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The Costs and Benefits of Urban Expansion: Evidence from Mexico, 1990–2010

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Abstract

Urbanization is generally linked to economic growth, and agglomeration economies mean that people in larger cities are more productive. However, urban expansion is also associated with congestion, localized environmental damage, and in many countries, deficiencies in infrastructure and housing conditions. Urban policies worldwide are increasingly based on an apparent international consensus that urban compactness is a desirable policy goal, for reasons of environmental sustainability and economic productivity. However, there is almost no evidence that compact cities are more productive outside of high-income countries, with a productive service sector. Given that land-intensive manufacturing activities is the economic base of many cities in Latin America, policies promoting compactness may reduce economic productivity by constraining expansion. The tensions between environmental, social and economic goals in the urban policy of countries with rapidly expanding cities has not been sufficiently studied. Mexico is an ideal case study because of the rapid rate at which cities have been growing in recent decades. In this report, we examine impacts—both positive and negative—of the way in which cities have been growing in Mexico. First, we test the relationship between urban form and economic productivity, testing the hypothesis that growing in a compact manner promotes productivity. We find that in Mexico, urban sprawl is associated with higher levels of economic productivity. This finding is counterintuitive and raises questions about the conventional wisdom related to cities and economic growth. We then examine two of the important 'costs' of urban expansion: transportation and socio-economic segregation. Findings in these cases confirm expectations that more sprawling cities have higher transportation costs and more socio-economic segregation. We conclude by arguing that policy makers must at least acknowledge the tradeoffs between productivity, transportation costs, and socio-spatial structure.

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The Costs and Benefits of Urban Expansion: Evidence from Mexico, 1990–2010

I. Introduction

Economic growth and productivity are correlated with urban expansion (Bertinelli and Black 2004; He and Sim 2015). Yet the relationship between productivity and urban form has been little examined outside of high-income countries. Specifically, the way in which the economic base of a country (e.g. services or manufacturing) relates to the form of urban expansion (e.g. sprawling or compact) is not well-studied. Instead, policymakers frequently focus on the negative impacts of urbanization, the congestion, pollution, density, environmental damage, and perception of social degradation.

Mexican cities grew dramatically between 1990 and 2010, in a relatively sprawling manner. This urban growth model has led to higher commuting costs; increases in socio-economic segregation (Monkkonen, 2012), and higher greenhouse emissions (CTS-Embarq, IMCO and Centro Molina 2013; ONU-Hábitat, Sedesol 2001). However, it has also supported the country's growing manufacturing sector, which mostly relies on the peri-urban development of large factories.

The federal government of Mexico began an urban policy program in 2013 that is aligned with the larger international sustainability agenda (OECD 2015), through National Development Plans (PND 2013–2018) and Urban Development Plans (PNDU 2014–2018). They highlight three urban sustainability principles: compact growth, mixed land use, and polycentric urban structures. Yet, these principles are being applied without study of the impacts of these proposed policies. Urban compactness is not associated with economic productivity in Mexico. A review of the academic literature reveals that the debate over the ideal urban structure continues, and there are potential negative effects of policies forcing higher densities (Boarnet 2011; Mills 2005; Parr 2004) especially in a country with an economy based in land-intensive manufacturing.

Therefore, this research examines the costs and benefits of urban expansion in Mexico, specifically for cities with different urban spatial structures. We analyze the impact of changing urban form on economic productivity, transportation outcomes, and social segregation, across Mexico's 100 largest urban areas between 1990 and 2010, using census data. Figure 1 shows their location.

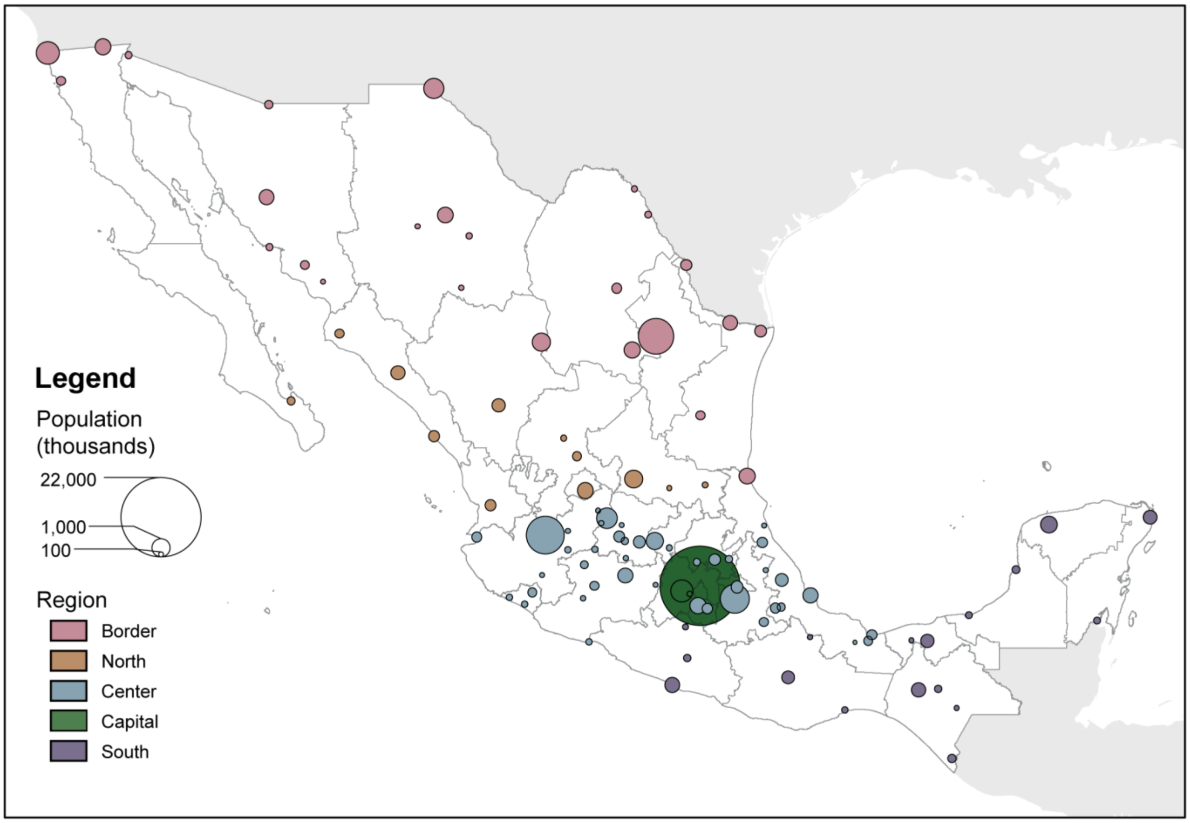
In the second section, we assess the relationship between urban form and urban economic productivity. Are more compact cities in Mexico more productive? How does the importance of manufacturing in labor productivity and its sprawling urban form affect this relationship? In a cross-sectional analysis, we first find that workers in Mexico are more productive in more sprawling, less centralized cities. A sophisticated, time-series analysis of this relationship confirms that cities in Mexico that became less centralized and compact, became more productive. We hypothesize that this derives from the manufacturing sector being both the most productive sector per worker, and one that demands more land area, usually in the urban periphery.

In section three, we investigate the relationship between urban form and transportation outcomes—such as mode choice, average travel times, and fatality rates. There is substantial variation in mode choice, vehicle ownership, travel times, and fatality rates across Mexico's cities and regions. As expected, various measures of urban form are consistently and often strongly related to transportation outcomes as well as economic productivity. Across the models tested, measures of urban form collectively and even sometimes individually are as powerful predictors of transportation outcomes as income and years of education. Although these relationships are not always uniform, the findings suggest that sprawling form is generally—though not always— associated with higher social transportation costs. City size and density are particularly important, while measures of circularity, distribution, and contiguity are generally weaker and less consistently associated with (more or less) desirable transportation outcomes.

In the fourth section, we examine how urban growth and changes in urban structure shapes socioeconomic segregation, or the uneven distribution of social groups within cities. We document the rapid urban growth, small increases in population densities, increasing centralization, increasing levels of socioeconomic segregation, and an increase in the geographic scale of that segregation. We find a strong, positive connection between urban expansion (in terms of land area not population) and socioeconomic segregation. Additionally, we find that greater increases in a Centrality Index, which measures how concentrated population is closer to the center of the city, are positively associated with changes in segregation and the scale of segregation. These last results are intriguing as they run counter to expectations.

In the conclusion, after summarizing the report's main findings, we lay out a larger research agenda including some policy recommendations.

Figure 1: Map Showing the Location of the 100 Largest Mexican Cities



II. Urban Form and Economic Productivity in Mexico

Urban agglomeration continues to play fundamental and changing roles in economic development in the 21st century. Although this has been acknowledged as far back as Marshall (1890), the details of how the concentration of people in space shapes economic productivity are still being unpacked. There is a large body of empirical evidence showing that larger cities are more productive. Yet beyond size, there are many questions remaining to be answered about the role of urban spatial structure, or urban form, in the economic efficiency of cities.

The debate over urban form is often oversimplified to one of sprawl versus compactness, horizontal cities versus vertical cities. Despite the negative connotations of the word sprawl, many scholars and policy advocate for allowing the market to guide urban development (Richardson and Gordon 1993). If people prefer to and have the recourses to live in the urban periphery and commute, then a more sprawling urban form can be efficient from a welfare maximization perspective. Advocates of compact, dense cities most often argue for the environmental problems generated by sprawl, principally the energy efficiency from lower travel, dense cities (Newman and Kenworthy 1989) and the preservation of rural environments (Jabareen 2006). But advocates of compact cities increasingly argue that there are productivity benefits from compactness, pointing to numerous studies in the United States and Europe for evidence (Steuteville 2013).

The oversimplified debate over an ideal urban form has policy implications. Mayors and higher levels of government have enacted strict urban growth boundaries and greenbelts in cities around the world to stop what is often characterized as 'chaotic' and 'uncontrolled' urban sprawl. These policies are supposed to yield environmental and economic benefits (Breheny 1992; Angel and Blei 2016), though critics assert they exacerbate negative externalities like congestion and raise the prices of land and housing unnecessarily (Quigley and Rosenthal 2005). The lack of evidence on their economic impacts in countries outside of the United States and Europe, however, has not been considered. We seek to remedy this dearth in knowledge.

In this paper, we focus on the relationship between urban growth, urban spatial structure and labor productivity in Mexico. We seek to answer the basic question, are more compact cities in Mexico also more productive? The research is motivated by federal policy in Mexico that seeks to curtail urban expansion through urban growth boundaries. In an initial observation, in a cross-section, we see that workers in more sprawling cities in Mexico are more productive. This finding runs counter to predictions based on theory, as well as most existing empirical evidence. Yet most (all) empirical evidence is from countries with economies that rely more on services than manufacturing as compared to Mexico. Therefore, we focus particularly on the manufacturing sector. Analyzing economic data aggregated at the traditional three-sectors level —namely industry, commerce, and services—we found manufacturing is the most productive sector in Mexico, one of the most land consuming activity. Thus, we hypothesize that urban sprawl and manufacturing productivity in Mexico are symbiotic.

This paper is organized as follows. The first section reviews the state of the knowledge about urban form related to economies of scale and urban agglomeration. Then, we examine recent industrial dynamics and urban spatial structure in Mexico. The third section discusses urban forms metrics, and how we select some for modelling. Section four describes the modelling strategy and the outcomes are presented in section five. Finally, we draw some preliminary conclusions connecting the model outcomes and theory.

Theory and Evidence on the Relationship Between Urban Productivity and Urban Form

Here, we review the state of the knowledge on urban form and how it could shape and be shaped by economic productivity. First, we outline the basic theory of urban agglomeration. Then we review empirical evidence of the productivity benefits of city size, and urban compactness separately. We conclude the section by highlighting a sometimes-unstated assumption in the work on this topic, which is the importance of the type of economic activity that is prevalent (and productive) in a country as an intervening variable in the relationship between urban form and productivity.

Theoretical Debates About Economic Efficiency and Urban Form

Agglomeration economies, the benefits derived from a proximate location between firms and people found in cities, are theorized to increase productivity in multiple ways. Most directly, larger cities generate economies of scale because they can support larger firms, which leads to reduced costs per produced unit (Camagni 2005); firms in large cities benefit from access to a larger, diversified and specialized labor pool (Chinitz 1961); there is a reduction in transportation costs between firms (Glaeser 2010); there are cost reductions when firms use shared inputs, like professional services; infrastructure costs are lower per capita in larger cities (Strogatz 2009); and it is thought that there are knowledge spillovers within and between firms that lead to innovation (Quigley 1998).

There is a size limit to agglomeration, of course, due to the congestion impacts of large city size, which reduce efficiency advantages above a certain size. These are the so-called diseconomies of agglomeration that are the reason cities do not increase in size without end. These are especially relevant for cities in poorer countries with worse urban management, public services, and infrastructure. The ability to mitigate diseconomies of scale is thought to be a key factor in harnessing the productivity advantages of agglomeration (Puga 2010).

With the dramatic decline in transportation costs during the 20th century and the rapid increase in the quality of communication technologies, many argued that cities would lose their importance (Cairncross 2001). Glaeser (2010), however, points out that although transportation costs have decreased, this is mostly true for the cost of moving goods. The cost of moving people is still relatively high, especially for face-to-face interactions, which are more important in knowledge-based, service industries. Thus, Camagni (2005) concludes that distance or transportation cost does not seems to be that relevant for industrial locational decisions, but it does for services, as transportation costs had a very noticeable impact on firms and consumers.

Empirical Evidence on the Connection Between City Size and Productivity

The most common and simplest ways to measure agglomeration is city size, and the connection between city size and labor productivity is well-established, especially in the United States. As far back as the 1970s, researchers confirmed that doubling city size in the United States was associated with an increase in productivity of between three and eight percent (Shefer 1973; Sveikauskas 1975). The importance of city size seems to be increasing, as tests of the relationship in the next decade found that productivity increases 10 percent when doubling city population (Fogarty and Garofalo 1988), and more recent studies found that doubling the metropolitan size increases metropolitan labor productivity by over 10 percent (Meijers and Burger 2010; Angel and Blei 2016). Glaeser and Resseger (2010), who also demonstrate the strong link between per-worker productivity and the size of the metropolitan population, show that the correlation is stronger in cities containing highly skilled workers. They argue that urban density is vital for highly productive sectors of the economy, because of knowledge spillovers.

Evidence of larger cities' higher productivity outside of the United States is less common. In a study of France, Prud'homme and Lee (1999) find that a city's efficiency (labor productivity) is a function of the size of its labor pool, which depends on the size of the city. Recently, Ahrend and colleagues (2014) at the OECD, estimated the benefits of scale economies based on the differentials on city productivity across five OECD countries: Germany, Mexico, Spain, United Kingdom, and United States. They find that productivity increases with city size in all five countries, between 2–5 percent (Ahrend et al. 2014). Ahrend et al. (2014) also emphasize that workers and cities also gain from being near large cities, if not in them. Locations proximate to populous cities enable individuals and firms to take advantage of their neighbor's agglomeration.

Empirical Evidence on the Connection Between City Structure and Productivity

The evidence on the connection between the role of urban form and the productivity advantages of agglomeration is slightly less robust, partly because of the greater complexity of measures. Nonetheless, several studies find a positive relationship between density and compactness, of population and employment, and productivity in US metropolitan areas. Early work (Fogarty and Garofalo 1988) on urban structure and productivity growth in manufacturing (for 13 large US metropolitan areas between 1957 and 1977) examined the manufacturing density gradient to test the hypothesis that agglomeration economies depend on population size, spatial structure and possibly, the age of an urban area. They sought to differentiate between two types of density externalities: diminished communication costs leading to improved information flows; on the other hand, reduction in transportation costs, by using the variable population squared (POPSQ) to capture the negative effects or the exhaustion of urbanization economies and by using the density gradient squared (GDSQ) to capture both the positive effects of agglomeration and urban congestion. They find that the central density of manufacturing and the density gradient significantly affect productivity in manufacturing. Beyond a certain size, however, density begins to negatively affect productivity and above a certain population size productivity diminishes.

More recent work confirms that this relationship holds. Ciccone and Hall (1996) examined the variation in productivity across US cities, first relating density to productivity instead of firm size. They find that doubling the employment density increases average labor productivity by around 6 percent. They also examine the relationship between sprawl and productivity, focusing on industrial productivity at a metropolitan level. Glaeser (2010) and Glaeser and Maré (2001) also find a strong relationship between density and high wages in the United States, and that high wages reflect higher per capita gross metropolitan product.

Ciccone and Hall (1996) also find a negative relationship between the industrial labor productivity and a metropolitan sprawl index. More recently, Fallah, Partridge, and Olfert (2011) also find a negative relationship between productivity and the amount of sprawl in the United States. Using Ordinary Least Squares (OLS) models, they found that metropolitan areas with more sprawl have lower levels of labor productivity.

Using a slightly different approach to measure urban form, Meijers and Burger (2010) find that polycentricism is associated with higher labor productivity in US metropolitan areas. Doubling the degree of polycentricism increases the metropolitan labor productivity by 5.5 percent. Meijers and Burger (2010) test two hypothesis: that polycentricism diminishes the effect of urbanization economies on labor productivity at the regional metropolitan scale and that less sprawling metro areas have higher labor productivity. They posit that even though agglomeration would augment productivity, under a polycentric urban condition, urbanization externalities are substituted by a network of cities, diminishing their relative importance. In this sense, their most notable contributions are to find that dispersion is not necessarily harmful to labor productivity and that more polycentric metropolitan areas show a better performance in terms of labor productivity. Their explanation for this is that diseconomies are lower in polycentric regions.

Outside of the United States, studies in Europe and Asia have confirmed the productivity benefits of density. For example, in addition to examining city size, Prud'homme and Lee (1999) also investigated labor productivity and sprawl in France. They found that the effective size of the labor market is negatively related to sprawl, and that the closer the people are to their place of employment, the more productive they are. Combes et al. (2010) also examined this question in France and confirmed that denser employment areas are more productive. They posit that since more productive places attract workers, they become denser as a result.

Azari et al. (2016) investigated the effects of agglomeration economies on urban labor productivity in the Korean manufacturing sector. In Korea, they found the relationship to be a little more complex, with labor density (job density) having a negative effect on productivity, while output density (density of production) had a positive impact. These results are consistent with Ke's (2010) study of agglomeration in China, which found that the spatial concentration of industrial production had a positive effect on productivity. Ke emphasizes the importance of congestion diseconomies in the Chinese context, however.

Apart from these two studies from Asia, most studies on this topic are from the United States or Europe. No studies on this topic were found in a Latin American context, other than a report edited by Kim et al. Eds. 2016, which finds that for the 100 biggest Mexican cities there is a negative relationship between density and labor productivity. More sprawling cities, with lower densities and less centralization, were more productive in Mexico.

A Gap in the Literature: The Land Use Needs of Different Economic Sectors

In their study on US Metropolitan Areas, Ciccone and Hall (1996) point out that the relationship between urban sprawl and labor productivity is ambiguous *a priori*. They also point out a key consideration in this area, that urban sprawl is likely to have different impacts on productivity in high-end services as compared to manufacturing, and even within the manufacturing sector different types of firms depend on different urban structures. Thus, the relationship between urban form and productivity should vary depending on the economic structure of a country. As they say, "urban sprawl's effect on productivity is an empirical question" (Ciccone and Hall 1996, 453).

Technology firms that demand highly skilled labor tend to locate in more central areas and benefit more from the technical infrastructure, supporting services, and concentration of human capital found with urban density (Glaeser and Resseger 2010). In contrast, many kinds of industrial production (car manufacturers, for example) have more location freedom and need more land, so they tend to locate in peripheral areas where land is cheaper (Méndez and Caravaca 1996). Yet manufacturing firms are not the only ones to encourage residential urban sprawl. According to Felsenstein (2002), high technology agglomerations do as well. In analysis of the impact of a technology cluster in Chicago, he found that it induced a new wave of dispersion, based primarily on the residential demand generated by this location. This latter point depends on the context of residential preferences and quality of life conditions in central urban areas and peri-urban ones.

