. We substitute $T_{i,c}$ for $Y_c - T_{i,c}$ in equations 14 and 15.

• Robustness check 3: We regress the logarithm of population densities and rents on the logarithm of transportation times (taking the minimum of the transportation time by driving and public transport). We substitute the minimum of the transportation time by driving and public transport $t_{i,c} = \min(t_{i,c}^{driving}, t_{i,c}^{publictransport})$ for $Y_c - T_{i,c}$ in equations 14 and 15.

• Robustness check 4: We regress the logarithm of population densities and rents on the logarithm of incomes net of transportation costs, but omitting the monetary cost of public transport as data are not consistently available for all cities.

• Robustness check 5: We regress the logarithm of population densities and rents on the logarithm of incomes net of transportation costs (equation 14). However, instead of taking the average rent per grid cell, rent data are aggregated by regressing rents on dwelling sizes in each grid cell (this robustness check is relevant for results regarding rent gradients, but does not affect the results regarding density gradients).

Annex B.2. Robustness checks - Rent gradients

With our main specification (subsection 4.1), we find rent gradients of the expected direction in 160 cities with OLS and 167 with 2SLS (Figure 2). We investigate whether this result holds under the five robustness checks (Table B.8).
With our main specification (subsection 4.1), we find that the median $R^2$ of regression 14 is 0.18 with OLS and 0.16 with 2SLS (Table 2). We investigate whether this result holds under the five robustness checks (Table B.9).

Then, we display the distribution of the rent gradients estimated in Robustness check 1. On average, moving 1km farther from the city center reduces rents per m² by 1.4%.
With our main specification (subsection 4.1), we find that the market data cover, the percentage of informal housing, and the dummy indicating whether the city is located in Asia explain the estimated rent gradients (Table 3). We investigate whether this result holds under the five robustness checks (Table B.10).
|                                | Main specification | Robustness check 1 | Robustness check 2 | Robustness check 3 | Robustness check 4 | Robustness check 5 |
|--------------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| Coastal city                  | -0.395             | 0.003              | 0.016              | 0.001              | -0.352             | -0.530             |
|                               | (0.409)            | (0.002)            | (0.028)            | (0.033)            | (0.414)            | (0.432)            |
| Monocentricity index          | 0.567              | -0.002             | 0.004              | 0.007              | 0.580              | 0.663              |
|                               | (0.487)            | (0.003)            | (0.035)            | (0.040)            | (0.493)            | (0.514)            |
| log(population)               | -0.255             | 0.001              | -0.091***          | -0.092***          | -0.280             | -0.207             |
|                               | (0.236)            | (0.001)            | (0.017)            | (0.019)            | (0.239)            | (0.250)            |
| log(income)                   | 0.000              | -0.042             | -0.049             | (0.002)            | (0.031)            | (0.036)            |
| Market data cover             | -0.000**           | 0.000***           | 0.000***           | 0.000***           | -0.000**           | -0.000**           |
|                               | (0.000)            | (0.000)            | (0.000)            | (0.000)            | (0.000)            | (0.000)            |
| Spatial data cover            | 3.196              | 0.010              | 0.128              | 0.134              | 3.545              | 3.273              |
|                               | (2.593)            | (0.015)            | (0.204)            | (0.234)            | (2.622)            | (2.737)            |
| Gini index                    | -0.037             | 0.000              | 0.004              | 0.004              | -0.038             | -0.013             |
|                               | (0.044)            | (0.000)            | (0.003)            | (0.004)            | (0.045)            | (0.047)            |
| Informal housing              | -0.091***          | 0.000***           | 0.006***           | 0.007***           | -0.092***          | -0.084***          |
|                               | (0.026)            | (0.000)            | (0.002)            | (0.002)            | (0.026)            | (0.027)            |
| Regulatory environment        | 0.374              | -0.003             | -0.034             | -0.044             | 0.394              | -0.064             |
|                               | (0.404)            | (0.002)            | (0.029)            | (0.034)            | (0.408)            | (0.426)            |
| Asia                          | 4.065***           | -0.022***          | -0.173**           | -0.024***          | 4.041***           | 3.999***           |
|                               | (0.919)            | (0.005)            | (0.069)            | (0.079)            | (0.930)            | (0.970)            |
| Africa                        | 0.329              | -0.002             | 0.025              | -0.012             | 0.203              | 0.454              |
|                               | (1.213)            | (0.007)            | (0.093)            | (0.107)            | (1.227)            | (1.280)            |
| Oceania                       | -1.275             | 0.004              | 0.015              | 0.040              | -1.309             | -0.950             |
|                               | (0.994)            | (0.005)            | (0.070)            | (0.080)            | (1.006)            | (1.049)            |
| North America                 | -0.060             | 0.002              | 0.131*             | 0.140*             | -0.210             | -0.096             |
|                               | (0.946)            | (0.005)            | (0.071)            | (0.078)            | (0.998)            | (0.999)            |
| South America                 | 1.429              | -0.014***          | -0.091             | -0.017             | 1.346              | 1.135              |
|                               | (0.987)            | (0.005)            | (0.071)            | (0.081)            | (0.998)            | (1.042)            |
| Constant                      | 6.576**            | -0.052*            | 1.292***           | 1.352***           | 7.030**            | 4.482              |
|                               | (3.213)            | (0.030)            | (0.407)            | (0.467)            | (3.249)            | (3.391)            |