Evidence of the above theories is robust. Carlino, Chatterjee, and Hunt (2007), for example, measure the importance of agglomeration for innovation. They find that the rate of invention (patents) per capita is positively correlated with employment density in US metropolitan areas, and their results suggest that doubling employment density leads to a 20 percent increase in patents. Similarly, work like that of Knudsen et al. (2007) found that urban density is a key component for knowledge spillovers.

The Economic and Urban Context of Mexico

The Inter-Metropolitan Spatial Evolution of Manufacturing in Mexico

Until the 1970s, Mexican industry was characterized by a very strong spatial and sectorial concentration. Just four manufacturing subsectors (from a total of 20) represented almost 50 percent of the gross industrial product and, according to Garza (1980), the urban area of Mexico City produced 46 percent of the overall gross industrial product. The next four largest urban areas (Monterrey, Guadalajara, Toluca and Puebla) produced roughly 20 percent.

The share of Industrial Gross Value Added (GVA) coming from the Mexico City region grew from 27% in 1930 to 48% in 1970. The primacy of this one metropolitan area led the Federal government to attempt a spatial dispersion of economic activity across the country. They actively promoted the construction of industrial parks, industrial polygons and industrial cities between 1953 and 1986, with mixed results (Garza 1988). All those actions were carried out under the 'import substitution' paradigm, which lasted from the thirties until the early eighties. During that time this industrial model seemed to be exhausted and, at the same time, the International Monetary Fund (IMF) suggested several measures to alleviate the public finance deficits through a commercial opening (Garza 1985; Sobrino 2002).

However, the dispersion of economic activity eventually did occur. Between 1980 and 2003, manufacturing in Mexico experienced an accelerated process of 'concentrated dispersion,' with a boom in the Northern Border states and the outskirts of the greater Mexico City region. This process was reflected in a decreasing dominance of Mexico City in the nation's manufacturing economy (Dávila 2004; Mendoza-Cota and Pérez-Cruz 2007; Sobrino 2002; Vieyra 2000).

To visualize the decentralization of manufacturing from Mexico City to the rest of the country, especially to the Northern Border states and the Bajío region, we calculated a Location Quotient of manufacturing jobs in 2000 and 2010 for the 100 largest cities in Mexico. A Location Quotient (LQ) (Benita and Gaitán 2011), is an indicator that measures the existing concentration of an economic activity within a region with respect to the average level of the total economy. It is usually evaluated using variables such as employment or GVA, and we use the former.

The quotient is calculated as follows:

$$LQ_{ij} = \frac{y_i / y_t}{Y_i / Y_t}$$

where LQ_{ij} is the Location Quotient in sector *i* in region *j*; y_i is the employment in each city analyzed in sector *i* (in this case manufacturing jobs) while y_t represents the total employment in the analyzed city. In the denominator, Y_i is the total employment in manufacturing for all 100 analyzed cities and Y_t is the total employment in all sectors for all 100 analyzed cities.

The LQ is assessed relative to 1. If it is greater than 1, it means there is a greater regional specialization of that activity in a given city, with respect to the set of the 100 analyzed cities. If it is less than 1 it means the city has less of that activity relative to the others. Appendix A presents LQs for all 100 cities.

Figures 2–4 show LQs in 2000, 2010, and the change over the decade. Figure 2 demonstrates that cities with the highest concentration of manufacturing employment were already located on the Northern Border and in the Bajío region in the year 2000.

Figure 2: Manufacturing Location Quotients for 2000

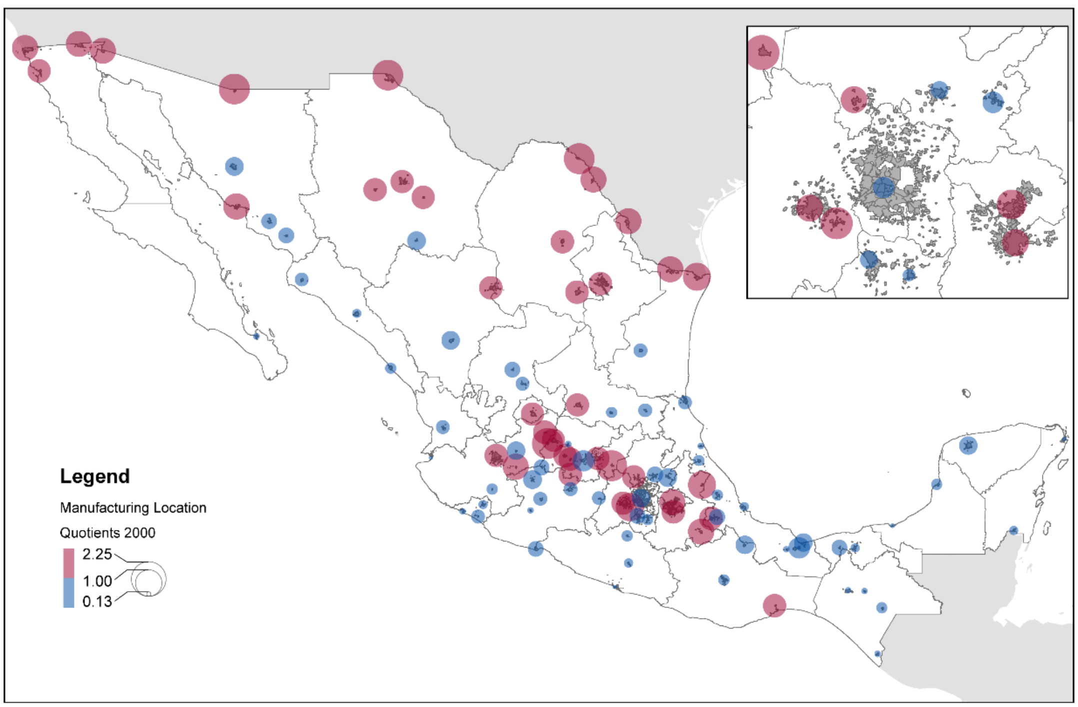
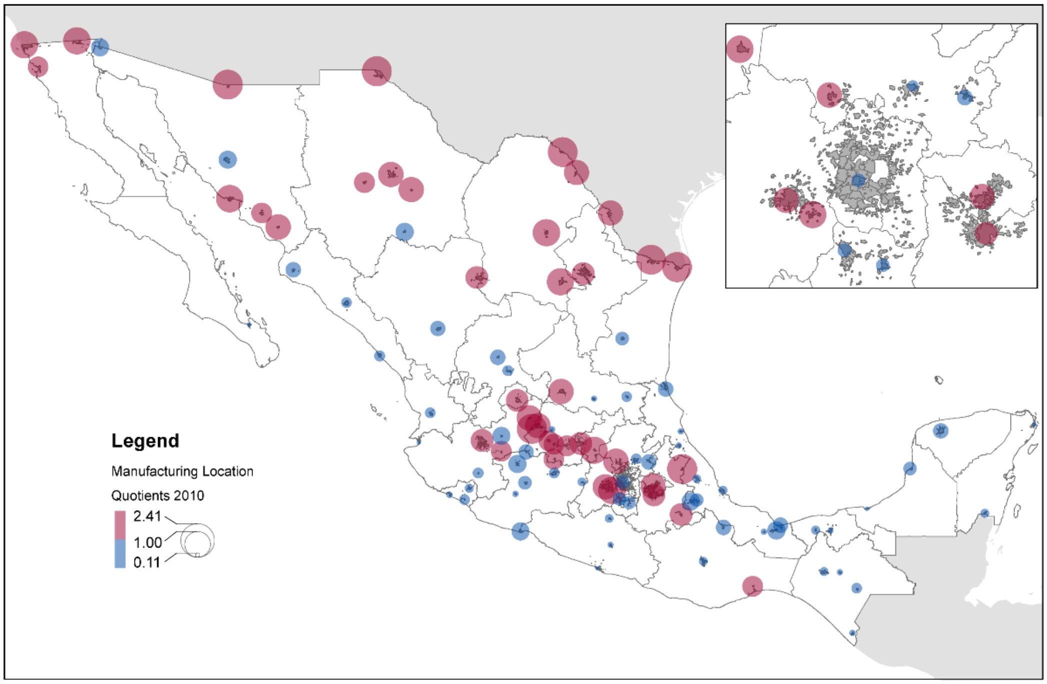


Figure 3: Manufacturing Location Quotients for 2010



Although there was still a high concentration of manufacturing jobs in the outskirts of Mexico City (Estado de México, Puebla and Hidalgo), by 2000, Mexico City itself already had relatively less manufacturing employment compared to the 100 cities (LQ of .80). Figure 3 shows the LQs in 2010, and we see that Mexico City had an even lower value (LQ of .70), showing the continuing trend towards greater concentration in other types of jobs.

Figure 4: Difference Between Manufacturing Location Quotients (2000–2010)

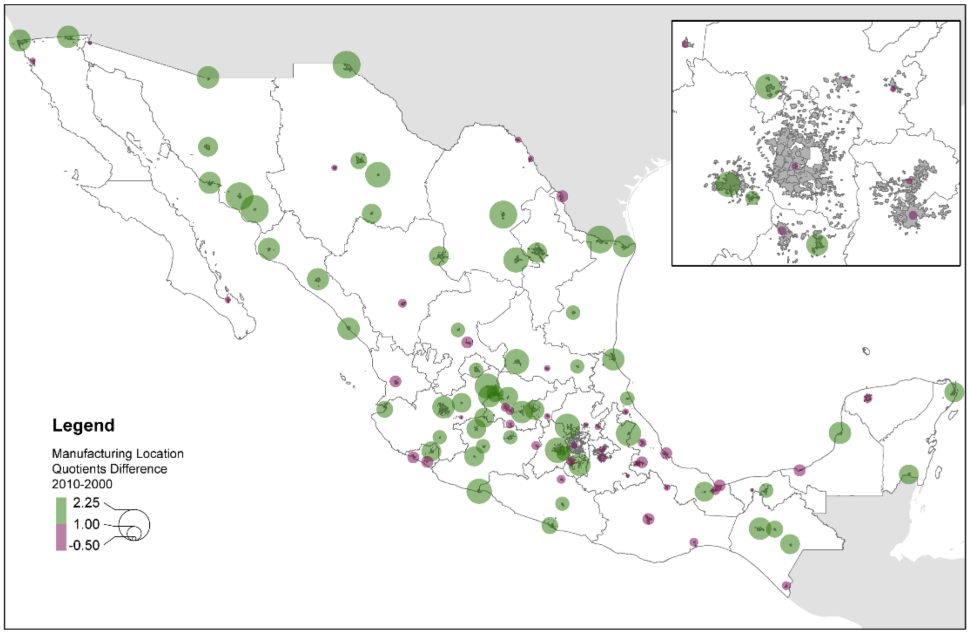


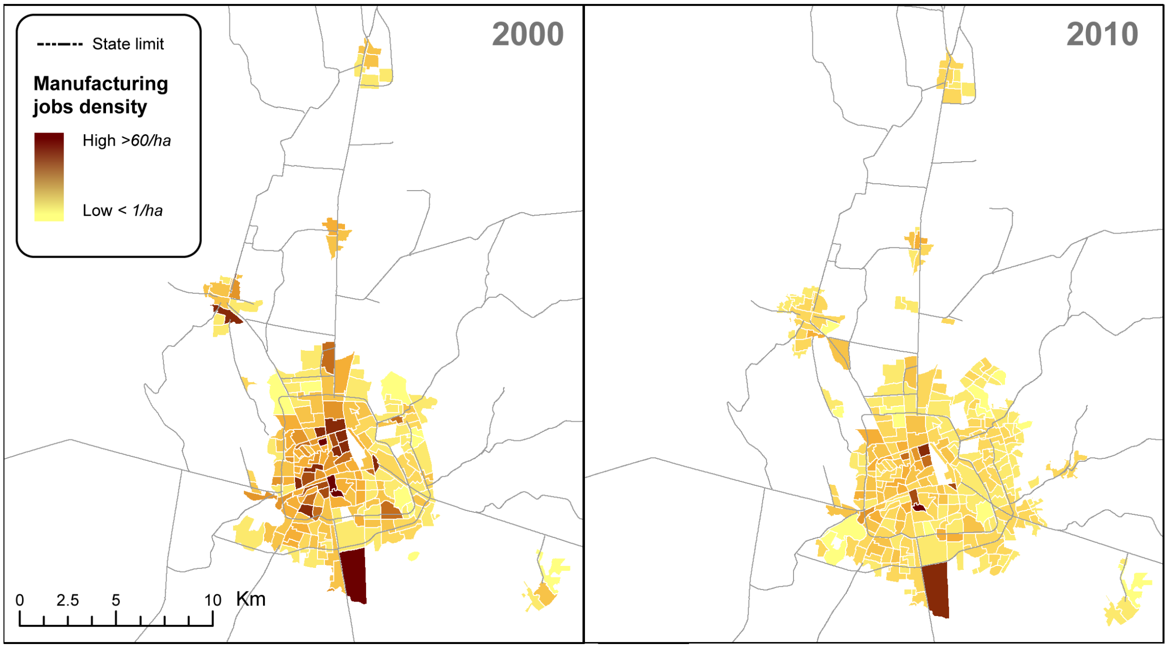
Figure 4 shows the change in the concentration of manufacturing jobs between 2000 and 2010. While Puebla, Hidalgo, Tlaxcala, Veracruz and Mexico City have been gradually losing manufacturing jobs (as also some border cities), we can see some cities in the Bajío and in the northern part of the country continue to gain relative importance in manufacturing. This explains the relative importance of Mexico City within the 100 analyzed cities. While its population is by far the largest in Mexico, its manufacturing activity is not as outsized. In fact, it is the 47th most concentrated in terms of manufacturing of the 100 cities.

The Intra-Metropolitan Spatial Evolution of Manufacturing in Mexico

As the process of 'concentrated dispersion' of manufacturing jobs occurred at the national level, another process has occurred within urban areas: a slow but constant process of suburbanization of manufacturing activity, and the loss of manufacturing in cities' cores. While this spatial dispersion is not as strongly evident as the first one (some cities still have industrial clusters attached in their historic centers due to the permanence of rail infrastructure), there are several pieces of evidence that emerge from comparing manufacturing job concentration at the census tract level between 2000 and 2010. As pointed out earlier, cities moving towards service sector activities in their central areas tend to raise central city land values and, combined with the opportunity for new infrastructure and roads industries are increasingly located in the urban periphery.

Figures 5–8 show changes in the concentration of manufacturing jobs between 2000 and 2010 for two metropolitan areas, a conurbation, and a town (the tree main categories of the *Sistema Urbano Nacional Mexicano* or SUN). The location of manufacturing has reshaped urban structures in Mexico, just as the location of population density has shifted with the expansion of financing for suburban homes. Though we have not concretely established this trend for all cities' manufacturing employment, spatial indicators developed for this study for all jobs (described in the following sections) confirm the general tendency.

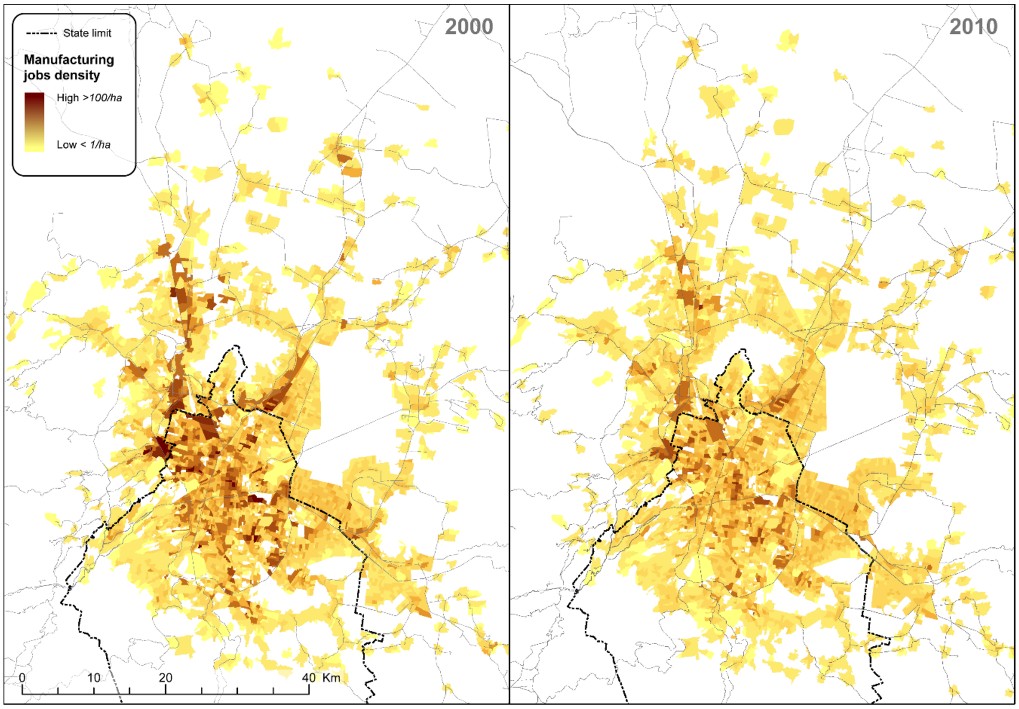
Figure 5: Population Density and Manufacturing Jobs Density in Aguascalientes (2000–2010)



In Figure 5 for instance, we clearly observe new manufacturing jobs clusters located not only in contiguity with peripheral urban fabric, but in exurban space of Aguascalientes metro area, while at the same time there is significant drop in the density of manufacturing in the city center. In the case of the Mexico City Metropolitan Area (MCMA), presented in Figure 6, the recent effect of deindustrialization did not seem to massively expel manufacturing jobs to the periphery between those years, though the relative concentration in the center has decreased.

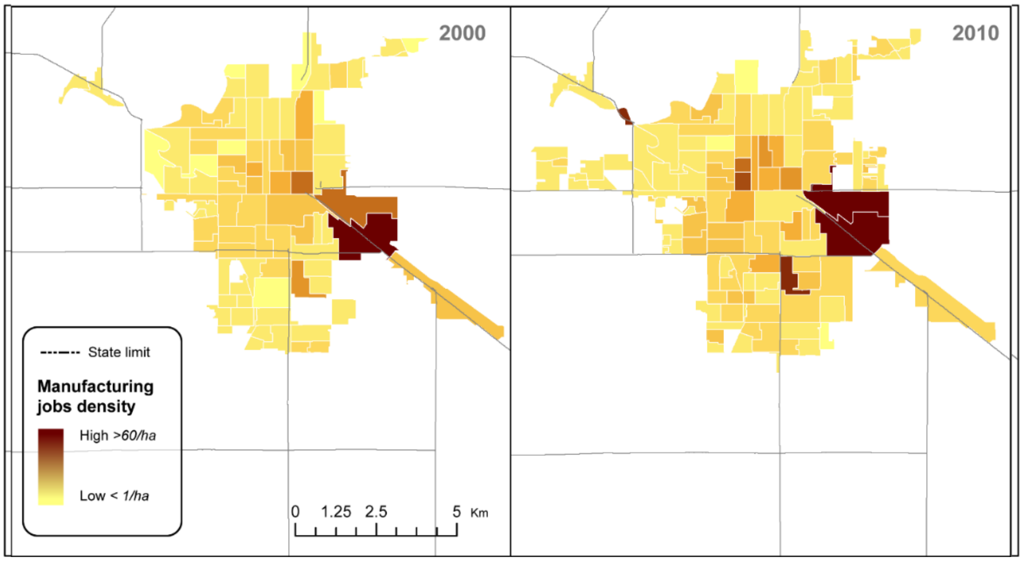
Instead, we can see a general decline in manufacturing employment density overall, suggesting industry is either being moved to other metro areas or that its share has been eclipsed by the service sector. This is true in traditional industrial areas like Azcapotzalco or Vallejo, where industrial land uses are being replaced by residential and commercial use. Employment concentration in certain industrial corridors is 'vanishing' without being reestablished in the outskirts.