**Note:**
* p < 0.1; ** p < 0.05; *** p < 0.01

Table B.10: Second-step regression of the estimates of rent gradients against city characteristics.
Annex B.3. Robustness checks - Density gradients

With our main specification (subsection 4.2), we find density gradients of the expected direction in 192 cities with OLS and 192 with 2SLS. We investigate whether this result holds under the four robustness checks (Table B.11).

|                                | Expected direction | Opposite direction | Non-significant (10% level) |
|--------------------------------|--------------------|--------------------|-----------------------------|
| Main specification             | OLS                | 192                | 0                           | 0                           |
| Main specification             | 2SLS               | 192                | 0                           | 0                           |
| Robustness check 1             | OLS                | 192                | 0                           | 0                           |
| Robustness check 2             | OLS                | 192                | 0                           | 0                           |
| Robustness check 2             | 2SLS               | 192                | 0                           | 0                           |
| Robustness check 3             | OLS                | 192                | 0                           | 0                           |
| Robustness check 3             | 2SLS               | 192                | 0                           | 0                           |
| Robustness check 4             | OLS                | 192                | 0                           | 0                           |
| Robustness check 4             | 2SLS               | 192                | 0                           | 0                           |

Table B.11: Robustness checks – direction of the density gradients.

With our main specification (subsection 4.2), we find that the median $R^2$ of regression 15 is 0.17 with OLS and 0.15 with 2SLS (Table 4). We investigate whether this result holds under the four robustness checks (Table B.12).

|                                | Mean   | Min.   | Q1    | Med.   | Q3    | Max.   |
|--------------------------------|--------|--------|-------|--------|-------|--------|
| Main specification             | 0.19   | 0.02   | 0.12  | 0.17   | 0.24  | 0.46   |
| Main specification             | 0.15   | -1.12  | 0.09  | 0.15   | 0.23  | 0.46   |
| Robustness check 1             | 0.18   | 0.03   | 0.12  | 0.17   | 0.24  | 0.56   |
| Robustness check 2             | 0.23   | 0.05   | 0.16  | 0.22   | 0.29  | 0.61   |
| Robustness check 2             | 0.23   | 0.04   | 0.16  | 0.22   | 0.29  | 0.61   |
| Robustness check 3             | 0.21   | 0.03   | 0.15  | 0.20   | 0.26  | 0.54   |
| Robustness check 3             | 0.20   | -0.19  | 0.14  | 0.19   | 0.25  | 0.53   |
| Robustness check 4             | 0.19   | 0.02   | 0.12  | 0.18   | 0.24  | 0.46   |
| Robustness check 4             | 0.15   | -1.12  | 0.08  | 0.15   | 0.23  | 0.46   |

Table B.12: Robustness checks - $R^2$ of equation 15.