Figure 6: Density of Manufacturing Jobs in the MCMA (2000–2010)



As demonstrated in Figure 7, a similar phenomenon is occurring in smaller cities like Ciudad Obregón, in Coahuila (a Northern Border State) or Mazatlán, Sinaloa, where manufacturing jobs are also spreading out. This is chiefly through the firms' relocation within existing or new peri-urban industrial parks. Logically, population tends to redistribute between the new settlements founded on the outskirts of the city, thus, diminishing central areas densities.

Figure 7: Population Density and Manufacturing Jobs Density in Ciudad Obregón, Coahuila (2000–2010)

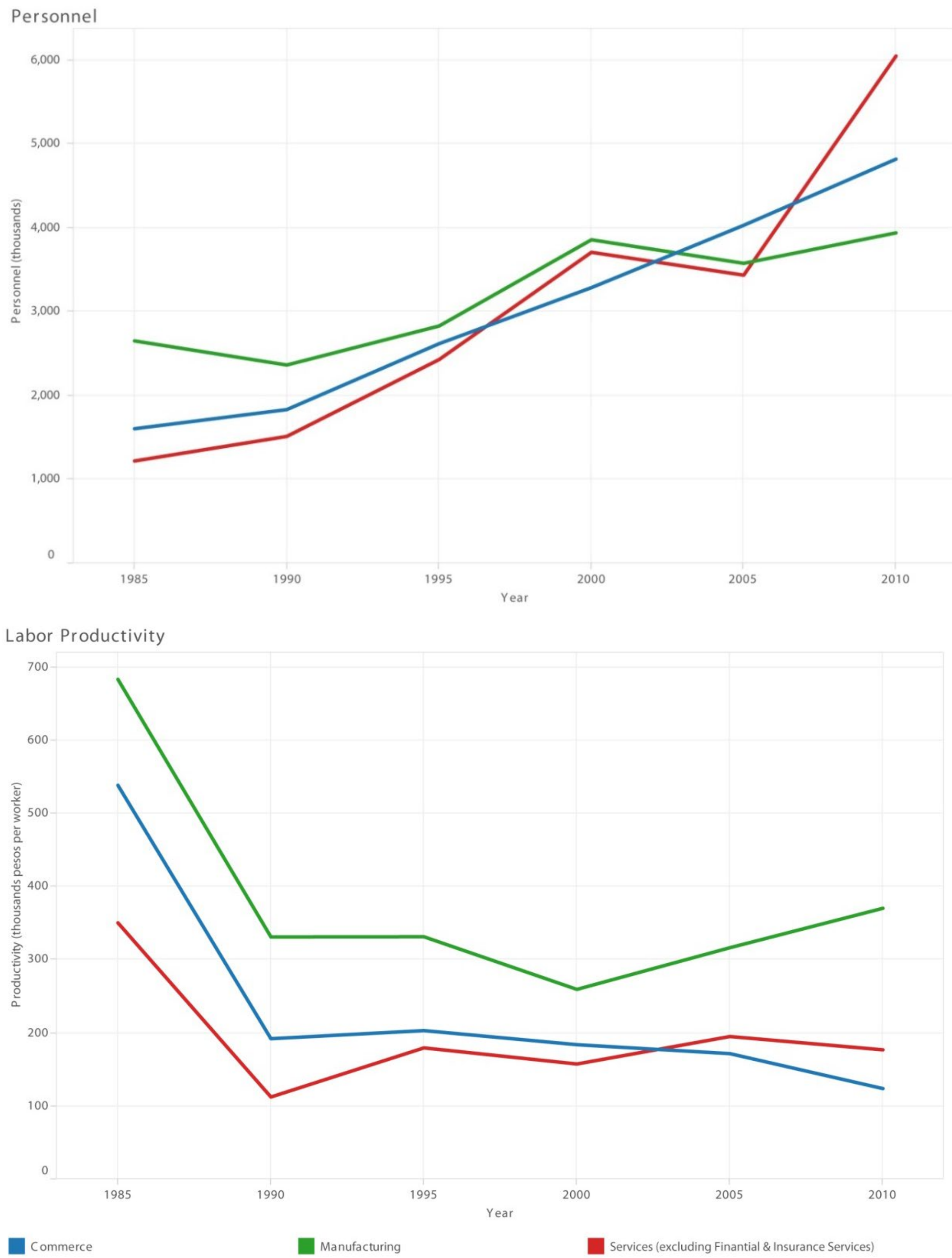


There are at least two likely reasons for this change in the spatial concentration of manufacturing across Mexican cities. First, the opening of Mexico to international trade and investment through efforts like the North American Free Trade Agreement is thought to have weaken the spatial concentration of manufacturing jobs in the central part of the country and encouraged maquila concentration near the border with the United States (Dávila 2004). At the same time, it is probable that diseconomies of scale in Mexico City and the State of Mexico began pushing manufacturing from these regions, as local governments were unable to provide adequate public infrastructure for the mega-region (Mendoza-Cota and Pérez-Cruz 2007).

Despite the industrial boom in the Northern Border states during the 1980s and 1990s, and the decentralization process of the MCMA, the share of jobs in manufacturing has been quite stable at the national level (roughly a quarter of all jobs) as has the share of manufacturing in GDP, representing 19 percent in 1981 and about 18 percent in 2013. In fact, the most noticeable change in Mexico's productive structure since the opening of its economy is the drop in the importance of agriculture from seven percent of GDP in 1981 to less than four in 2010 (Pérez et al. 2013, 22).

However, the levels of economic productivity in different economic sectors is crucial, especially in relation to the different land use needs of each sector. We compare labor productivity in three economic sectors in Mexico from 1985 to 2010 in Figure 8, and see that, at this level of aggregation, productivity is consistently higher in the manufacturing sector.

Figure 8: Jobs and Productivity in the 100 Largest Mexican Cities from 1985 to 2010

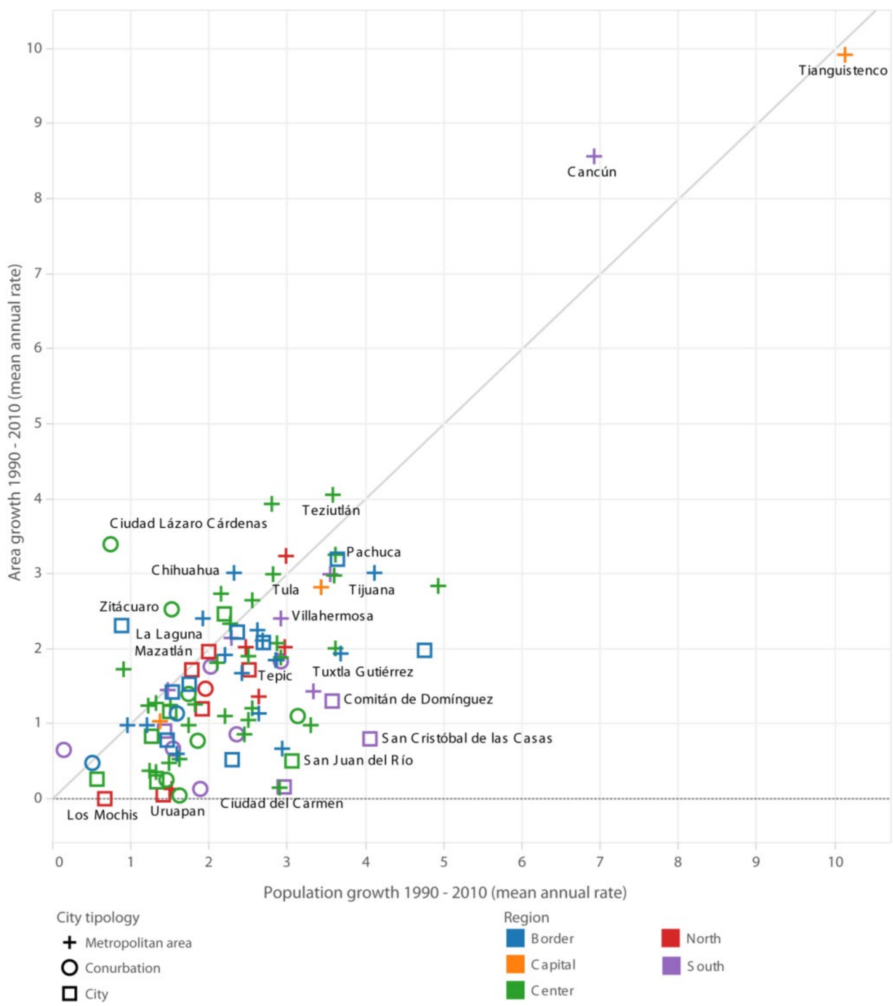


<u>The Spatial Evolution of Mexican Cities in the 21st Century</u>

Although Mexico's most rapid period of urbanization began in the second half of the 20th century, cities have continued to grow rapidly until present day. In each decade between 1990 and 2010, the 100 largest cities in Mexico grew in land area by almost 20 percent and over 20 percent in population. Overall, urban population density also increased during this period (Monkkonen and Comandon 2016).

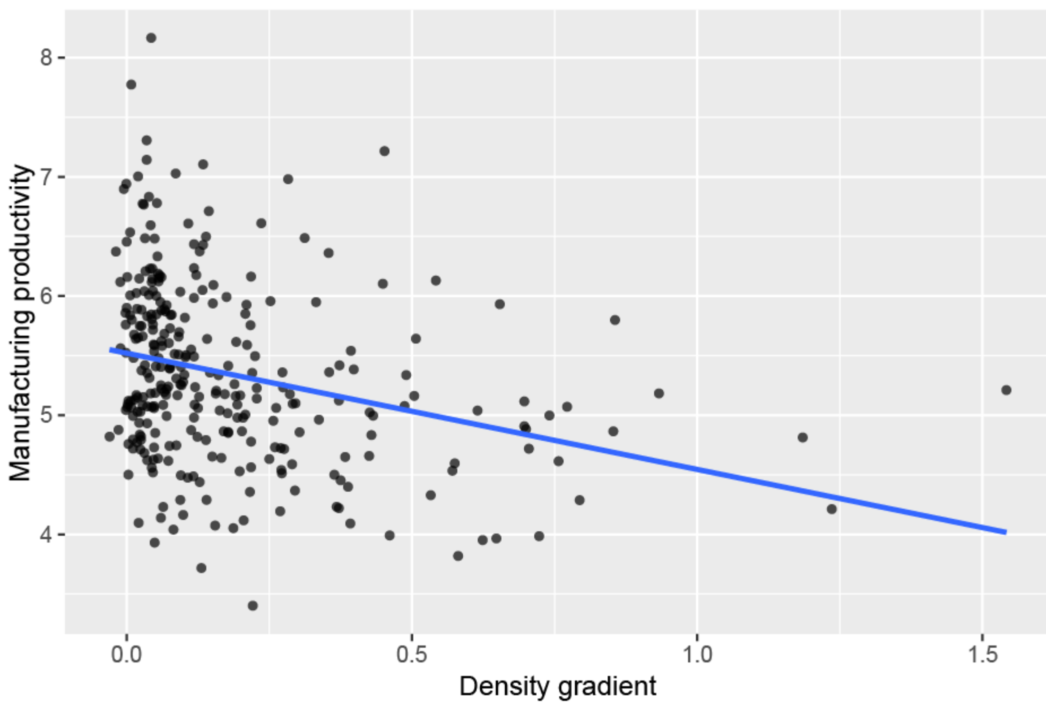
Figure 9 shows the rate of population growth as well as urban expansion in the 100 cities under study, classified by region and city typology. In general, the urban agglomerations grew at a mean annual rate (both in population and developed land) of around four percent. Two outlier cities grew at high rates (more than seven percent annually). Cities in which the rate of growth of the urbanized area was higher than that of the population are located above the diagonal line, and clearly there are fewer of these. We also see that the growth in the largest metro areas slowed down during this period.

Figure 9: Population Versus Area Growth for the 100 Largest Mexican Cities (1990–2010)



This pattern of growth is derived substantially from the reform and expansion of the housing finance system. Since the restructuring of INFONAVIT in the early 1990s, a new kind of housing construction boom has shaped urban growth substantially. The country's housing transition was a shift from primarily incremental, self-help construction process to one based on speculative building and mortgage finance (Monkkonen 2011b). This change led to much higher densities in the urban periphery and has been connected to high levels of housing vacancy (Monkkonen 2014) and a loss of population in most city centers (Monkkonen and Comandon 2016). There was a concurrent flattening of population density gradients, of almost 20 percent in both time periods, indicating that city populations became less centralized as their populations moved from centers to peripheries.

Figure 10: Relationship Between Manufacturing Productivity and Density Gradient (2010)



This description of changes in urban structure in Mexico contrasts somewhat from the portrayal of the nation's cities in reports by the federal government (SEDESOL 2011) and in the policy presentations of the new federal urban development secretariat (SEDATU 2013). In fact, the idea of uncontrolled sprawl, and the mistaken calculations of changes in urban population densities (for more, see Monkkonen and Comandon 2016) have led to various urban containment policies, without considering the potential for negative impacts on economic productivity. A visualization of the relationship between urban form and productivity shows that more sprawling cities in Mexico are more productive. Figure 10 shows the correlation between a city's density gradient and labor productivity for the 100 largest cities in Mexico. We can see that cities that are more spread out are more productive.

Measuring Urban Form / Urban Structure

The spatial form or spatial structure of cities is complex, and as such, numerous indicators and measures have been developed over the years to characterize and compare cities (Wong 2015). Recently, many of these indicators have been developed in connection within the paradigm of sustainability (Bourdic, Salat, and Nowacki 2012), due to the link between land use and transportation. Urban economists have also spent considerable energy to better understand the spatial structure of cities, because of its own interest as well as its connection to productivity and welfare (Anas, Arnott, and Small 1998).

Reis and colleagues (2016) provide a useful classification of the many measures of urban form/structure identifying four groups: landscape metrics, geo-spatial metrics, spatial statistics, and accessibility metrics. Landscape metrics date back to 1980s landscape ecology and have four basic types: shape irregularity, which measures the regularity degree of a specific shape; fragmentation, which measures whether urban settlements are contiguous or fragmented; diversity, which seeks to quantify the distribution of different urban characteristics (e.g. land use); and connectivity, or the degree to which arteries within a city are linked.

According to Reis and colleagues (2016), geo-spatial metrics are mostly indicators developed in an ad hoc manner for specific case studies, whereas landscape metrics have been used and applied more consistently. There are also several categories of geo-spatial metrics, some of them reminiscent of the landscape metric categories like fragmentation, diversity or connectivity. Others, developed specifically for urban areas, are density; centrality/proximity, which measure the position of some features of the city in relationship with the whole city; and polycentricism, which measures the absence or presence of other sub-centers in relationship to a dominant center (Reis, Silva, and Pinho 2016).

Spatial statistics are based on statistical tools that seek to measure the distribution of events across space (Reis, Silva, and Pinho 2016). They include regression metrics; spatial autocorrelation that measure how specific attributes are distributed within a territory (e.g. Global and Local Moran's I); metrics of evenness of distribution, who measure inequalities of specific urban features (e.g. the Gini Coefficient, Location quotient). Finally, accessibility metrics are those that assess "the amount of effort for a person to reach one more location, or the opportunities for activity available in a geographical location" (Geurs and van Eck 2001, 33). These measures include cumulative opportunities measures, gravity-based measures, or measures based on random utility theory (Handy and Niemeyer 1997).

In selecting urban form metrics for this study, we attempt to measure general urban structure as well as the particularities of sprawl in Mexico. Urban sprawl is generally characterized by low-density, fragmented, leapfrog, single-use development (Ewing and Hamidi 2015; Galster et al. 2001; Tsai 2005), though in Mexico, as Monkkonen (2011a) describes, peri-urban developments are often at a high population density. Sprawl is also related to urban decentralization (Torrens 2008) and the process of an urban area becoming polycentric (Meijers and Burger 2010). Since urban sprawl is a multi-factorial and complex spatial phenomenon, it cannot be described with one or two variables (Angel, Parent, and Civco 2010b; Ewing, Pendall, and Chen 2002). Thus, there are many studies attempting to capture different aspects of sprawl. Reis, Silva, and Pinho (2016) identify at least 162 urban form metrics of which 110 correspond to geospatial metrics used for explaining urban expansion, urban sprawl, polycentrism, and densification.

We select the most commonly used and robust 10 of these metrics for this study. Table 1 presents these metrics, with their sources, categorized by type (density, centrality, compactness, fragmentation, and evenness).

Table 1: Urban Form Related Metrics Tested in this Study

Category	Metric	Source(s)
Density	(1) Population / Job Density	Boyko and Cooper 2011; Galster et al. 2001
Centrality	(2) Density Gradient	Galster, et al. 2001
	(3) Centrality Index	Galster, et al. 2001
	(4) Proximity Index	Angel et al. 2010a
Compactness	(5) Compactness Rho	Bertaud and Malpezzi 1999; Malpezzi and Guo 2001
	(6) Compactness	Amindarbari and Sevtsuk 2015
Fragmentation	(7) Discontiguity	Amindarbari and Sevtsuk 2015
	(8) Gini Coefficient	Burt et al. 2009
Evenness of distribution	(9) Clustering Index	Pereira et al. 2013
	(10) Moran I	Tsai 2005

Density

1) Density is perhaps the most common and simple measure of urban structure. It is simply the number of units or events found in a given area (Boyko and Cooper 2011). Depending on the scale and scope, it can measure population, jobs, or dwelling unit density. Urban sprawl is generally characterized by low density, especially in the peri-urban areas (Galster et al. 2001), though what defines low- or high-density is context dependent. As discussed above, the Mexico case is confounding to the typical definition of urban sprawl in that new peri-urban housing developments are generally high-density.

$$Density = \frac{\sum Population}{\sum Urbanized\ Area} \quad (1)$$

In this study we use the simplest measure of urban population density, which is the number of residents in an urban area divided by the size of urbanized land. Our effort is facilitated by the way in which the Mexican census bureau, INEGI (Instituto Nacional de Estadística y Geografía), draws census tracts. They distinguish between urban and rural tracts and publish maps separately. This means that urban census tracts end at the edge of the urbanized area of a city, and effectively create a boundary of urbanized land from which we can calculate urban extent.

Centrality

2) The Density Gradient is the simplest measure of an urban area's central tendency. It is the rate at which density falls at larger distances from the city center. Density is generally highest in the city center, and the rate of decrease is exponential moving outward in most cities (Clifton et al. 2008). First developed by Clark in 1951 and later used by Mills (1972), it has often been used to test the monocentricity of a city's form. Critics argue that because this model is built under the assumption that all employment occurs in the city center it has become less relevant in contemporary urban areas (Bertaud and Malpezzi 1999) and is unduly affected by city size.

The Density gradient *(D)* is expressed as follows:

$$D(u) = D_0 e^{-rue} \quad (2)$$

Where D_0 is the density in the urban center, u is the distance to the city center, r is an exponential decay parameter (the gradient), and e represents an error term. Higher values indicate greater centrality, thus, a more monocentric urban structure.

3) The Centrality Index (Galster et al. 2001) measures the degree to which urban features are closely located near the CBD. Lower levels of centralization indicate a higher level of sprawl. The main difference between this index and the density gradient is that this tool does not measure decay. It is calculated by adding up the inverse distance of each census tract, weighted by its population. Then, the 'average distance' is standardized by the city's size in question, dividing it by the squared root of the total urban area.

$$CI = \frac{T(i)u(A^{\frac{1}{2}})}{\sum_{m=1}^{M} F(k,m)T(i)m} \quad (3)$$

Where $T(i)u$ is the total number of observations (population) of land use i in Urban Area *u;* $A^{\frac{1}{2}}$ is the square root of the Urban Area for normalization purposes; $F(k,m)$ is the distance between the centroids of grid k and grid m; $T(i)m$ is the total number of observations(population) of land use *i* in land area *m*.

Compactness

4) The Proximity Index was developed by Angel and colleagues (2010a) to assess urban compactness. It is the 'ratio of the average distance from all points in the equal-area circle to its center and the average distance to the city center from all point in the city footprint' (Angel, Parent, and Civco 2010a, 11). It takes advantage of the fact that the circle is the most compact shape, thus, the most efficient form. Proximity Index (PI) takes the value of 1 when urban form is a circle, and 0 under perfect linearity. We improve on the measure as presented by Angel and colleagues by including the issue of non-developable land, such as bodies of water or steep hills. The PI is effective in its simplicity but does not account for the distribution of people or activities within the city.

$$PI = \frac{2\sqrt{A/\pi}}{3d_{CS}} \quad (4)$$

Where A is the circle area, d_{CS} is the average distance to the proximate center, the $\frac{2}{3}$ factor is to compute the average distance to the centre in a circle of radius $\sqrt{A/\pi}$

5) The Compactness *Rho* was developed by Bertaud and Malpezzi (1999). It is supposed to be an index applicable either to a monocentric or polycentric city, and is defined as "the ratio between the average distance per person to the CBD, and the average distance to the center of gravity of a cylindrical city whose circular base would be equal to the build-up area, and whose height will be the average population density" (Bertaud and Malpezzi 1999, 3). They argue it is useful to measure sprawl for dominantly monocentric cities, and that the measure of the average distance per person to the CBD is a good proxy to understand the performance of the city shape. The formula is:

$$\rho = \frac{\sum_i d_i w_i}{C} \tag{5}$$

Where rho is the index; *d* the distance from the i^{th} tract from the CBD weighted by the tract's share of the city's population *w*; and *C* is the similar, hypothetical calculation for a cylindrical city of equivalent population and built up area (Bertaud and Malpezzi 1999). "If a city area X for which the average distance per person to the CBD is equal to the average distance to the central axis of a cylinder which base is equal to X would have a compactness index of 1" (Malpezzi and Guo 2001, 7). It can be interpreted as the inverse: *the lower the value of rho, more sprawl.* Although this measure is similar in concept as the PI (both depart from the circular principle of efficiency), it is weighted by population.

6) Another compactness index developed by Amindarbari and Sevtsuk (2015) is defined as 'the degree to which the resources of a city—people, buildings, jobs, etc.—are spatially spread-out: the closer they are located to each other, the more compact the city is (Amindarbari and Sevtsuk 2015, 12). They critique the Bertaud and Malpezzi (1999) Rho index because this measure just includes developed areas and the center and overlooks the spatial relationships with each other, making that measure suitable just for monocentric situations. Their proposal relies on the Hansen (1959) gravity model, arguing that this measure should be able to capture the accessibility degree from different parts of the city to each other. In other words, the more accessible different locations are within a city, the more compact it is.

First, one computes the Gravity Index for each census tract:

$$G_i = \sum_{j \in G - \{i\}} \frac{W[j]}{e^{\beta \cdot d[i,j]}} \tag{6}$$

where G_i is the Gravity index for census tract *i*; $W[j]$ is the weight of the *j* destiny, and $d[i,j]$ is the distance between centroids of census tracts *i* and *j*. β is the decay. This tool computes G_i for every census tract and reports the weight of the gravity index for every case study (i.e. cities). This can be weighted by population or jobs, so the spatial relationships between larger distances have a proportional stronger effect over the index than smaller locations. The index can be normalized by population, geographical constrains (by subtracting non-buildable area) or by the density of the reference city. Once normalized, it could be used for comparing compactness among different cities.

We normalize the compactness measure by population, manufacturing jobs and total of jobs. For a cross-sectional study of 100 cities, calculating compactness at census tract levels—given the quality of the national spatial data—was robust enough for this research project. Though time consuming, compactness was also calculated at block level with very similar results as with census tract. Since block level represents the most detailed urban footprint element, for that case it was not necessary to normalize it geographically.

Fragmentation

7) Although there are several fragmentation measures in the literature, we found Amindarbari and Sevtsuk's (2015) Discontiguity (DC) measure the most straightforward. Galster et al. (2001) propose a continuity measure—whose inverse value would be discontiguity or the extent to which urban areas develop by leapfrogs—yet it is quite complex to implement. Other fragmentation measures depend on satellite imagery data that, while preferable in many ways, require extensive post processing before they can be used as an input.

The DC measures the degree in which urban areas grew without spatial contiguity:

$$DC = \frac{\sum_{n=1}^{N}\left(\frac{\sum_{i=n+1}^{N} A_i}{A_n} \cdot A_n\right)}{A_{total}} \quad (7)$$

where N is the number of urbanized clusters and A_n the area of cluster *n*, and A_{total} the joint area of the urban extent (Amindarbari and Sevtsuk 2015, 20). The lower the outcome of discontiguity measure, the less fragmented the urban area.

Evenness of distribution

8) The Gini Coefficient is a common measure of inequality and can also be applied to the distribution of population or employment across the different spatial units in a city (Burt, Barber, and Rigby 2009). It has been used as a sprawl index, though it is unclear theoretically whether a more or less equal distribution would be considered sprawling (Tsai 2005). But as it lacks a spatial dimension, this author suggests it should be used better as a dimension of metropolitan form, although theoretically can characterize certain aspects of compactness or decentralized sprawling areas. Higher coefficients close to 1 mean population, jobs or dwelling density is very high in just some sub areas, whether values near to 0 would reflect an equally distribution in a city. Gini was calculated as follows:

$$\text{Gini} = 0.5\sum_{i=1}^{N}\left|X_i - Y_i\right| \quad (8)$$

where N is the number of census tracts or sub-areas; X_i the proportion of land area in sub-area i; and Y_i the proportion population, employment or dwellings in sub-area i (Tsai 2005; Burt, Barber, and Rigby 2009). Gini was calculated for population, total jobs, and manufacturing jobs.

9) A Clustering Index developed by Pereira et al. (2013) measures the uneven distribution of population, jobs, or housing across a city. It is like the Gini Coefficient, but uses tracts as the unit of observation, assuming each to be equally sized, and considers whether similar tracts are next to one another.

$$CLI = 0.5\sum_{i=1}^{n}\left|s_i - 1/n\right| \tag{9}$$

where n is the number of census tracts of a city, and s_i is the share of the city's population or jobs in a given tract. Lower values of this index mean people or jobs are more homogeneously distributed across the city, and higher values indicate people or jobs are concentrated.

10) A global spatial autocorrelation measure, the Moran's I, also measures whether tracts with high values of a variable are clustered, dispersed, or randomly distributed.[1] Moran's I vales are expected to be high, medium and low for monocentric, polycentric, and a decentralized sprawling urban structure. The partial conclusions of Tsai (2005) were that this index could effectively characterize compactness/sprawl alone but recommends it to be used with the Gini Coefficient. The Moran's I does not distinguish among different distributions of densities, such as polycentric or leapfrog development.

$$I = \frac{N}{\sum_i \sum_j w_{ij}} \frac{\sum_i \sum_j w_{ij}(X_i - \bar{X})(X_j - \bar{X})}{\sum_i (X_i - \bar{X})^2} \tag{10}$$

Where N is the number of spatial units indexed by i and j; X is the variable of interest; $\bar{X}$ is the mean of X and w_{ij} is an element of a matrix of spatial weights.

Also, it is hard to find a specific threshold or range for identifying when the Moran's I indicates a monocentric, polycentric or decentralized sprawling urban structure. Nonetheless, he found that higher values match monocentric conditions; intermediate values correspond to potential polycentric situations and values closer to 0 are related with sprawl.

[1] This index is now a basic spatial analysis tool in most GIS software. For further details, see http://resources.esri.com/help/9.3/arcgisengine/java/gp_toolref/spatial_statistics_tools/how_spatial_autocorrelation_colon_moran_s_i_spatial_statistics_works.htm

Table 2: Urban Form Metrics Descriptive Statistics

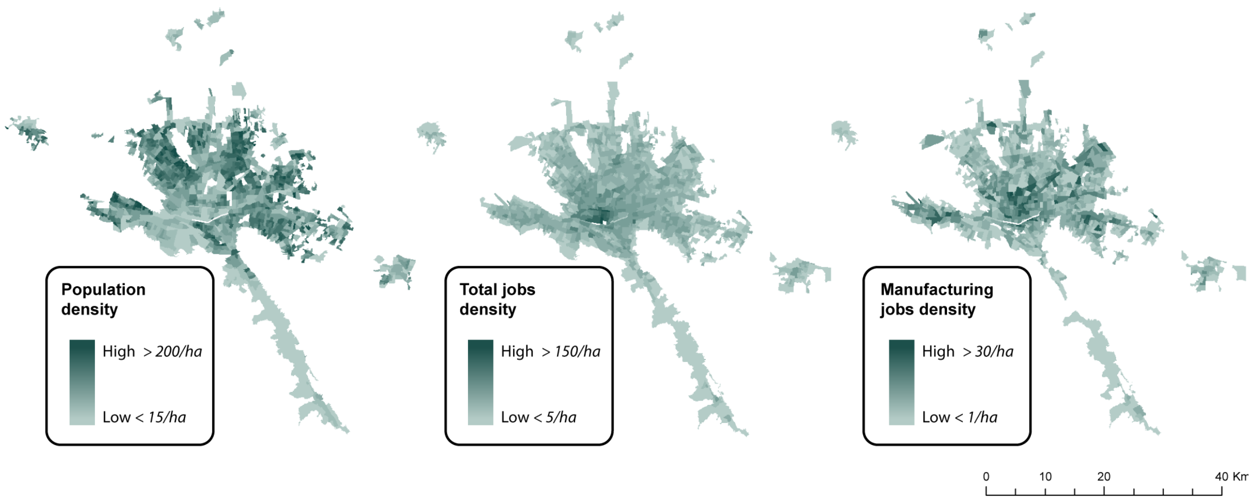
	Year					
	1990		2000		2010	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Raw Compactness	744.84	898.02	538.39	646.48	994.37	952.86
Raw Compactness (log)	5.590	1.778	5.244	1.967	6.269	1.396
Compactness Normalized by Population	.007	.013	.005	.009	.007	.010
Compactness Normalized by Population (log)	-6.640	2.438	-7.079	2.423	-6.363	2.099
Discontiguity	0.545	1.125	0.569	1.044	0.537	0.967
Discontiguity (log)	0.316	0.420	0.333	0.429	0.321	0.418
Gini (Pop)	0.299	0.061	0.350	0.076	0.350	0.067
Moran´s I (Pop)	0.193	0.444	0.168	0.128	0.270	0.161
Proximity Index I	0.508	0.246	0.613	0.210	0.627	0.189
Clustering	0.296	0.061	0.311	0.065	0.358	0.079
Gradient	0.200	0.293	0.183	0.175	0.149	0.173
Centrality Index (Pop)	0.492	0.176	0.712	0.239	0.825	0.299
Gradient (Jobs)			-.302	.294	-.354	.355
Centrality Index (Jobs)			.984	.332	.867	.303
Raw Compactness of Manufacturing jobs			43.687	78.537	31.843	159.073
Raw Compactness of Manufacturing (log)			2.552	1.810	1.154	1.932
Compactness Normalized by Manufacturing jobs			.0113	.0189	.0045	.0187
Compactness Normalized by Manufacturing jobs (log)			-6.36	2.49	-8.09	2.61
Manufacturing Discontiguity			.573	1.029	.629	1.114
Manufacturing Discontiguity (log)			.342	.418	.365	.441
Gini (Total Jobs)			.464	.055	.510	.064
Gini (Manufacturing jobs)			.466	.085	.560	.106
Moran´s I (total jobs)			.329	.130	.174	.188
Moran´s I (Manufacturing jobs)			.110	.114	.069	.110
Clustering (Jobs)			.583	.057	.570	.059

We calculate all measures for jobs—from the economic censuses 1989, 1999, and 2009 at the census-tract (AGEB) level—and population—from the population and housing censuses 1990, 2000, and 2010. Table 2 presents summary statistics.

Our dependent variable will be manufacturing productivity as the ratio of gross value added (GVA) and personnel, from the same economic censuses. Given its skewness, it will be necessary to transform it logarithmically to fit regression models.

Given the lack of high granularity in economic data for 1990, we only computed urban metrics related to the population distribution or the "pure form" ones—that is, metrics with inputs only related with the shape, area or distance to the CBD or city centroid.

Figure 11: Urban Form Metrics from Monterrey, Nuevo León (2010)



	Population	Jobs	Manufacturing jobs
Centrality Index	0.626	1.064	
Density gradient	0.076	-0.115	
Discontiguity	0.389		0.644
Raw Compactness	194.9		0.250
Compactness Normalized	0.00006		0.0000009
Moran's I	0.244	0.146	0.072
Gini	0.420	0.510	0.608
Clustering	0.626	1.064	
Proximity Index	0.772		

Figure 11 presents the example of calculations for one metropolitan area, Monterrey, Nuevo Leon. The Centrality Index indicates that jobs are less sprawling than population; and the Density Gradient reveals different urban structures for jobs and population. The region's population is more centrally concentrated than its jobs. The Discontiguity measure expresses the degree to which the city's growth 'leapfrogs' non-contiguously, and it shows a more compact structure for the city's population than jobs. Compactness indicates how close things are between them. In this case, people are closer to each other than manufacturing jobs, which are more dispersed.

Moran's I values are high, medium and low for cities that are monocentric, polycentric, and decentralized, respectively. In Monterrey, the population tends to be monocentric, while manufacturing jobs are more likely to be dispersed. The Gini coefficient and Clustering Index tell us the degree of homogeneity of density across this region. Values closer to 0 reflect a regular distribution in Gini, so it seems none of the variables are highly concentrated. This is coherent with empirical evidence: jobs tend to cluster more than houses due to the constant search of economies of scale. The Clustering Index matches that of the Gini. The final measure of compactness, the Proximity Index, takes the value of 1 when the city is a circle, and 0 under perfect linearity. It shows Monterrey is relatively circular.

Modelling Approach

In previous cross-sectional analyses over the 100 biggest Mexican cities, we found statistically significant correlations between productivity and urban sprawl (see Table 3). From it, it can be inferred that workers in Mexico are more productive in more sprawling, less centralized cities.

It is well known that cross-sectional data is of limited use in addressing questions to do with causal ordering. Thus, we model changes in urban labor productivity over time, and test whether urban form measures have a significant relationship to these changes. To do this, we use two strategies: (1) a three-occasion panel data model from 1990 to 2010, which uses longitudinal mixed models or growth curve models; and (2) a two-occasion panel data from 2000–2010 that uses both longitudinal mixed models and panel data models (for further details regarding the modelling approach, see Appendix B).

Table 3: Cross-Sectional Regressions of Worker Productivity in 2010

Variable	Model 1	Model 2	Model 3	Model 4	Model 5
Population (ln)	0.175***	0.094	0.122**	0.130**	0.102*
	-0.056	-0.057	-0.052	-0.052	-0.056
% College degree	-1.316	-1.327	-0.709	-1.041	-1.342
	-1.320	-1.291	-1.286	-1.295	-1.290
% Jobs manufacturing	1.496***	1.659***	1.416***	1.659***	1.690***
	-0.388	-0.377	-0.371	-0.374	-0.378
Herfindahl Index	-4.736***	-4.291***	-4.526***	-4.717***	-4.490***
	-1.013	-1.027	-0.975	-0.986	-1.008
Population density	-0.253				
	-0.166				
Density Gradient		-0.670**			
		-0.290			
Centralization Index			-0.482***		
			-0.151		
Circularity Index				-0.603**	
				-0.231	
Clustering Index					-1.399**
					-0.606
Constant	4.899***	4.927***	4.907***	4.834***	5.278***
	-0.744	-0.695	-0.660	-0.672	-0.759
Observations	100	100	100	100	100
R-squared	0.389	0.408	0.435	0.416	0.408

Notes: 100 biggest cities. Mining productivity and employees not included.

Analysis

We first run three sets of models using data from 1990 to 2010.[2] Because of the limited availability of tract level employment data, we run a second set of models on data from 2000 to 2010 to consider urban form measures calculated with employment data. Since we have only a two occasion panel data, the longitudinal mixed models will probably overfit the data. So, to get nuanced results, we run two sets of linear regression panel models—one with fixed and one with random effects—to use a more flexible functional form. In all cases, we fit a reference model with only time and some controls, and then add the various urban form variables one at a time on the right-hand side.

[2] Those models use tabular and spatial data provided by INEGI. It is well known that INEGI has been improving its methodologies for the extraction of spatial data. Yet, we found some spatial mismatches in some cities (i.e. shrinkage of census tracts sizes between the analyzed periods) that at first glance, could jeopardize our research. To be sure of the results, we ran a parallel set of models without the cities affected by this inconsistency. Results were similar to those presented here.

Productivity and Urban Form Based on Population, 1990–2010

As pointed out in Appendix B, for the 1990–2010 panel, we want to assess both the effects of time and the effects of urban form on manufacturing productivity. First, we fit a null model (with no explanatory variables and only a random intercept) to assess the intra-class correlation (ICC), to determine if a mixed model is necessary. The ICC of 66 percent is evidence in favor of a mixed model. Secondly, we fit a random intercept model with only time as predictor, finding a likelihood ratio test highly significant (Chi-square of 23.44), indicating a better fit of the later model. Thirdly, we fit a random slope model. The likelihood ratio test is highly significant (Chi-square of 26.42). Thus, the model can be written as:

$$y_{ij} = \beta_{0j} + \beta_1 t_{ij} + \beta x_{ij} + u_{1j} t_{ij} + e_{ij} \qquad (11)$$

The term βx_{ij} is the time-variant controls and explanatory variables.

Table 4 reports the results of the models with only statistically significant UF variables. We controlled for city population size, given its important connection to both urban structure and agglomeration economies. The main hypothesis we want to test is that more sprawling cities have a different level of effects on labor productivity. The basic model controls for city population has a Bayesian Information Criterion (BIC) = 566.

Table 4: Results of Longitudinal Random Slope Mixed Models

	(1)	(2)	(3)	(4)	(5)
Fixed effects					
(Intercept)	3.725***	4.299***	3.901***	4.185***	3.869***
	(0.747)	(0.790)	(0.739)	(0.766)	(0.714)
Time (2000 centered)	0.063	0.074	0.084*	0.060	0.179***
	(0.039)	(0.039)	(0.041)	(0.039)	(0.049)
Log(pop)	0.131	0.077	0.134*	0.099	0.159**
	(0.060)	(0.065)	(0.059)	(0.061)	(0.058)
log(1 + Discontiguity)		0.292*			
		(0.146)			
Proximity Index			-0.376*		
			(0.187)		
Gradient				-0.384*	
				(0.185)	
Centrality Index (pop)					-0.744***
					(0.190)
Random Effects					
Intercept (Between) u_{0j}^2	0.381	0.363	0.361	0.363	0.337
Time (Between) u_{1j}^2	0.074	0.073	0.078	0.074	0.075
Residual (Within) e_{ij}^2	0.116	0.118	0.114	0.117	0.112
Correlation Intercept/slope	0.397	0.412	0.382	0.417	0.364
BIC	566.3	570.1	569.6	569.3	558.8

Notes: The dependent variable is Log(Manufacturing Productivity), control variable is Log(Population). ***, **, *, and † indicate significance at $p < 0.001$, $p < 0.01$, and $p < 0.05$, and $p < 0.1$ levels.

Four urban forms variables are statistically significant: the Discontiguity Index, the Proximity Index, the Density Gradient, and the Centrality Index. All these significant relationships indicate that more sprawling urban areas are more productive. That is, more fragmentation is associated with more productivity, whereas less compactness and less centrality are also associated with more productivity. In this model, the fixed and random effects are significant, meaning it better accounts for both the between-cities and within-cities variance. The positive correlation between random intercept and random slope indicates a typical fanning-out pattern of the growth curves over time, centered in the overall mean intercept (3.87) and the overall slope of 0.18.

The second set of models, results of which are presented in Table 5, are of identical form but incorporate a city-level measure of economic specialization, the Herfindhal-Hirschman Index (HHI). The HHI ranges from 0 to 1, with zero indicating complete diversification and one equaling complete concentration economic activity in one sector. There are four sectors considered in this study: mining, manufacturing, services and commerce).