We then display the distribution of the density gradients estimated in Robustness check 1. On average, moving 1km farther from the city center reduces population density by 8.5%.
With our main specification (subsection 4.2), we find that the population, the monocentricity index, the percentage of informal housing, the regulatory environment, and the dummies indicating whether the city is located in Africa and Oceania explain the estimated rent gradients (Table 5). We investigate whether this result holds under the four robustness checks (Table B.13).
| Dependent variable: density gradients          | Main specification | Robustness check 1 | Robustness check 2 | Robustness check 3 | Robustness check 4 |
|-----------------------------------------------|--------------------|--------------------|--------------------|--------------------|--------------------|
| log(population)                               | -5.428***          | 0.018***           | -0.155**           | -0.159*            | -5.735***          |
|                                               | (0.856)            | (0.003)            | (0.075)            | (0.091)            | (0.856)            |
| log(income)                                   | -0.001             | 0.158              | 0.392***           |                    |                    |
|                                               | (0.005)            | (0.110)            | (0.138)            |                    |                    |
| Monocentricity index                          | 4.346***           | -0.007             | -0.316**           | -0.393**           | 4.843***           |
|                                               | (1.591)            | (0.007)            | (0.128)            | (0.178)            | (1.611)            |
| Gini index                                     | -0.104             | 0.001              | 0.004              | 0.005              | -0.107             |
|                                               | (0.147)            | (0.001)            | (0.011)            | (0.015)            | (0.146)            |
| Percentage of informal housing                | -0.176**           | 0.000              | 0.004              | 0.015              | -0.172**           |
|                                               | (0.070)            | (0.000)            | (0.008)            | (0.011)            | (0.070)            |
| Coastal city                                  | 1.583              | -0.012**           | -0.133             | -0.225             | 1.553              |
|                                               | (1.508)            | (0.006)            | (0.116)            | (0.152)            | (1.508)            |
| Regulatory environment                         | 3.119*             | -0.016***          | -0.141             | -0.147             | 2.868              |
|                                               | (1.749)            | (0.005)            | (0.111)            | (0.153)            | (1.741)            |
| Asia                                          | 2.602              | -0.015             | 0.932***           | 1.015***           | 2.963              |
|                                               | (3.939)            | (0.014)            | (0.270)            | (0.377)            | (3.963)            |
| Africa                                         | -8.157***          | -0.002             | 1.067***           | 1.094***           | -8.148***          |
|                                               | (2.968)            | (0.014)            | (0.280)            | (0.452)            | (3.953)            |
| Oceania                                        | -9.958***          | 0.034***           | 0.059              | 0.138              | -10.992***         |
|                                               | (2.442)            | (0.008)            | (0.324)            | (0.397)            | (2.283)            |
| North America                                 | 2.598              | 0.022***           | 0.379              | 0.627**            | 2.682              |
|                                               | (3.429)            | (0.010)            | (0.238)            | (0.296)            | (3.423)            |
| South America                                 | -3.264             | 0.022*             | 0.228              | -0.038             | -3.503             |
|                                               | (3.801)            | (0.016)            | (0.264)            | (0.402)            | (3.814)            |
| Constant                                      | 95.918***          | -0.329***          | -1.772             | -4.628**           | 99.449***          |
|                                               | (12.958)           | (0.076)            | (1.677)            | (2.026)            | (13.071)           |

**Note:**

*p<0.1; **p<0.05; ***p<0.01

Table B.13: Second-step regression of the estimates of density gradients against city characteristics.
Annex C. Regulatory environment

When the categorical variable coding for the regulatory environment is different from 0 based on the authors’ judgements, an explanation is provided as a footnote.