Table 5: Results of Longitudinal Random Slope Mixed Models

	(1)	(2)	(3)	(4)
Fixed effects				
(Intercept)	2.917***	3.074***	3.400***	3.114***
	(0.715)	(0.701)	(0.729)	(0.693)
Time (2000 centered)	0.135**	0.164***	0.134**	0.238***
	(0.042)	(0.044)	(0.042)	(0.050)
Log(pop)	0.163**	0.169**	0.128*	0.187***
	(0.056)	(0.054)	(0.056)	(0.054)
HHI (GVA)	0.995***	1.052***	1.031***	0.924***
	(0.250)	(0.249)	(0.249)	(0.247)
Proximity Index		-0.440*		
		(0.182)		
Gradient			-0.424*	
			(0.179)	
Centrality Index (pop)				-0.680***
				(0.187)
Random Effects				
Intercept (Between) u_{0j}^2	0.319	0.296	0.299	0.291
Time (Between) u_{1j}^2	0.069	0.073	0.068	0.070
Residual (Within) e_{ij}^2	0.121	0.120	0.124	0.117
Correlation Intercept/slope	0.434	0.424	0.463	0.413
BIC	558.6	560.2	560.5	552.6

Notes: The dependent variable is Log (Manufacturing Productivity), control variables are Log (Population) & HHI (GVA). ***, **, *, and † indicate significance at p < 0.001, p< 0.01, and p< 0.05, and p< 0.1 levels.

The reference model includes only population and the HHI as controls. With a BIC = 558.6 it improves the fit compared to the former reference model. Additionally, the specialization index resulted as a significant predictor for labor productivity. In these models, we only get non-zero effects for three measures of urban form: Proximity, Density Gradient, and Centrality, with the same negative sign and even stronger coefficients. Once again, the best fitting model is the Centrality Index.

In a third set of models, we tried several combinations of two urban form metrics to account for the multifaceted nature of urban form while avoiding multicollinearity issues. We included the Centrality Index (CI) on the right hand-side and added the other metrics one by one. The only added metric with a non-zero effect was the Moran's I index, which captures the spatial autocorrelation or clustering in the population distribution. The positive coefficient means cities with more clustering are more productive. Table 6 reports the results from these random slope mixed models with two urban form metrics as predictors.

Table 6: Results from Longitudinal Random Slope Mixed Model

Fixed effects	Coefficient
(Intercept)	3.017***
	(0.693)
Time (2000 centered)	0.234***
	(0.050)
Log(pop)	0.193***
	(0.054)
HHI (GVA)	0.911***
	(0.246)
Centrality Index (pop)	-0.727***
	(0.186)
Moran's I (pop)	0.206*
	(0.101)
Random Effects	
Intercept (Between) u_{0j}^2	0.538
Time (Between) u_{1j}^2	0.259
Residual (Within) e_{ij}^2	0.341
Correlation Intercept/slope	0.418
BIC	556.8

Notes: The dependent variable is Log (Manufacturing Productivity). ***, **, *, and † indicate significance at p < 0.001, p< 0.01, and p< 0.05, and p< 0.1 levels.

The mean trend in time of manufacturing productivity is captured by the fixed effects intercept (3.017) and slope of time (0.234). The random intercepts will fall within 1.23 and 4.45 and the random slopes within -0.76 and 1.56, so the method can take account for each city's trend. To better illustrate the last model with two UF predictors (Table 5), we present the following figures (see Figures 3 and 4). As the both within and between variance components change from one city to another, it is not feasible to plot all the 100 curves. Instead, Figure 12 shows the fanning out effect of the conditional effects of the random coefficients in a sample of 15 cities together (note that some cities as Chilpancingo, Puerto Vallarta, or Ocotlán have a negative trend, and others as Túxpam, Cuauhtémoc, or San Juan del Río a positive one).

Figure 12: Sample of 15 Cities' Random Intercepts and Slopes

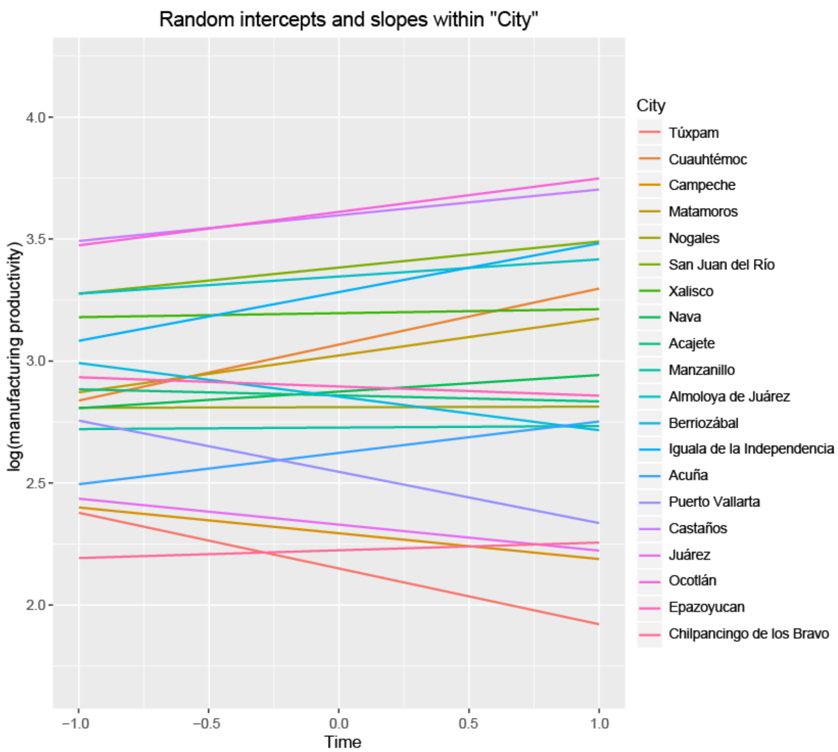


Figure 13: Plots of the Fixed Effects Variables

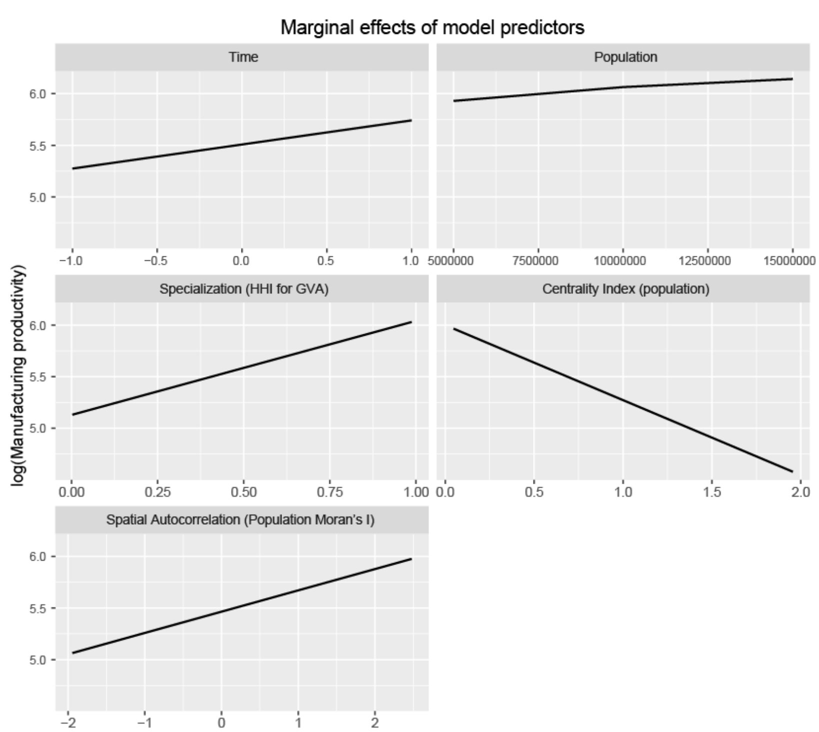


Figure 13 shows the effect of each independent fixed variable keeping the others constant. These results can be counter intuitive in the light of previous empirical outcomes. Yet, housing and jobs location patterns are often opposite or complementary. High Moran's I values indicate that there are tracts in the city with high concentrations of population next to other tracts with high population concentration. These tracts can be in the urban periphery.

Productivity and Urban Form Based on Employment, 2000–2010

For the 2000–2010 data, we can calculate urban form metrics using jobs data at the tract level. We do this for total jobs and manufacturing jobs, as well as population patterns. We conducted similar analyses as in the previous section, but we will report only results from the models controlling by population since the specialization variable is not significant. Table 7 reports the results of the reference model (with only population as control) and the models with employment based urban form metrics with non-zero effects.

Table 7: Results from Longitudinal Random Slope Mixed Model (2000–2010)

	(1)	(2)	(3)	(4)
Fixed effects				
(Intercept)	3.208***	3.326***	3.772***	3.116***
	(0.844)	(0.820)	(0.862)	(0.850)
Time (2000 centered)	0.214***	0.165**	0.205***	0.266***
	(0.050)	(0.056)	(0.050)	(0.057)
Log(pop)	0.164*	0.185**	0.159*	0.160*
	(0.068)	(0.066)	(0.067)	(0.068)
Centrality Index (Jobs)		-0.385*		
		(0.181)		
Proximity Index			-0.801*	
			(0.321)	
Moran's I (Population)				0.500†
				(0.274)
Random Effects				
Intercept (between)	0.418	0.388	0.404	0.423
Time (Between)	0.135	0.144	0.133	0.129
Residual (within)	0.050	0.049	0.049	0.049
Correlation Intercept/slope	0.187	0.150	0.151	0.188
BIC	391.6	394.2	391.2	394.3

Notes: The dependent variable is Log(Manufacturing Productivity). ***, **, *, and † indicate significance at $p < 0.001$, $p< 0.01$, and $p< 0.05$, and $p< 0.1$ levels.

As with the previous models, only a few urban form measures are significantly associated with productivity. The Centrality and Proximity Index are again significant and negative. The Moran's I index for the population distribution is also significant. When the control variable for specialization is introduced in the model, the goodness of fit worsened and the HHI index had no significant effect. The results (available upon request) are similar than before, that is, the same three variables have non-zero effects but with higher standard errors.

Linear Regression Panel Models

Finally, we use two sets of linear regression panel models—with fixed and random effects—because of their more straightforward interpretation of difference regressions for two occasion observations. The fixed effects panel models identify the relationship between the change in productivity and the change in the urban form variables. Table 8 presents the results. As before, we fitted a reference model with only controls and then ran models adding one UF metric at the time. The goodness of fit is low, yet we find that three of the measures that capture the evenness of employment distribution are significant and positive: the Gini index, the Moran's I, and the clustering index. This indicates that cities where industry is more concentrated in space are more productive.

Table 8: Results from Fixed Effects Panel Linear Models for 2000–2010 Data

Variables	(1)	(2)	(3)	(4)
log(pop)	0.972***	0.50	0.666*	1.119***
	(0.238)	(0.337)	(0.278)	(0.248)
Gini (Manufacturing Jobs)		1.187†		
		(0.606)		
Moran's I (Total Jobs)			-0.478*	
			(0.234)	
Clustering (Jobs)				2.151†
				(1.146)
R-squared	0.144	0.176	0.179	0.174
Adjusted R-squared	0.071	0.086	0.088	0.085

Notes: Difference regressions. The dependent variable is Log(Manufacturing Productivity). ***, **, *, and † indicate significance at $p < 0.001$, $p< 0.01$, and $p< 0.05$, and $p< 0.1$ levels.

A Hausman test supports the use of a random effects model so we ran one last model with two urban form metrics together to better capture the relationship between productivity and urban form. Table 9 presents the results. In this random-effects model, the Theta parameter indicates that there is a significant amount of variability in the levels of productivity between the cities, so is suitable to use the random effects model. Even with two urban form metrics on the right-hand size, the goodness of fit is still low (around 15 percent of the variance explained by the model). The coefficients' signs are the same but smaller. All urban form measures in the difference regressions are related with the distribution pattern of the jobs.

Table 9: Results from a Random Effects Panel Data Model

(Intercept)	2.886	(0.871) **	
log(pop)	0.158	(0.072) *	
Gini (Manufacturing Jobs)	1.174	(0.453) *	
Moran's I (Total Jobs)	-0.411	(0.214) †	
Variance components			
	Var	Std. Dev.	Share
idiosyncratic	0.120	0.347	0.211
individual	0.451	0.672	0.789
Theta	0.657		
R-squared	0.151		
Adjusted R-squared	0.148		

Note: The dependent variable is Log(Manufacturing Productivity).

Because these measures all account for different aspects of urban form, we performed an analysis of the structure of the correlation matrix between them. A hierarchical cluster suggested three groups, and the three variables significant in this model each belong to a different group (full results available upon request).

Summary and Discussion

This section of the study analyses the relationship between urban form and productivity in the 100 largest cities in Mexico, between 1990 and 2010. Most urban economics theory, and empirical studies on the way in which urban agglomeration and urban spatial structure affect economic productivity are in the United States and Europe, where more of the economy is driven by higher skilled, less land intensive activities such as professional services. Additionally, the quality of infrastructure and urban governance, which can serve to mitigate diseconomies of agglomeration in large urban areas, is generally higher in richer countries.

In Mexico, urban sprawl and economic productivity are positively correlated, the opposite of observed evidence from that of the United States and Europe. In Mexico, manufacturing workers are more productive, and they tend to be more productive in more sprawling, less centralized cities. This study examines this relationship in a time-series analysis to test the hypothesis that changes in urban form affect changes in productivity, especially in the manufacturing sector. After reviewing the large body of research on measuring urban form, we identify the ten most relevant indicators to assess urban form in Mexico.

The more nuanced analysis confirms that of the simple cross section. Of the ten measures of urban form, several are consistently, negatively associated with productivity. They are the Proximity Index, which measures compactness, and the two measures of central concentration of population (and jobs): the Density Gradient and the Centrality Index. Cities in Mexico that became less centralized and compact, also became more productive in manufacturing. This likely reflects the fact that the manufacturing sector is both the most productive per worker, and generally demands more land area and is often located in the urban periphery. We also run models that include the Centrality Index and additional urban form variables. In this case, only Moran's I index adds significant fit, indicating that the clustering of population and jobs in neighboring tracts is conducive to productivity. This fits with agglomeration theory, though in this case the clustering is often occurring in the urban periphery rather than the city center.

The results of this study are academically important and raise questions about federal urban policy in Mexico. On the one hand, the study provides some of the only evidence for the discussion by Ciccone and Hall (1996) about the ambiguity of the impact of urban compactness and centralization on labor productivity. The results are important because there are several studies on this topic from countries where services are the high-value added sector of the economy, and fewer from middle-income countries where manufacturing is what is productive. We hope these results can push the field to engage in more comparative work and begin to test hypotheses about international variation in urban phenomena.

In terms of policy, the recently created Secretariat for Urban, Territorial and Agricultural Development (SEDATU) along with the National Housing Commission (CONAVI) have been advancing an agenda of urban containment by linking housing subsidies to urban growth boundaries set at the federal level. Although this policy likely has only a limited impact on urban development processes, the frame of urban containment that shapes federal urban policy should be reconsidered and reframed. There are clear problems with the way housing development has occurred in Mexico since the mid-1990s, however, urban expansion is not itself a problem, and curtailing it in a blunt manner runs the risk of negative economic consequences. The specific form of urban expansion in Mexico is connected to a significant part of the national economy.

III. Urban Form and Travel Outcomes in Mexico's 100 Largest Cities

Perhaps the most visible and widespread cost of urbanization and agglomeration is congestion, and a reduction in travel times. The traffic, noise, and pollution associated with traffic congestion—be it automobiles, motorbikes, buses, or auto-rickshaws—is also one of the primary problems that governments are beseeched to address. And it is a problem that does not disappear in the cities of high-income countries.

Across cities, neighborhoods, and individuals, the built environment influences how, where, and how much people travel. Barring some radical non-linear differences in a population—e.g., everyone above median income drives, while everyone below takes the bus—differences in urban form are likely to have the strongest influence on aggregate mode choice where roughly the same proportion of people chooses each option.

In Mexico's 100 largest urban areas, there is substantial regional variation in form, industrial composition, and travel behavior. The proportion of non-motorized trips ranges from 9% to 57% with an average of 24%. Public transit use ranges from 12% to 67% with an average of 43%, and private car use ranges from 9% to 62% with an average of 34% (INEGI 2015). This variation and modal share suggest that there is likely an opportunity to influence transportation outcomes by shaping urban growth. Since the public sector subsidizes and regulates most new housing construction—for an overview of the importance of the public sector in housing production, see Monkkonen (2011b)—central and local governments have a substantial ability to influence transportation opportunities through their control of urban growth.

This section examines the relationship between aspects of urban form—such as compactness and spatial contiguity—and transportation outcomes—such as mode choice, average travel times, and fatality rates—over the last two decades across Mexico's 100 largest urban agglomerations, where 65% of all Mexicans lived in 2015. We aim to develop a better understanding of how urban structure relates to travel in understudied, small- and medium sized-cities. Although Mexico's smaller cities have experienced substantial urban expansion and a rapid increase in car ownership, many continue to rely primarily on non-motorized modes and public transportation. Understanding the relationship between how these cities grow and how people travel is essential to comprehend whether and how directing future growth might influence fuel consumption, traffic fatalities, and public transit use. As in other low- and middle-income countries, nearly all of Mexico's recent and projected population and economic growth is occurring outside of the largest city centers (United Nations Population Division, 2014).

Urban Form and Transportation Outcomes: A Brief Overview

Urban form, land use, and the built environment are associated with mode choice (Boarnet 2011; Ewing and Cervero 2010), public transit service (Guerra and Cervero 2011; Taylor et al. 2009), traffic collisions and fatalities (Dumbaugh and Rae 2009; Ewing and Dumbaugh 2009), and local and global pollution (Ewing et al. 2008; Schipper, Marie-Lilliu, and Gorham 2000). Most knowledge about the relationship between urban form and travel behavior in low-to-moderate income countries comes from the largest, most transit-friendly cities such as Hong Kong (Zhang 2004), Santiago de Chile (Zegras 2010), Bogota (Cervero et al. 2009), or Mumbai (Shirgaokar 2015). These studies find statistically significant associations between quantifiable aspects of the built environment, car ownership, car use, and non-motorized travel. In Mexico City, researchers have studied travel behavior and urban form extensively (Guerra 2015a; 2015b; 2014a; 2014b; Montejano, Caudillo, and Silván 2016; Suárez, Murata, and Delgado 2015; Montejano, López-Ramírez, and Caudillo 2013; Suárez and Delgado 2009). However, large cities are distinct from medium and small cities in many ways, e.g. longer average trip distances, better transit services, more specialized industries, and higher wages.

Data and Background

Table 10 presents the source and structure of the transportation data used in this study. Prior to the most recent 2015 Intercensus, the national statistics agency asked only one transportation related question on the Census: whether households had one or more cars. Prior to 2000, there were no transportation-related questions on the Census. The 2015 Intercensus thus provides the first national snapshot of travel behavior in Mexico—albeit only commute trips to work and school. Although data are available at the household level, we aggregate data to the urban area for consistency and because greater geographic precision is only available for more populous localities. The survey includes data from 7.2 million individuals in 1.9 million households across the nation's 100 largest urban areas. These urban areas account for 64% of the national population and 86% of the employed population. Vehicle ownership and traffic collision data are reported in a national municipal database (INEGI 2016).

We also collected annual municipal-level data on traffic collisions (1997–2014), micro data on hospital-reported transportation fatalities (1990–2014), and vehicle registrations (1980–2014). We drop household transportation expenses and fuel sales from the study due to insufficient observations in smaller cities and insufficient spatial resolution of high-quality data. We opt to use the hospital-reported fatality data because it covers a long period and closely matches transportation-related fatalities reported by the World Health Organization (2014). The number of fatalities reported by hospitals is around three times higher than the number reported through INEGI's municipal database (INEGI 2016).