| City          | Country           | Regulatory env. | Source                                      |
|---------------|-------------------|-----------------|---------------------------------------------|
| Abidjan       | Côte d’Ivoire     | 1               | Bertaud and Malpezzi (2014)                 |
| Adana         | Turkey            | 0               | Authors’ judgement                          |
| Addis_Ababa   | Ethiopia          | 0               | Authors’ judgement                          |
| Adelaide      | Australia         | 1               | Authors’ judgement                          | 8
| Ahmedabad     | India             | 1               | Bertaud and Malpezzi (2014)                 |
| Amsterdam     | Netherlands       | 0               | Authors’ judgement                          |
| Ankara        | Turkey            | 0               | Authors’ judgement                          |
| Antwerp       | Belgium           | 0               | Authors’ judgement                          |
| Arequipa      | Peru              | 0               | Authors’ judgement                          |
| Athens        | Greece            | 0               | Authors’ judgement                          |
| Atlanta       | United States of America | 0 | Bertaud and Malpezzi (2014) |
| Auckland      | New Zealand       | 0               | Authors’ judgement                          |
| Bandung       | Indonesia         | 0               | Authors’ judgement                          |
| Bangalore     | India             | 1               | Bertaud and Malpezzi (2014)                 |
| Bangkok       | Thailand          | 0               | Bertaud and Malpezzi (2014)                 |
| Barcelona     | Spain             | 0               | Bertaud and Malpezzi (2014)                 |
| Barranquilla  | Colombia          | 0               | Authors’ judgement                          |
| Basel         | Switzerland       | 0               | Authors’ judgement                          |
| Beijing       | China             | 0               | Bertaud and Malpezzi (2014)                 |
| Belém         | Brazil            | 0               | Authors’ judgement                          |
| Belo_Horizonte| Brazil            | 1               | Authors’ judgement                          | 9
| Bergen        | Norway            | 0               | Authors’ judgement                          |
| Berlin        | Germany           | 1               | Bertaud and Malpezzi (2014)                 |
| Bern          | Switzerland       | 0               | Authors’ judgement                          |
| Bilbao        | Spain             | 0               | Authors’ judgement                          |
| Birmingham    | United Kingdom    | 0               | Authors’ judgement                          |
| Bogota        | Colombia          | 0               | Authors’ judgement                          |
| Bordeaux      | France            | 0               | Authors’ judgement                          |
| Braga         | Portugal          | 0               | Authors’ judgement                          |

8Adelaide is a planned city, designed in 1836 by the first surveyor-general of South Australia, Colonel William Light. Adelaide was designed as a grid, with five squares in the city center, surrounded by a ring of parks.

9Belo Horizonte was created as the new state capital in the 1890s. It was Brazil’s first planned city. In particular, its urban core has a very specific street pattern, with a wide grid of broad ceremonial avenues and a regular street grid, offset at a 45-degree angle, and a city square at the intersections of the streets of the two grids.
| City            | Country       | Regulatory env. | Source                           |
|-----------------|---------------|-----------------|----------------------------------|
| Brasilia        | Brazil        | 2               | Bertaud and Malpezzi (2014)      |
| Bremen          | Germany       | 0               | Authors’ judgement               |
| Brisbane        | Australia     | 0               | Authors’ judgement               |
| Bristol         | United Kingdom| 0               | Authors’ judgement               |
| Brussels        | Belgium       | 0               | Authors’ judgement               |
| Bucharest       | Romania       | 0               | Authors’ judgement               |
| Budapest        | Hungary       | 1               | Bertaud and Malpezzi (2014)      |
| Buenos Aires    | Argentina     | 0               | Bertaud and Malpezzi (2014)      |
| Bursa           | Turkey        | 0               | Authors’ judgement               |
| Cali            | Colombia      | 0               | Authors’ judgement               |
| Cape_Town       | South Africa  | 2               | Bertaud and Malpezzi (2014)      |
| Cartagena       | Colombia      | 0               | Authors’ judgement               |
| Casablanca      | Morocco       | 0               | Authors’ judgement               |
| Charleroi       | Belgium       | 0               | Authors’ judgement               |
| Chelyabinsk     | Russian Federation | 0    | Authors’ judgement               |
| Chiang Mai      | Thailand      | 0               | Authors’ judgement               |
| Chicago         | United States of America | 0   | Bertaud and Malpezzi (2014)      |
| Christchurch    | New Zealand   | 0               | Authors’ judgement               |
| Cluj_Napoca     | Romania       | 0               | Authors’ judgement               |
| Coimbra         | Portugal      | 0               | Authors’ judgement               |
| Concepcion      | Chile         | 0               | Authors’ judgement               |
| Cordoba         | Argentina     | 0               | Authors’ judgement               |
| Cork            | Ireland       | 0               | Authors’ judgement               |
| Cracow          | Poland        | 1               | Bertaud and Malpezzi (2014)      |
| Curitiba        | Brazil        | 2               | Bertaud and Malpezzi (2014)      |
| Delhi           | India         | 1               | Authors’ judgement               |
| Detroit         | United States of America | 0   | Authors’ judgement               |
| Dresden         | Germany       | 0               | Authors’ judgement               |
| Dublin          | Ireland       | 0               | Authors’ judgement               |
| Edinburgh       | United Kingdom| 0               | Authors’ judgement               |
| Faisalabad      | Pakistan      | 0               | Authors’ judgement               |
| Fez             | Morocco       | 0               | Authors’ judgement               |
| Fortaleza       | Brazil        | 0               | Authors’ judgement               |
| Frankfurt_am Main | Germany      | 0               | Authors’ judgement               |

10 Delhi has a long history of urban planning. The street network was designed for defense purposes, with some transverse streets leading from one major gate to another. In 1911, the decision was made to transfer the capital to Delhi, and the new city of New Delhi was planned inside the existing Delhi. New Delhi was planned with wide, straight streets, trees in double rows on either side and a broad central avenue. The Delhi Development Authority’s 20-year (1962-1981) plan, the first Master Plan for the whole of Delhi, also largely impacted land use in the city.
| City         | Country                          | Regulatory env. | Source                                      |
|-------------|----------------------------------|-----------------|---------------------------------------------|
| Geneva      | Switzerland                      | 0               | Authors’ judgement                          |
| Genoa       | Italy                            | 0               | Authors’ judgement                          |
| Ghent       | Belgium                          | 0               | Authors’ judgement                          |
| Glasgow     | United Kingdom                   | 0               | Authors’ judgement                          |
| Goiania     | Brazil                           | 0               | Authors’ judgement                          |
| Gothenburg  | Sweden                           | 0               | Authors’ judgement                          |
| Guadalajara | Mexico                           | 0               | Authors’ judgement                          |
| Hamburg     | Germany                          | 0               | Authors’ judgement                          |
| Hanover     | Germany                          | 0               | Authors’ judgement                          |
| Helsinki    | Finland                          | 0               | Authors’ judgement                          |
| Hong_Kong   | China, Hong Kong SAR             | 0               | Bertaud and Malpezzi (2014)                 |
| Houston     | United States of America         | 0               | Bertaud and Malpezzi (2014)                 |
| Hyderabad   | India                            | 1               | Bertaud and Malpezzi (2014)                 |
| Isfahan     | Iran (Islamic Republic of)       | 0               | Authors’ judgement                          |
| Istanbul    | Turkey                           | 1               | Authors’ judgement                          |
| Izmir       | Turkey                           | 0               | Authors’ judgement                          |
| Jakarta     | Indonesia                        | 0               | Bertaud and Malpezzi (2014)                 |
| Jinan       | China                            | 0               | Authors’ judgement                          |
| Johannesburg| South Africa                     | 2               | Bertaud and Malpezzi (2014)                 |
| Karachi     | Pakistan                         | 0               | Authors’ judgement                          |
| Kazan       | Russian Federation               | 0               | Authors’ judgement                          |
| Lahore      | Pakistan                         | 0               | Authors’ judgement                          |
| Lausanne    | Switzerland                      | 0               | Authors’ judgement                          |
| Leeds       | United Kingdom                   | 0               | Authors’ judgement                          |
| Leicester   | United Kingdom                   | 0               | Authors’ judgement                          |
| Leipzig     | Germany                          | 0               | Authors’ judgement                          |
| Lille       | France                           | 0               | Authors’ judgement                          |
| Lima        | Peru                             | 0               | Authors’ judgement                          |
| Lisbon      | Portugal                         | 0               | Authors’ judgement                          |
| Liverpool   | United Kingdom                   | 0               | Authors’ judgement                          |
| Ljubljana   | Slovenia                         | 1               | Bertaud and Malpezzi (2014)                 |
| Lodz        | Poland                           | 0               | Authors’ judgement                          |
| London      | United Kingdom                   | 0               | Bertaud and Malpezzi (2014)                 |
| Los_Angeles | United States of America         | 0               | Bertaud and Malpezzi (2014)                 |
| Lyon        | France                           | 0               | Authors’ judgement                          |