Table 10: Transportation Data in Mexico

Data	Unit of analysis	Geographic specificity	Years	Source
Mode choice to work and school. Travel times to work and school.	Household	Municipality (locality if over 50,000 people)	2015	Intercensus
Traffic fatalities	Hospital-reported fatality	Municipality (locality after 2002)	1990 - 2014	Estadísticas de defunciones generales
Vehicles	Vehicle registrations	Municipality	1980 - 2014	Sistema Estatal y Municipal de Bases de Datos (SIMBAD)
Dropped from study due to sample size, geographic specificity, or data quality				
Fuel expenditures	Aggregate sales	State	2000 - 2010	PEMEX
Transit and car expenditures	Household	Census Tract	1984 - 2014 (generally biannual)	National Household Earnings and Expenditure Survey
Traffic collisions and traffic fatalities	Municipal crash reports	Municipality	1997 - 2014	SIMBAD

Commuting: Mode and Times

Across Mexico's 100 largest urban areas, public transit is the most common way for people to access work (Table 11). Since public transit use tends to be highest in the largest cities, the share of people using transit is even higher (roughly 50% compared to 43%). Driving is the next most common mode, followed by walking and biking (combined as non-motorized). Even in the most car-reliant city, La Paz, 40% of commuters walk, bike, or take transit. Most commuters walk or bike to work in three of Mexico's 100 largest cities, while the plurality does in six additional cities.

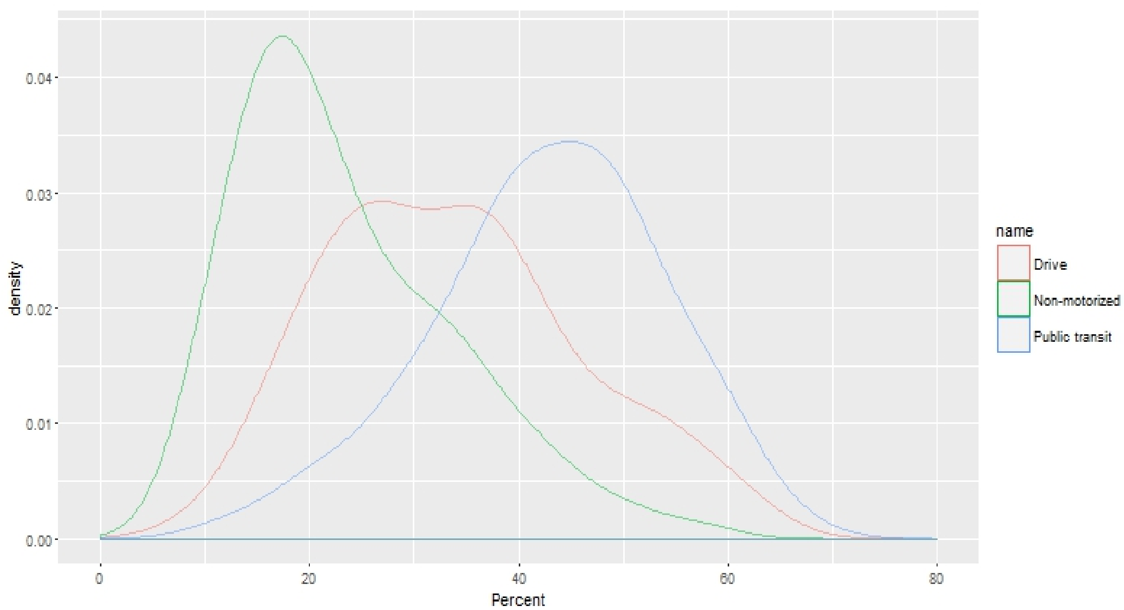
Table 11: Mode Split for Commute to Work Across 100 Largest Urban Areas

Statistic	Mean	St. Dev.	Min	Max
Non-motorized	23.5	10.5	8.5	57.3
Public transit	42.7	11.1	11.7	66.9
Drive	33.7	12.1	9.2	62.1

Source: Authors with Intercensus 2015.

Figure 14 plots the distribution of mode share—mode share is normally distributed across cities rather than binary. In short, Mexico's cities are highly multimodal with a substantial and continuous variation in modal importance. Note that these figures are aggregated from six modes reported in the Intercensus. Of special interest, the public transit mode share includes shared buses, minibuses, microbuses, minivans, work transportation, and all types of taxis (shared or unshared) in addition to trains and bus rapid transit. The drive share includes light-duty trucks and motorcycles. We provide a modal combination key from the original 6 modes in Spanish to the three modes using in the study in Appendix C.

Figure 14: Distribution of Mode Splits Across 100 Largest Urban Areas



This variation differs substantially by region (Table 12). Car use is highest in the northern cities (including those bordering the US). The southern and central cities (including those around the capital) tend to have higher rates of transit use and non-motorized transportation. At between 6,000 and 7,000 pesos per month, mean income does not vary much across the different regions. The capital region cities include Mexico City, the largest city in the Americas. Although the city size is substantially different, neither mode share and nor income are substantially different from other urban areas in the center and capital.

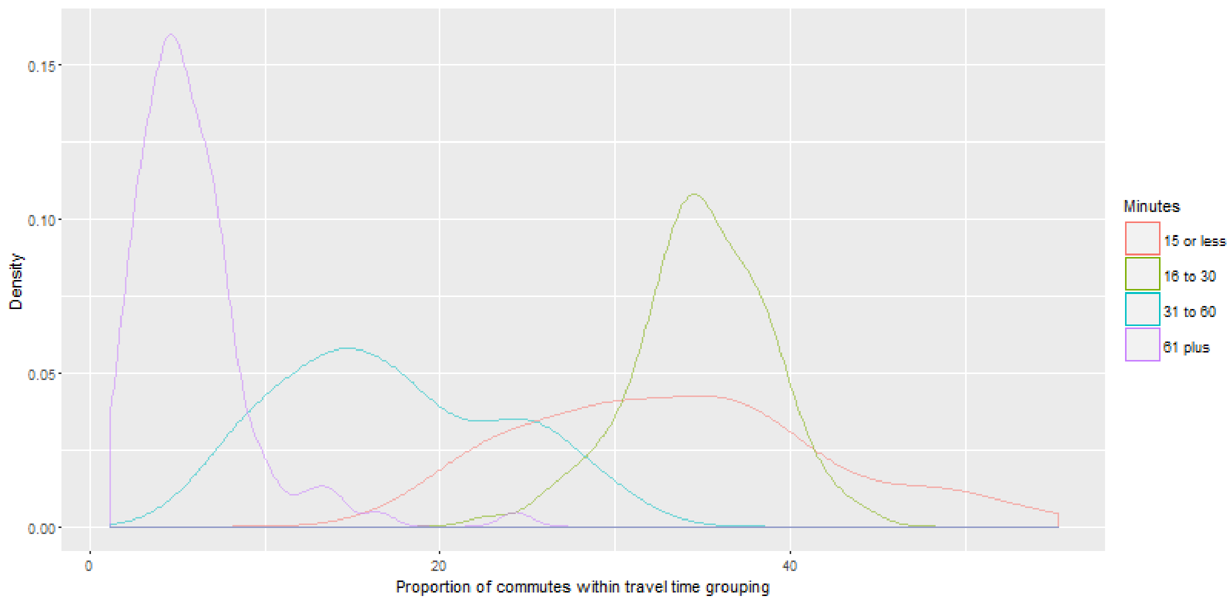
Table 12: Mode Split for Commute to Work by Region

Urban areas		Non-motorized		Public transit		Driving		Population (000s)	
Region	Number	Mean	S.d.	Mean	S.d.	Mean	S.d.	Mean	S.d.
Border	25	14.5	4	39.4	10	46.1	9.6	718	912
North	12	22.3	11.4	36	9.3	41.7	8.9	473	342
Capital	3	24.8	8.7	52.2	8.3	23	2.1	7727	11444
Center	43	29.3	9.1	43	11.4	27.8	8.2	546	845
South	17	22.9	9.1	50.2	9.1	26.9	9.2	399	335

Source: Authors with Intercensus 2015.

The duration of commutes is an important indicator of transportation costs. Reductions in the amount of time spent traveling are the primary measure of the benefits of transportation investments to consumers (Small 1999)—though the value of this measure has been questioned (Metz 2008). Longer commutes are also associated with higher stress, lower levels of happiness, and higher divorce rates (Choi, Coughlin, and D'Ambrosio 2013; Gottholmseder et al. 2009; Morris 2011; Morris and Guerra 2015; Sandow 2013).

Figure 15: Distribution of Commute Times Across 100 Largest Urban Areas



Across Mexico's hundred largest cities, roughly two-thirds of commuters have commutes that are shorter than 30 minutes (Figure 15). Only 6% have commutes that are longer than an hour. The distribution of commute times by city, like mode share, vary by region. The large, central cities have particularly long commutes. In Mexico City, a quarter of workers commute for over one hour. Northern cities tend to have the smallest share of workers with short commutes, while Central cities have the highest share.

Table 13: Commute Times by Region

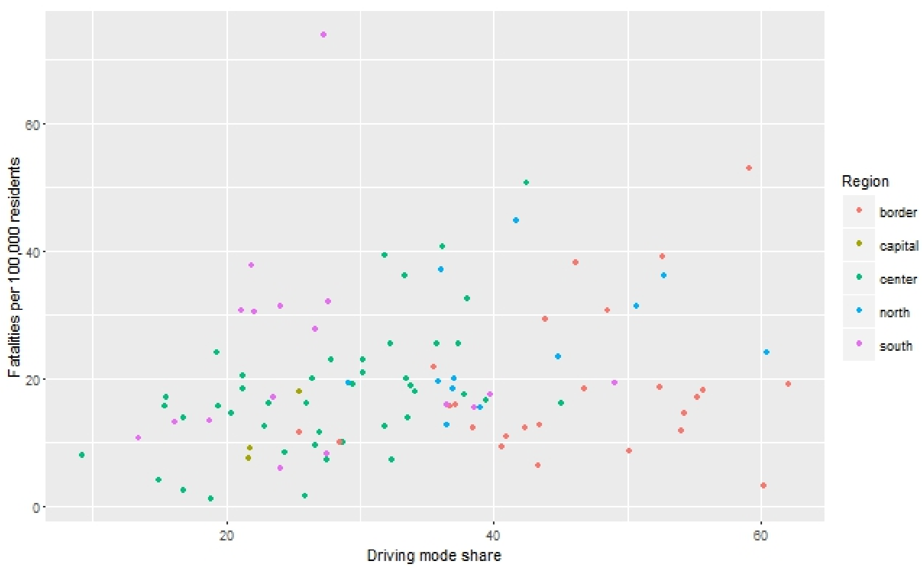
Urban areas		15 or less		15 – 30		31 – 60		61 or more	
Region	Number	Mean	S.d.	Mean	S.d.	Mean	S.d.	Mean	S.d.
Border	25	34.6	8.5	36	3.6	18.2	6.2	4.8	2.6
North	12	21.7	5.9	26.6	4.2	22.8	6.2	18.2	5.4
Capital	3	33.8	8.4	34.2	3.3	16.6	6.2	5.8	2.4
Center	43	37.9	7.5	35.1	2.9	16	5.5	4.2	1.5
South	17	30.1	7.9	36.2	4.3	17.4	8	6.1	2.7

Source: Authors with Intercensus 2015

Traffic Fatalities

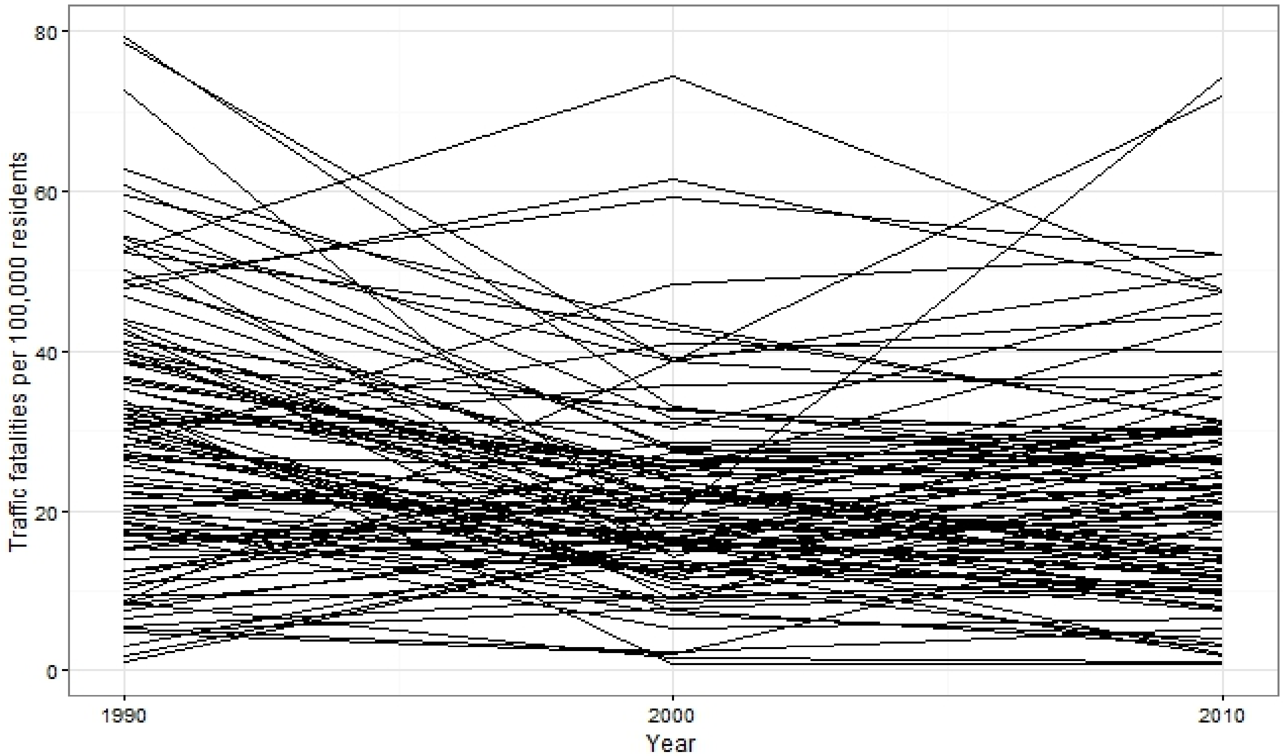
According to reported statistics, Mexico's largest cities have a rather poor safety record with an average of 20 annual fatalities per 100,000 residents. This rate is substantially higher than the national rate of 12 and 4-to-5 times higher than the safest cities in the United States, such as New York, Boston, and Washington, D.C. Since fatality rates are lower in more populous cities, the total fatality rate within the 100 largest cities is 13.5. As expected, the most dangerous cities tend to be the ones where residents drive the most—though there is substantial variation particularly in the highest fatality cities (Figure 16). In general, the lowest fatality rates occur in the cities with the lowest rates of commuting to work by car. There is more variation in the high fatality cities, but these also tend to have higher driving rates. Cárdenas, near the southern tip of Mexico, has the highest fatality rate despite driving rates.

Figure 16: Fatality Rates and Driving Mode Share Across Mexico's 100 Largest Urban Areas



Due to erratic and substantial variation in the report number of fatalities over time, we opt to use only the most recently reported data and take a three-year average (2012–2014). Figure 17 matches the fatality data to decennial population counts and plots the fatality rates for Mexico's largest cities in 1990 and 2010. This type of variation in fatality rates is uncommon over such a short period of time. The erratic nature of the change also makes it unlikely for change regressions to produce any kind of reliable results. Table 12 presents the three-year average fatalities per 100,000 residents by region at the time of the 2015 Intercensus. Despite generally higher driving rates, northern cities have relatively safe transportation systems. Due to high variation, we also report median fatality rates for each region. These are lower than the mean in every region.

Figure 17: Fatalities Rates Over Time Across 100 Largest Urban Areas



Vehicle Ownership

The vehicle fleet has grown steadily from 5 million in 1980 to 30 million in 2014. Table 14 normalizes the vehicle fleet per 100 residents in 2014 and presents averages and standard deviations by region. Vehicle ownership is highest in the center and capital. Despite higher rates of driving in the north (including border cities), vehicle ownership rates there are lower.

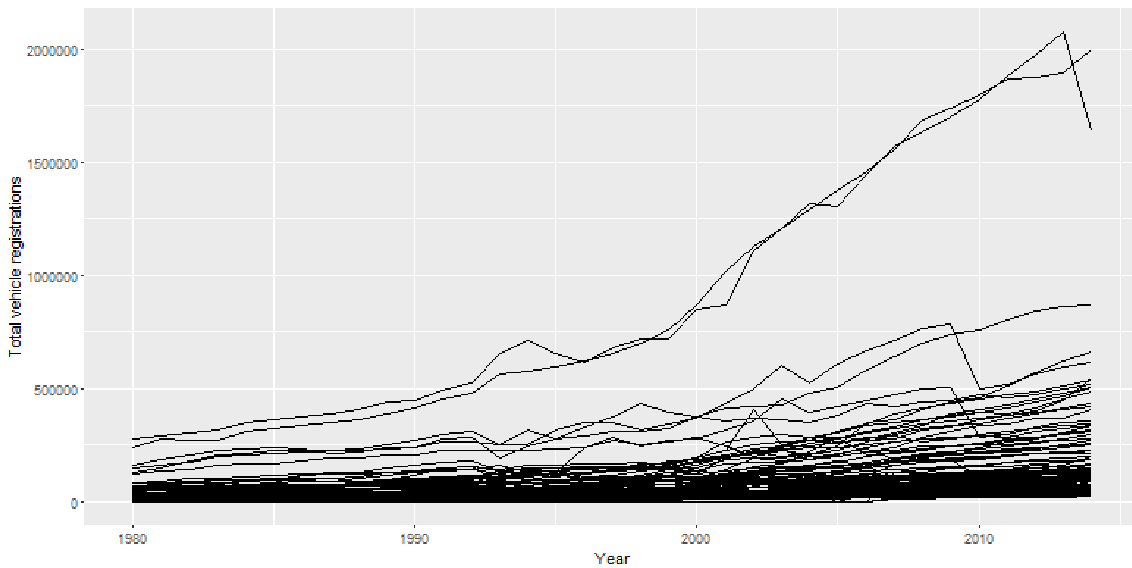
Table 14: Vehicles per 100 Residents and Traffic Fatalities per 100,000

Urban areas		Vehicle rate		Fatality rate		
Region	Number	Mean	S.d.	Mean	S.d.	Median
Border	25	38.9	9.6	18.4	11.5	15.7
North	12	44.9	1.6	11.7	5.7	9.3
Capital	3	47.4	16.2	18.1	10.4	16.8
Center	43	54.6	16.4	25.3	9.9	21.7
South	17	42.3	13.7	23.7	16.1	17.6

Source: Authors with INEGI. 2017. "*Estadísticas de defunciones generales 1990–2014*."

Figure 18 plots the growth in the vehicle fleet by city over time. Mexico City, which accounts for almost a third of the total vehicle fleet, is excluded from the plot.

Figure 18: Vehicle Fleet in the 100 Largest Urban Areas (Excluding Mexico City) from 1980 to 2014



Research Approach

This section of the study examines how mode share, travel times, traffic fatalities, and vehicle ownership vary across Mexico's 100 largest urban areas. Due to data limitations, most of the analyses are cross-sectional. Where possible, we test changes over time across these urban areas using fixed effects and random effects models. Part I, Section 4 describes the various measures of urban form generated and selected for use in this study. As noted earlier, we dropped transportation expenses and fuel expenditures from the analysis due respectively to insufficient observations in smaller cities and insufficient spatial resolution of high-quality data.

Research Hypotheses

We test a series of hypotheses about the relationship between urban form, mode choice, travel time, and traffic fatalities. Each model includes controls for household income (or GVA), education, and regional geography. Due to extreme collinearity with overall urban population, we dropped aggregate population density and total land area from the hypotheses tested in cross-sectional models (across the 100 cities, the variables are strongly correlated and including all three in a model produces VIF scores well above 10.) The following sentences summarize our expected findings in relationship to the measures of urban form. We elaborate on our expectations when discussing the results of specific models in the following section.

Large, dense cities. In general, we expect large, dense cities to rely more heavily on transit and have lower fatality, vehicle ownership rates, and walking rates (due to longer trip distances).

Compact, circular cities. In general, we expect compact cities to support more non-motorized transportation and have lower fatality and vehicle ownership rates. In addition to size and density, we test the relationship between our transportation metrics and a proximity index.

Within a given density, it is assumed that the most compact urban form approximates a circle around the CBD.