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11Istanbul has a long history of urban planning. Major developments occurred before World War II, with the idea of comprehensive city development in Istanbul introduced in plans drawn up by city planner Henri Prost and in a planning competition organized in 1933. In the second half of the nineteenth century, comprehensive planning on a metropolitan scale was institutionalized.
| City            | Country                | Regulatory env. | Source                      |
|-----------------|------------------------|-----------------|-----------------------------|
| Madrid          | Spain                  | 0               | Authors’ judgement          |
| Malaga          | Spain                  | 0               | Authors’ judgement          |
| Malmo           | Sweden                 | 0               | Authors’ judgement          |
| Manaus          | Brazil                 | 0               | Authors’ judgement          |
| Marseille       | France                 | 0               | Bertaud and Malpezzi (2014) |
| Mar_del_Plata   | Argentina              | 0               | Authors’ judgement          |
| Mashhad         | Iran (Islamic Republic of) | 0            | Authors’ judgement          |
| Medan           | Indonesia              | 0               | Authors’ judgement          |
| Medellin        | Colombia               | 0               | Authors’ judgement          |
| Melbourne       | Australia              | 0               | Authors’ judgement          |
| Mexico_City     | Mexico                 | 0               | Bertaud and Malpezzi (2014) |
| Milan           | Italy                  | 0               | Authors’ judgement          |
| Monterrey       | Mexico                 | 0               | Authors’ judgement          |
| Montevideo      | Uruguay                | 0               | Authors’ judgement          |
| Montpellier     | France                 | 0               | Authors’ judgement          |
| Moscow          | Russian Federation     | 2               | Bertaud and Malpezzi (2014) |
| Mumbai          | India                  | 1               | Bertaud and Malpezzi (2014) |
| Munich          | Germany                | 0               | Authors’ judgement          |
| Nantes          | France                 | 0               | Authors’ judgement          |
| Naples          | Italy                  | 0               | Authors’ judgement          |
| New_York        | United States of America | 0             | Bertaud and Malpezzi (2014) |
| Nice            | France                 | 0               | Authors’ judgement          |
| Nizhny_Novgorod | Russian Federation     | 0               | Authors’ judgement          |
| Nottingham      | United Kingdom         | 0               | Authors’ judgement          |
| Novosibirsk     | Russian Federation     | 0               | Authors’ judgement          |
| Nuremberg       | Germany                | 0               | Authors’ judgement          |
| Omsk            | Russian Federation     | 0               | Authors’ judgement          |
| Oslo            | Norway                 | 0               | Authors’ judgement          |
| Palermo         | Italy                  | 0               | Authors’ judgement          |
| Paris           | France                 | 0               | Bertaud and Malpezzi (2014) |
| Patras          | Greece                 | 0               | Authors’ judgement          |
| Perth           | Australia              | 0               | Authors’ judgement          |
| Portland        | United States of America | 1             | Bertaud and Malpezzi (2014) |
| Porto           | Portugal               | 0               | Authors’ judgement          |
| Porto_Alegre    | Brazil                 | 0               | Authors’ judgement          |
| Poznan          | Poland                 | 0               | Authors’ judgement          |
| Prague          | Czechia                | 1               | Bertaud and Malpezzi (2014) |
| City                  | Country              | Regulatory env. | Source                        |
|----------------------|----------------------|-----------------|-------------------------------|
| Puebla               | Mexico               | 1               | Authors’ judgement<sup>12</sup> |
| Rabat                | Morocco              | 0               | Authors’ judgement            |
| Recife               | Brazil               | 0               | Authors’ judgement            |
| Rennes               | France               | 0               | Authors’ judgement            |
| Riga                 | Latvia               | 1               | Bertaud and Malpezzi (2014)   |
| Rio de Janeiro       | Brazil               | 0               | Bertaud and Malpezzi (2014)   |
| Rome                 | Italy                | 0               | Authors’ judgement            |
| Rosario              | Argentina            | 0               | Authors’ judgement            |
| Rostov on Don        | Russian Federation   | 0               | Authors’ judgement            |
| Rotterdam            | Netherlands          | 0               | Authors’ judgement            |
| Salvador             | Brazil               | 0               | Authors’ judgement            |
| Samara               | Russian Federation   | 0               | Authors’ judgement            |
| Santiago             | Chile                | 0               | Authors’ judgement            |
| San Diego            | United States of America | 0 | Authors’ judgement |
| San Francisco        | United States of America | 1 | Bertaud and Malpezzi (2014) |
| Sao Paulo            | Brazil               | 0               | Authors’ judgement            |
| Seattle              | United States of America | 0 | Authors’ judgement |
| Seville              | Spain                | 0               | Authors’ judgement            |
| Sfax                 | Tunisia              | 0               | Authors’ judgement            |
| Shanghai             | China                | 0               | Bertaud and Malpezzi (2014)   |
| Singapore            | Singapore            | 0               | Bertaud and Malpezzi (2014)   |
| Sofia                | Bulgaria             | 1               | Bertaud and Malpezzi (2014)   |
| Sousse               | Tunisia              | 0               | Authors’ judgement            |
| Split                | Croatia              | 0               | Authors’ judgement            |
| Stavanger            | Norway               | 0               | Authors’ judgement            |
| Stockholm            | Sweden               | 2               | Bertaud and Malpezzi (2014)   |
| Strasbourg           | France               | 0               | Authors’ judgement            |
| Stuttgart            | Germany              | 0               | Authors’ judgement            |
| St Petersburg        | Russian Federation   | 1               | Bertaud and Malpezzi (2014)   |
| Surabaya             | Indonesia            | 0               | Authors’ judgement            |
| Sydney               | Australia            | 0               | Authors’ judgement            |
| Tampere              | Finland              | 0               | Authors’ judgement            |
| Tehran               | Iran (Islamic Republic of) | 0 | Authors’ judgement |
| Thessaloniki         | Greece               | 0               | Authors’ judgement            |