Clustered cities. In general, we expect clustered concentrations of jobs and people to allow for shorter trips and more ability to rely on transit and non-motorized modes. The clustering index decreases as in cities where the population is distributed most homogenously. However, high scores may also indicate dense concentrations of residents in peripheral neighborhoods, not just central ones.

Fragmented cities. Fragmented cities with high amounts of leap-frog development are likely to required longer trips than other cities. As a result, we expect cities with a high discontiguity index score to have lower rates of non-motorized travel, higher fatality rates, and higher car-ownership levels.

Findings

This section presents the results of the cross-sectional ordinary least squares and fixed effects models.

<u>Urban Form and Mode Choice</u>

Including controls for income and education, city size and form are correlated with rates of driving, public transit use, and walking/biking (Table 15). Larger, denser cities (total population is highly correlated with the number of hectares and population density) have higher proportions of residents commuting to work by transit and lower proportions by car and non-motorized modes. A rough doubling in the size of a city's population correlates with 4.4 percentage points higher public transit mode share. This increase comes roughly equally from driving (-2.0) and non-motorized modes (-2.4). Big cities tend to have the kinds of long trip distances best suited to motorized modes, but also relatively better transit service, higher congestion, and higher vehicle ownership costs (parking, insurance, etc.). The discontiguity index is not statistically associated with mode share across the 100 cities studied.

Table 15: OLS Models of Commute Mode Share Across Mexico's 100 Largest Urban Areas

	Dependent variable:		
	Drive	Public transit	Non-motorized
	(1)	(2)	(3)
Average household income	0.005^{***}	-0.003^{***}	-0.002^{***}
	(0.001)	(0.001)	(0.001)
Average years of schooling	-1.678	7.530^{***}	-5.853^{***}
	(1.425)	(1.638)	(1.117)
Total population (log)	-2.011^{**}	4.370^{***}	-2.358^{***}
	(1.005)	(1.155)	(0.787)
Clustering index	5.029^{**}	-4.877^{*}	-0.152
	(2.518)	(2.894)	(1.974)
Proximity index	9.477^{**}	-17.644^{***}	8.173^{**}
	(4.480)	(5.149)	(3.511)
Discontiguity (log)	0.224	-1.921	1.700
	(2.937)	(3.375)	(2.301)
Border region	14.277^{***}	-5.804^{**}	-8.472^{***}
	(2.215)	(2.546)	(1.736)
Northern region	10.192^{***}	-9.639^{***}	-0.552
	(2.692)	(3.094)	(2.109)
Southern region	-2.218	5.115^{*}	-2.896
	(2.301)	(2.644)	(1.803)
Constant	26.751^{**}	-37.954^{**}	111.203^{***}
	(12.579)	(14.457)	(9.857)
Observations	100	100	100
R^2	0.691	0.519	0.747
Adjusted R^2	0.661	0.470	0.722

Notes: Std. err. *in parentheses*; *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.

Higher clustering and proximity are both associated with higher driving rates and lower transit rates. This is somewhat surprising since these measures are meant to capture different aspects of urban sprawl. However, there are also reasonable interpretations of the correlations that are consistent with theory about transit. Recall that the proximity index approaches 1 as a city's shape approaches a circle and 0 as the shape approaches a line. Since transit relies on fixed corridors, more rectangular cities that concentrate activities along given corridors may outperform more evenly spread out cities. An even distribution of form is better suited to walking, biking, and driving which can go easily from many origins to many destinations.

More surprisingly, cities with higher relative clustering of residents in fewer tracts have statistically higher rates of driving and lower rates of transit. Similar findings result when the residential clustering index is replaced with a job clustering index. This may relate to two potential issues with the clustering index. First, it is common in Mexican cities for high density housing clusters to form in suburban and exurban locations that are far from job centers. Second, high clustering of jobs and people may indicate segregated land uses, if jobs and households cluster in different and distant locations—this phenomenon is common in Mexico City's suburbs (Guerra 2014b; 2015b).

As expected, driving rates increase with mean income, while walking, biking, and public transit use decrease. The strength of this relationship (as measured by using demeaned predictor variables) is roughly equivalent to that of city size and the other measures of form. Average years of schooling is correlated with higher transit use and lower walking rates.

All three models have reasonable predictive power with adjusted R-squared values ranging from 0.47 to 0.72. Appendix D shows three different versions of each model with fewer controls. Including the urban form variables trips the predictive power of the model of public transit mode share but has a much smaller influence on the predictive power of the models for driving and non-motorized modes share. Income and education are solid predictors of driving and non-motorized travel but only explain about a tenth of the variation in transit use across the 100 largest cities.

<u>Changes in Urban Form and Vehicle Ownership</u>

Although mode share data only became available with the 2015 Intercensus, vehicle ownership data are available back to 1980 and a proxy for driving rates. Including regional fixed effects, vehicles per capita explains roughly 60% of the driving rates across Mexico's 100 largest urban areas. Vehicle ownership is also a policy variable of interest. Table 16 presents the results of fixed effects (FE) and random effects (RE) regressions investigating the impact of changes in urban form and income on changes in vehicle ownership from 1990, 2000, and 2010. Since household income data from the 1990 Census are inconsistent (with means an order of magnitude higher than medians) and unreliable (raw values higher in 1990 than in 2000), we opt to use Gross Value Added (GVA) per capita. Regional dummy variables do not vary within an urban area over time and are therefore dropped from the fixed effects models (also known as the within estimator). The random effects models allow for variation over time and across places, and thus can include the regional dummy variables. Since total population and land area do not always move in the same direction over time, we include both in the panel regressions. A Hausman test indicates that Fixed Effects are most appropriate. We choose to report both to provide additional information about which parameters vary similarly with vehicle ownership over time and across cities.

Table 16: Fixed Effects (FE) and Random Effects (RE) Estimates of Vehicle Ownership Rates from 1990 to 2010

	Dependent variable:			
	Vehicles per 100 residents			
	(1) FE	(2) FE	(3) RE	(4) RE
GVA per capita	0.003	0.005	0.005	0.007*
	(0.005)	(0.005)	(0.004)	(0.004)

Average years of schooling	7.650***	8.500***	6.070***	6.167***
	(0.447)	(1.017)	(0.433)	(0.594)
Total population (log)		-21.111***		-7.388***
		(6.204)		(2.506)
Land area (log)		12.726**		4.257
		(5.417)		(2.795)
Clustering index		8.779**		9.697***
		(4.363)		(3.138)
Proximity index		3.511		4.418
		(4.782)		(3.279)
Discontiguity (log)		1.209		-0.350
		(2.390)		(0.977)
Border region			-0.660	-0.499
			(2.053)	(2.261)
Northern region			1.950	0.976
			(2.650)	(2.705)
Southern region			-6.012**	-7.280***
			(2.331)	(2.361)
Constant			-20.224***	24.590**
			(3.396)	(11.729)
Observations	300	300	300	300
R^2	0.605	0.641	0.430	0.509
Adjusted R^2	0.399	0.412	0.422	0.490

Note: Std. err. in parentheses; *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.

As with mode choice, measures of the built environment are statistically associated with vehicle ownership rates over time. Both within and across cities, increases in city size and density correlate with lower car ownership rates. Holding land area constant, a rough doubling of city size over time corresponds to 21 fewer vehicles per hundred residents. This is a substantial decrease. Across the three-time periods and hundred cities, the average vehicle ownership rate is 26 per hundred. A physically expanding city with a constant population has an inverse but weaker relationship: a doubling in city size over time corresponds to 13 more vehicles per hundred residents. Inputting population density instead of total population and total land area produces similar results. A one person increase in people per hectare correlates with a 0.32 fewer vehicles per hundred residents.

Neither the proximity nor the discontiguity indices—measures of circularity and leapfrog settlements—correlated with vehicle ownership over time. Recall that across the 100 cities in 2015, driving rates associated positively with proximity and did not significantly correlate with discontiguity. Changes in clustering are positively correlated with vehicle ownership. This gives added credibility to the suggestion (from the mode choice models) that clustering of population may indeed correspond to segregated land use patterns or high-density suburbs, rather than compact neighborhoods. However, the panel models also introduce the possibility of time-related spurious correlations. This is certainly possible since vehicle ownership and the clustering index both increased across nearly the entire sample from 1990 to 2000 and 2000 to 2010. Including the year as a factor variable, however, does not diminish the positive statistical correlation between vehicle ownership rates and clustering.

Collectively, the measures of the built environment explain a third of the variation in changes in vehicle ownership over time (adjusted R-squared of 0.328, model unreported). However, much of this variation is also captured by the two socioeconomic control variables: GVA per capita and average years of schooling.

Contrary to expectations, GVA per capita does not do a good job of predicting vehicle ownership rates. Excluding other variables, GVA per capita explains less than 1% of the variation in vehicle ownership rates both over time and across cities. Average years of schooling, by contrast, explains more than a third of the variation within and across Mexico's cities over time. This is roughly the equivalent explanatory power of models that include all measures of urban form and GVA per capita. Likely, average years of schooling and changes in average years of schooling serve as a better proxy for overall household prosperity than GVA per capita.

Urban Form and Commute Times

The relationships between commute durations, demographic, and spatial measures tend to be non-linear. For example, higher income cities tend to have a higher share of trips that take 15 minutes of less, a lower share between 16 and 30 minutes, and no statistical relationship with the number of trips that are longer than 31 minutes.

In terms of urban form, large dense cities tend to have more commutes that are longer than 61 minutes and far fewer that are 15 minutes or less. A city with double the population has on average 6.8 percentage points fewer commuters with commutes under 16 minutes. Cities that score highly on the proximity index (i.e., that most closely resemble a perfect circle) have more commutes in the shortest travel time bands and fewer in the 16 to 60-minute range. They also however have statistically more of the most onerous commutes. A higher clustering score (i.e., more of the population live in relatively fewer tracts) is associated with more commutes that are 15 minutes of less. Finally, higher discontiguity (a measure of leapfrog development patterns) correlates more of the most onerous commutes and fewer in the middle range (16 to 60 minutes). This suggests that leap frog development encourages the longest duration commutes, but not the kinds of short commutes that are often made by non-motorized modes.

Table 17: OLS Models of Commute Times Across Mexico's 100 Largest Urban Areas

	Dependent variable:			
	15 or less	16 to 30	31 to 60	61 plus
	(1)	(2)	(3)	(4)
Average household income	0.002***	-0.001*	-0.0001	-0.0003
	(0.001)	(0.0004)	(0.0004)	(0.0003)
Average years of schooling	-3.184***	1.584**	1.260*	0.340
	(0.958)	(0.725)	(0.675)	(0.452)
Total population (log)	-6.814***	-0.161	5.656***	1.457***
	(0.675)	(0.511)	(0.476)	(0.318)
Clustering index	3.583**	-1.340	-1.653	-0.879
	(1.692)	(1.281)	(1.192)	(0.798)
Proximity index	9.335***	-3.976*	-7.948***	2.715*
	(3.010)	(2.278)	(2.121)	(1.419)
Discontiguity (log)	3.153	-3.409**	-3.632**	3.301***
	(1.974)	(1.493)	(1.390)	(0.931)
Border region	3.614**	1.115	-1.747*	-0.944
	(1.489)	(1.126)	(1.049)	(0.702)
Northern region	6.150***	-0.134	-2.721**	-1.300
	(1.809)	(1.369)	(1.274)	(0.853)
Southern region	-2.735*	0.828	0.276	0.663
	(1.546)	(1.170)	(1.089)	(0.729)
Constant	123.669***	33.061***	-56.580***	-15.738***
	(8.453)	(6.396)	(5.955)	(3.986)
Observations	100	100	100	100
R^2	0.721	0.212	0.755	0.602
Adjusted R^2	0.693	0.134	0.731	0.562

Note: Std. err. in parentheses; *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.

Urban Form and Fatality Rates

Urban form explains about a third of the variation in fatality rates across Mexico's largest urban areas (Table 18). City size and density are again particularly strong predictors with a doubling of city size correlated with 7 fewer traffic fatalities per 100,000 residents. Other things being equal, the fatality rate is lower in larger, denser cities. Larger, denser cities have longer trip distances, but likely slower speeds due to congestion and older narrower neighborhood streets. This finding should be interpreted with caution, however, since the total population is the denominator of any fatality rate. Appendix E presents an additional set of models, which predicts the natural log of total traffic fatalities. As would be expected larger cities have more fatalities. A doubling of a city's size correlates with a 66% increase in fatalities. Thus, the fatality rate tends not to rise proportionally with population, suggesting that fatality rates are indeed statistically lower in larger, denser cities.

The proximity index also has a strong relationship with fatality rates. Recall that higher scores on the proximity index correlates with higher walking and driving rates, but lower public transportation use. Fatality rates tends to be lower in cities with high rates of transit use, but higher in cities with higher driving and walking rates. Pedestrians are vulnerable road users and the intersection of high-speed traffic with high numbers of pedestrians tends to lead to large numbers of fatalities. Accounting for other measures of urban form, northern cities have higher than expected fatality rates.

Table 18: OLS Predictions of Traffic Fatalities per 100,000 Residents

	Dependent variable:		
	Fatality rate		
	(1)	(2)	(3)
Average household income	0.001	0.002**	0.003**
	(0.001)	(0.001)	(0.001)
Average years of schooling	1.218	0.840	-0.488
	(2.123)	(1.804)	(1.916)
Total population (log)		-7.124***	-7.463***
		(1.280)	(1.351)
Clustering index		2.868	2.298
		(3.327)	(3.385)
Proximity index		18.281***	18.612***
		(5.999)	(6.022)
Discontiguity (log)		3.840	6.102
		(3.329)	(3.948)
Border region			0.773
			(2.978)
Northern region			6.297*
			(3.618)
Southern region			4.267
			(3.092)
Constant	5.959	72.878***	82.536***
	(13.082)	(15.747)	(16.908)
Observations	100	100	100
R^2	0.017	0.395	0.422
Adjusted R^2	-0.003	0.356	0.364

Note: Std. err. in parentheses; *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.

Manufacturing Productivity and Concentration

We also tested all reported transportation models with the inclusion of two additional variables: manufacturing productivity and the proportion of workers in the manufacturing sector. While these two measures are likely influenced by urban form and transportation systems, we also hypothesized that they might measure aspects of urban form that our other variables do not capture. Specifically, manufacturing jobs tend to cluster in exurban areas in Mexico, while services are more likely to cluster in central or at least fewer peripheral locations. Table 19 summarizes the results of this modeling exercise.

Table 19: Results of Adding Manufacturing Productivity and Concentration to Transportation Models

Manufacturing indicator	Measure	Mode choice	Vehicle ownership	Travel times	Fatality rates
Concentration	Percent of jobs in manufacturing	None	None	None	None
Productivity	GVA per manufacturing job	Positively correlated with transit, negatively correlated with driving. Kicks clustering out of the model.	None	None	None

Including the other covariates, the concentration and productivity of the manufacturing sector generally are not statistically correlated with the transportation outcomes of interest. Where there are correlations, high manufacturing concentration/productivity tends to be associated with higher transit use and lower fatality rates. The relationships, however, are weak and tend to draw significance from other covariates already included in the model. In sum, including the manufacturing indicators generally does not improve the statistical or conceptual understanding of the relationship between urban form and transportation outcomes. If there is a relationship, higher manufacturing productivity and concentration appear more prevalent in less auto-dependent cities.

Summary and Discussion

As expected, various measures of urban form are consistently and often strongly related to transportation outcomes as well as economic productivity. Across the models, measures of urban form collectively and even sometimes individually are as powerful predictors of transportation outcomes as income and years of education. Although these relationships are not always uniform, the findings suggest that sprawling form is generally—though not always—associated with higher social transportation costs. Table 20 summarizes the results of the series of models presented in the preceding section and appendix.

Table 20: Summary of Relationship Between Urban Form and Transportation Indicators

Urban indicator	Measure	Mode choice			Vehicle ownership	Travel times*		Fatality rates**
		Drive	Transit	NMT		Short	Long	
Size/Density	Log of population/ People per hectare	-	+	-	-	-	+	-
Distribution/ Clustering	Population clustering index	+	-	NA	+	+	NA	NA
Compactness/ Circularity	Population proximity index	+	-	+	NA	+	+	+
Fragmentation	Log of discontiguity index	NA	NA	NA	NA	NA	+	NA

*Short is 15 minutes or less; long, is 61 minutes or more. **Includes mode share as control.

The remaining text summarizes the key takeaways related to each of the individual measures of urban form:

Size and Density

Of all the measures of urban form, city size and density have the strongest, most consistent relationships with the transportation metrics. In general, these correlations suggest that large cities have lower transport-related social costs. For example, large and dense cities are less car reliant and have lower transportation fatality rates—after including mode share in fatality models, only city size remains correlated with the percentage of the population that dies in traffic collisions. However, large cities are also the places where more commuters face long trips, and fewer have commutes under 15 minutes. Although we were unable to collect reliable data on household transportation expenditures, it is almost certainly more expensive to own, operate, and park a private vehicle in a large, dense city.

Offsetting these higher costs are two likely benefits. First, transit needs mass to thrive and large cities have the best and often least expensive transit options. In Mexico, a rough doubling of city size associates with a 4% increase in public transit use. These trips use space more efficiently and produce substantially less pollution per mile of travel than private cars. Second, large cities tend to have more economic, cultural, and educational opportunities. These opportunities not only draw new households to big cities but allow households to choose longer commutes in favor of preferred jobs and other activities.

Sprawl

Unlike size and density, the other three measures of urban form did not tend to conform to prior expectations. This suggests that the shape and distribution of people within cities is not particularly important after accounting for overall densities. For example, cities where the population clusters together in relatively few census tracts have lower transit use. This may relate to the way that households cluster together in dense, poor suburban tracts in Mexican cities—like many other Mexican cities, the highest density tracts in Chihuahua and Ensenada are in the periphery (Monkkonen 2011b)—or relate to more segregated land uses. More circular cities also have higher rates of driving, lower transit use, and higher fatality rates. They also have a higher share of very long and very short commutes. Unlike population distribution, these more compact, circular cities also have higher rates of non-motorized transportation.

Leap-frog development (fragmentation/discontiguity) generally does not correlate with transportation outcomes. This may be because it only affects the small share of the population that live in these further off neighborhoods. The higher share of commutes longer than an hour suggest that this may be a possibility. Nevertheless, it appears that at least across Mexico's 100 largest city, this most visible type of sprawl is not particularly important for a city's overall mode share, vehicle ownership, or fatality rates.

Regional Context

Regional context matters substantially. This may relate to a mix of cultural, environmental, economic, infrastructural, and spatial differences. Specifically, the northern cities—which are generally the most economically productive—have the highest costs associated with the transportation system. Even in these cities, however, a high share of the population gets to work by transit, foot, or bike. It is unclear whether and what types of policies might influence the transportation outcomes associated with the different regions of Mexico.

People make travel decisions. Cities do not. Aggregating the way that a population is distributed within a region into a single measure may substantially bias findings about the relationship between urban form, income, and travel outcomes. For example, a household that lives in a leap-frog development may have much higher transportation costs (time and money) and be substantially more reliant on cars than similar households in other parts of the city despite the insignificance of the relationship at a metropolitan scale. Similarly, median and average measures of household income do not capture the full importance of household income in household transportation decisions. For example, members of a wealthy household may choose to drive regardless of the built environment, while the poorest households' members may walk because they cannot afford anything else.

Nevertheless, aggregate figures provide a broad brushstroke picture of how city form and associated travel outcomes vary together across cities and over time. These figures suggest that urban density and size matter as much to transportation outcomes as income or regional GDP. Sprawl, however, is complex to measure and, when measured, not necessarily associated with travel in ways that we might have originally hypothesized. Some of this may relate to the unit of analysis and aggregation bias. While outside the scope of this analysis, a next step to better understand the relationship between urban form, household income, demographics, and travel behavior would be to use disaggregate household-level micro data on commute times and mode choice to work and more spatially refined measures of urban form, where possible.

IV. Urban Expansion and Segregation by Income and Education in Mexico: 1990–2010

In addition to the congestion costs and consequent environmental damage that results from urbanization—especially in certain types of urban spatial structures—there is a widespread perception that large cities create social problems. Though much of the 'around cities' and 'social decay' is unfounded, one of the more well-documented negative impacts of cities on social relations is that of spatial segregation. Socially homogenous neighborhoods can exacerbate inequalities through unequal service provision or environmental conditions and perpetuate group rifts in societies.