<sup>12</sup>Puebla was the first planned city in the Americas with streets traced in rectangular 100m by 200m blocks, and where the city’s whole central district is oriented to the movement of the sun in the sky. Most of the major arteries follow the regular orientation of the plan, but one main street, the “Diagonale de Los Defensores de la Republica,” crosses the city on a diagonal. Puebla’s Zocalo, the central esplanade of the historic area, is considered one of the great achievements of colonial urban planning.
| City          | Country             | Regulatory env. | Source                                    |
|---------------|---------------------|-----------------|-------------------------------------------|
| The_Hague     | Netherlands         | 0               | Authors’ judgement                        |
| Tianjin       | China               | 0               | Bertaud and Malpezzi (2014)               |
| Tijuana       | Mexico              | 0               | Authors’ judgement                        |
| Timisoara     | Romania             | 0               | Authors’ judgement                        |
| Toluca        | Mexico              | 0               | Authors’ judgement                        |
| Toulouse      | France              | 0               | Bertaud and Malpezzi (2014)               |
| Trujillo      | Peru                | 0               | Authors’ judgement                        |
| Tunis         | Tunisia             | 2               | Bertaud and Malpezzi (2014)               |
| Turin         | Italy               | 0               | Authors’ judgement                        |
| Turku         | Finland             | 0               | Authors’ judgement                        |
| Ulan_Bator    | Mongolia            | 0               | Authors’ judgement                        |
| Valencia      | Spain               | 0               | Authors’ judgement                        |
| Valparaiso    | Chile               | 0               | Authors’ judgement                        |
| Warsaw        | Poland              | 1               | Bertaud and Malpezzi (2014)               |
| Washington_DC | United States of America | 0      | Bertaud and Malpezzi (2014)               |
| Wellington    | New Zealand         | 0               | Authors’ judgement                        |
| Wroclaw       | Poland              | 0               | Authors’ judgement                        |
| Wuhan         | China               | 0               | Authors’ judgement                        |
| Yekaterinburg | Russian Federation  | 0               | Authors’ judgement                        |
| Yerevan       | Armenia             | 2               | Bertaud and Malpezzi (2014)               |
| Zagreb        | Croatia             | 0               | Authors’ judgement                        |
| Zhengzhou     | China               | 0               | Authors’ judgement                        |
| Zurich        | Switzerland         | 0               | Authors’ judgement                        |