After reform and expansion of the country's housing finance system beginning in the early 1990s, Mexican cities have expanded at a rapid rate through the construction of large-scale suburban housing developments (Monkkonen 2011b). Prior research has connected housing finance to increasing segregation during the 1990s (Monkkonen 2012a). Yet this work did not address the mechanism of this connection, namely the way in which urban growth and the changing spatial structure of cities inevitably shapes the distribution of people within them. This is especially relevant in the Mexican context of a dramatic new form and scale of housing production (Alegría 2008; OECD 2015). With the boom in gated communities for the working-class (Peralta and Hoffer 2006), we expect to see changes in the social mix of urban neighborhoods in Mexico.

This study, therefore, examines whether and how patterns of socioeconomic segregation in Mexico are related to urban expansion and urban form. To examine this relationship, we address three questions. Do cities that grow more rapidly experience a larger increase in segregation by income or education? Does a more sprawling form of urban growth also lead to more spatial separation between social groups? Is the scale of segregation affected by changes in urban form?

The analysis combines cutting edge measures of urban form (discussed above) and segregation. The measures of segregation are explicitly spatial (Reardon and O'Sullivan 2004), measuring and comparing segregation levels for multiple sizes of neighborhoods. They are also ordinal and decomposable across levels of income and education (Reardon 2009; Reardon and Bischoff 2011). This allows us to compare changes in, for example, segregation of high-income and lo-income households separately. We use small area census data from 1990, 2000, and 2010 for the 100 largest cities in Mexico, which depends on the creation of census tract maps for 1990 (detailed in Monkkonen and Comandon 2016). After we calculate indexes in these three-time periods, we model their changes and changes in the spatial scale of segregation as a function of urban growth and urban form.

We find that in Mexico, urban expansion (of land area, not population growth) is significantly associated with increases in segregation by education and income. Somewhat unexpectedly, we show that this change was driven by increases in the isolation of high-income households, rather than low-income households. Additionally, we find that cities that became more centralized experienced greater increases in segregation by education and income, a trend also driven by the isolation of high-income households. Unlike the experience of some countries, then, a more sprawling urban form in Mexico is not associated with more segregation. A similarly counterintuitive finding is that increasing centralization is also associated with an increasing scale of segregation, that is, the geographic scale of neighborhood homogeneity was larger in more centralized cities.

The findings about urban expansion and segregation are expected, yet the association between centralization and segregation is counter to our conceptual model. The boom in large, peri-urban housing developments for working class households—which is mildly associated with less centralization—is expected to lead to larger scale of segregation among low-income households. These findings prompt us to question assumptions about the effects of urban growth, and further study of urbanization patterns in countries like Mexico.

The section is organized as follows. A brief literature review precedes an in-depth discussion of the measures of segregation and urban form. Further, the section describes changes in segregation and urban form in Mexico from 1990 to 2010 and reports the results of an analysis of the connection between the two in a regression framework. The conclusion summarizes the findings and outlines directions for future research.

Segregation and Urbanization in Mexico

The relationship between urban growth, urban form and social segregation, though highly context dependent, are relevant to all cities. Research in the United States, for example, has shown a significant association between segregation and certain kinds of urban spatial structure, such as sprawl, though the relationships are not linear (Galster and Cutsinger 2007). This work has mostly focused on racial segregation, however, because of its importance and clearer connection to United States suburbanization trends (Mieszkowski and Mills 1993). The basic insights, such as the positive relationship between city size and socioeconomic segregation (Mills and Hamilton 1994), generate important questions for the Mexican context and motivate this study, in part so that scholars from other countries learn from the Mexican experience.

The study of socioeconomic segregation has a long history in Mexico, though methods have changed over the years. In recent decades, quantitative research on levels and patterns of segregation has gained importance using different techniques. This has been aided by greater access to quality georeferenced data, which are now freely available online from INEGI (INEGI 2000; 2010), as well as the use of more comparable indexes of segregation such as dissimilarity and entropy. The importance of establishing a consistent set of measures of the phenomenon is made clear by the edited book by Roberts and Wilson (2009) on segregation across the Americas, in which each chapter focuses on a different city and a different question related to segregation, leaving the reader without an understanding of the similarities or differences between places.

Case studies of segregation in the large cities of Mexico such as Mexico City (Delgado 1990), Tijuana (Alegría 1994; Hernández Gómez 2001), and Monterrey (Garza 1999; González-Arrellano and Villeneuve 2007) have led to a growing body of evidence on the topic, as well as some comparisons of these large metros (Ariza and Solís 2009; Duhau 2003; Rubalcava and Schteingart 2000). The analysis of segregation across the national urban system by Monkkonen (2012b) confirms many of the extant descriptions of Latin American cities (Borsdorf 2003; Ford

1996; Sobrino 1996); larger cities are more segregated, and poor neighborhoods tend to be more segregated than wealthy ones (Monkkonen 2012b).

As in cities in most of Latin America, new forms of urban growth are considered to exacerbate social inequality and segregation, as well as the geographic scale of these phenomena (Sabatini 2006; Sabatini, Cáceres, and Cerda 2001). In Mexico, Monkkonen (2012a) tested the relationship between new forms of housing finance and segregation and found that in cities where more new housing was built under the public finance system, segregation increased by a greater amount. The basic conceptual model of that study is that the new form of housing development—speculative building of identical houses in large tracts—will create neighborhoods more homogenous than those built in the traditional, incremental manner, in which households expand and improve their homes as their incomes and families grow. However, that study (Monkkonen 2012a) did not examine the spatial aspect of this process explicitly, which is a central aspect given the size of the housing developments being built.

Measuring Urban Growth, Urban Form and Socioeconomic Segregation

Measuring urban growth and urban form is a complex endeavor. Based on an extensive review of existing measures and consideration of the particularities of urbanization in Mexico (see previous section), we use the most basic measures of urban growth (population and land area), a simple gross population density, and three measures of urban form; a Centrality Index (Galster et al. 2001), a Discontiguity Index (Amindarbari and Sevtsuk 2015), and a Proximity Index (Angel, Parent, and Civco 2010a) to measure urban compactness. In this case, these measures are calculated exclusively based on census tract (AGEBs in Mexico) populations, with the acknowledgement that measures based on AGEB job counts would reveal additional information about urban structure.

In the context of this paper, socioeconomic segregation is the relative residential location of different socioeconomic groups in cities. Relative, that is, to one another. The indexes we use measure the homogeneity of neighborhoods by income or education, and then compare this to the overall distribution of income or education in a city. The rank-order spatial entropy index—developed by Reardon and colleagues (Reardon and Bischoff 2011; Reardon and O'Sullivan 2004)—is based on the information or entropy index developed by Theil (1972). A brief description of the index we use is provided below. For more detail, see Monkkonen and Comandon (2016).

One of the chief advantages of the rank-order spatial entropy index is that it accounts for the ordinal nature of most socioeconomic variables. Based on the assumption that when low-income households have high-income neighbors it is different than when they have middle-income neighbors, measures of segregation should not treat the co-location of every income group equally. The rank-order spatial entropy index considers the social distance of different groups. This also means it can be easily disaggregated across the distribution of a variable (to calculate the segregation of high-income households separately from that of low-income households). Thus, we examine the segregation of high and low-income households separately. The index can also be used to graphically represent segregation continuously across the income (or education) distribution as shown in Monkkonen and Comandon (2016).

A second advantage is that the rank-order spatial entropy index is explicitly spatial. All measures of segregation are spatial. They assess the relative homogeneity of different neighborhoods. In general, however, the spatial nature of a measure is implicit. Measures are usually based on census tract or small area data with neighborhood boundaries determined by whatever data aggregation the national census bureau chooses. Some countries have larger neighborhood boundaries than others, some draw tracts based on population, whereas others draw tracts based on size (for an in-depth discussion, see Monkkonen and Zhang 2014). To calculate the spatial-rank-order entropy index, we create neighborhoods of different sizes using AGEB data as a base, and aggregating AGEBs in circles of increasing radii; 200 meters, 500 meters, 1,000 meters, and 2,000 meters.

Not only does this then create a clearer geographic scale for the segregation indexes, it allows us to compare segregation at different scales, something Sabatini and colleagues (2001) have discussed as a common problem in measuring segregation in Latin America. We calculate a Macro/Micro Ratio—segregation at the 2,000-meter scale divided by that of the 500-meter scale—to assess the degree to which larger scale segregation trends dominate small scale trends in a city.

Table 21 reports the averages (means and medians) of segregation indexes for education in 1990 and 2010 and income in 1990 and 2000 across 100 cities in Mexico. We report values for the overall segregation along these two dimensions, the segregation of groups with high and low incomes and education levels, and the macro-micro ratio, which as described above is the ratio of segregation for large neighborhoods (a radius of two kilometers) to that of small neighborhoods (tract sized). There are two gaps in the data used for this study: education data for 2000 and income data for 2010. INEGI changed the way it measured education in 2000 and because the categories do not match we do not calculate it for 2000. Unfortunately, INEGI did not report data on household income at the AGEB level for the 2010 census, thus we can only measure income segregation in 1990 and 2000.

Table 21: Measures of Segregation by Education and Income

	1990		2000		2010	
Variable	Mean	Median	Mean	Median	Mean	Median
Education (overall)	0.06	0.06	NA	NA	0.07	0.06
High-education	0.09	0.08	NA	NA	0.09	0.08
Low-education	0.03	0.03	NA	NA	0.05	0.05
Education Macro-Micro	0.17	0.12	NA	NA	0.19	0.17
Income (overall)	0.04	0.03	0.04	0.04	NA	NA
High-Income	0.06	0.05	0.07	0.07	NA	NA
Low-Income	0.02	0.02	0.02	0.02	NA	NA
Income Macro-Micro	0.11	0.12	0.17	0.14	NA	NA

Source: Authors with INEGI 1990, 2000, and 2010.
Note: NA indicates data not available.

We can see from Table 21 that the average values of segregation across the 100 cities either remained constant or increased slightly. The average geographic scale of segregation by education and income increased to a greater degree. Higher values of the macro/micro ratio indicate higher levels of segregation at a large scale relative to the small scale, such that larger scale patterns of segregation dominate. The average (median) macro/micro ratio for education increased to 0.12 in 2010 from 0.17 in 1990, and that of income segregation went from 0.12 in 1990 to 0.14 in 2000, increases of 42 and 17 percent respectively. However, these changes in the average value obscure somewhat the changes in each individual city. Therefore, the section below delves into a more individualized look at changes.

Changes in Segregation and Urban Form

Mexican cities have continued to grow rapidly in the end of the 20th and beginning of the 21st centuries. A report by the Secretary of Social Development (SEDESOL) in (2011) presents dramatic statistics and maps of the expansion of urban areas from 1980 to 2010, showing how some cities added urban space many times their size in 1980 during this period. Yet it is important to assess more than just a city's degree of urban growth to understand how its social-spatial structure is affected by expansion, as raw numbers can hide important variations. Many cities, but not all, lost population in their central zones in Mexico during the 1990s and 2000s as they added new, high-density housing developments in the periphery (Monkkonen and Comandon 2016), thus examining changes in overall density can overlook important differences between cities.

Table 22: Changes in urban form, 1990–2000, 1990–2010

	Change 1990-2000			Change 1990-2010		
Variable	Mean	Median	Std. Dev	Mean	Median	Std. Dev
Population	0.35	0.29	0.50	0.66	0.57	0.64
Land Area	0.26	0.20	0.46	0.47	0.33	0.67
Density	0.08	0.07	0.16	0.16	0.12	0.22
Centrality	0.63	0.42	1.07	0.91	0.60	1.21
Discontiguity*	0.18	0.00	1.24	0.17	0.00	1.02
Proximity*	0.68	0.06	2.41	0.73	0.13	2.43

Source: Authors with INEGI 1990, 2000, and 2010.
Notes: * Extreme outliers (above 10,000 percent change) were excluded, for discontiguity there were seven observations and for proximity two.

Table 22 presents percentage changes in the different measures of urban growth and urban form, for the two-time periods under study (1990–2000 and 1990–2010) to match the available change data for the segregation measures. Clearly, the changes during a twenty-year period will be larger than those in a ten-year period, so their comparison does not yield much information. We see that cities' population grew by a much greater degree than their land areas did, and thus urban population densities also increased. This refutes the argument made by the abovementioned report by SEDESOL (2011), which incorrectly used municipality populations to calculate urban population densities. A longer description of this discrepancy can be found in Monkkonen and Comandon (2016).

The other big change is found in the measure of cities' centrality, which increased by more than half. The combination of rapid horizontal expansion, with increasing density and centralization, reflects the complex nature of urban growth in Mexico. Using the term sprawl to describe these changes is perhaps not appropriate, despite the homogenous appearance of single-family tract homes being built, because of the high density of the new peri-urban housing developments (Monkkonen 2011a).

Table 23: Changes in Segregation by Income and Education

Variable	Mean	Median	Std. Dev
Change in Income Macro–Micro Ratio (%)	43.3	13.7	201.5
Change in Low-Income Segregation (%)	33.1	29.2	52.6
Change in High-Income Segregation (%)	32.4	25.1	38.2
Change in Overall Income Segregation (%)	31.2	26.7	41.3
Change in Education Macro–Micro Ratio (%)	55.5	34.6	145.2
Change in Low-Education Segregation (%)	68.4	44.4	85.7
Change in High-Education Segregation (%)	8.9	7.3	34.0
Change in Overall Education Segregation (%)	14.2	8.0	29.7

Source: Authors with INEGI 1990, 2000, and 2010.

Table 23 presents the averages of city-level changes in segregation. These give us a better sense of changes as they are averages of the 100 cities percent changes. For example, the means are all higher than medians, indicating that a few cities experienced disproportionately large increases. We see that the increases in segregation by income were evenly distributed across the distribution of income, with the median city experiencing an increase in segregation of high- and low-income households of 25 and 29 percent. The changes are very different for education. The median city experienced a much larger increase in the segregation of low-education households, roughly 44 percent, whereas the segregation of high-education households only increased by 7 percent.

Analysis of the Relationship Between Urban Growth, Urban Form, and Segregation

We analyze the relationship between urban expansion and segregation in two steps. First, we estimate simple pairwise correlations between the percent change in the four different types of segregation outcomes described above, and the six measures of changes in urban form (including growth in population and land area). Then, we regress changes in segregation on these urban form variables, to test the associations while controlling for time-invariant characteristics of cities using fixed effects panel models.

The first piece of analysis is presented in Table 24, which reports correlations between the percent change in segregation and percent changes in measures of urban expansion and urban form. Note that the changes in segregation by education are from 1990–2010 and changes in segregation by income are from 1990–2000.

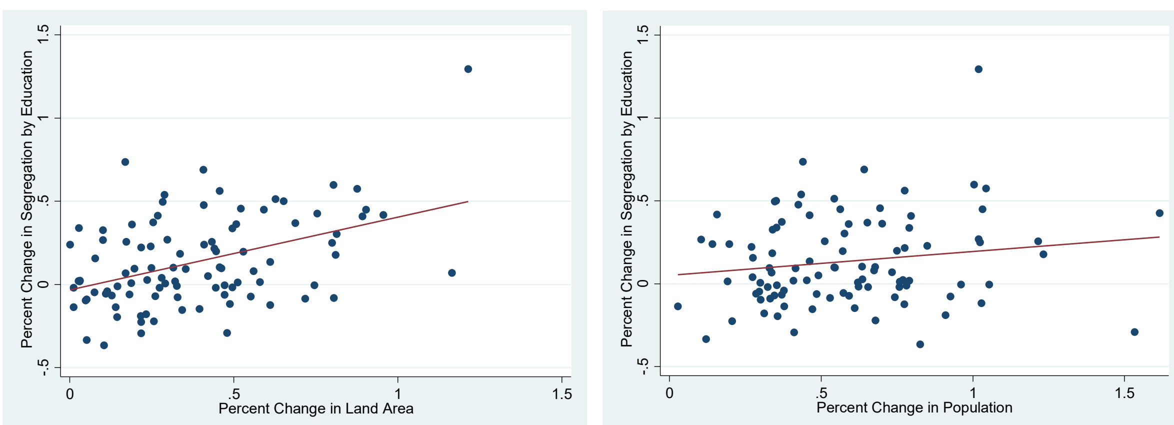
Table 24: Correlations Between Changes in Urban Form and Segregation, 1990–2010

Variable	Overall Education	High-Education	Low-Education	Overall Income	High-Income	Low-Income
Population	0.16	0.14	0.13	0.11	0.12	-0.03
Land Area	0.43***	0.36***	0.38***	0.26***	0.27***	0.13
Density	-0.13**	-0.21**	-0.17***	-0.10	-0.07	-0.14
Centrality	0.11	0.04	0.02	0.04	0.13	0.04
Discontiguity	0.15	0.24**	-0.04	0.00	-0.06	0.15
Proximity	-0.02	-0.12	0.13	-0.24**	-0.13	-0.20**

Notes: *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels. First three columns (changes in segregation by education) are for 19902010 period and second three (changes in segregation by income) are for 19902000 period.

Many of the correlations between changes in urban form and segregation are not consistent or strong. For example, changes in population or urban centrality are not correlated with any changes in segregation, and changes in the indexes of Discontiguity and Proximity (circularity) are only significantly associated with one or two segregation measures. Increasing population density is significantly and negatively associated with segregation by education, with higher density cities being more mixed.

Figure 19: Urban Expansion, Population Growth and Increasing Segregation by Education



The most striking result from this analysis is that the strongest and most significant correlation with increasing segregation is urban expansion as measured by land area growth. The measure of urban population growth, which is itself strongly correlated to urban land growth[3] is also positively associated with increasing segregation but not strongly enough to be statistically significant. Figure 1 visualizes the difference between the two measures of urban growth, showing the scatter plot of correlation in changes in segregation by education and land growth on the left and population growth on the right.

The regression analysis reveals a more accurate picture of the relationships described in Table 25, as it controls for time-invariant characteristics of cities as well as other measures of urban

[3] The correlation coefficient is 0.58 for the period 19902000 and 0.47 for the period 20002010.

form in the same models. We report models focused on income and education segregation separately. Table 25 reports the results of four separate OLS regressions that assess the impacts of changes in different measures of segregation by income on changes in urban spatial structure from 1990 to 2000. The use of year fixed effects means these models control for time-invariant characteristics of cities. Again, changes in cities' circularity (Proximity Index) and their fragmentation (Discontiguity Index) are not statistically significantly related to changes in income segregation.

Table 25: OLS Regressions Results: Changes in Urban Form on Income Segregation

	Segregation levels			
Variables	Overall Income	Low-Income	High-Income	Macro-micro ratio
Area (ln hectares)	0.0263***	0.008	0.0481***	0.006
	-0.006	-0.006	-0.008	-0.034
Proximity Index	-0.005	-0.005	0.009	-0.036
	-0.005	-0.006	-0.007	-0.032
Discontiguity	0.001	0.006	-0.003	0.013
	-0.003	-0.004	-0.005	-0.021
Centrality Index	0.015***	0.007	0.019***	0.052*
	-0.005	-0.005	-0.007	-0.031
Constant	-0.196***	-0.055	-0.368***	0.081
	-0.047	-0.050	-0.066	-0.289
Observations	193	193	193	193
R-squared	0.47	0.15	0.57	0.082
Number of cities	99	99	99	99
F-statistic	15.49***	3.23*	24.00***	1.58

Notes: *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.

Cities that grew more in terms of land area experienced increases in overall levels of segregation by income. The different models show that this relationship was driven by large increases in the spatial isolation of high-income households rather than low-income households. Similarly, cities that grew in a more centralized manner also experienced increases in overall levels of segregation by income, again driven by the isolation of high-income households.

Changes in the macro-micro ratio, which measures the relative scale of segregation, were positively associated with changes in cities' centrality. That means cities that became more centralized also saw increases in the scale of segregation, with a larger scale of homogeneity in neighborhood composition. This is counter to what might be expected if suburban sprawl is the driving force behind increases in the scale of segregation. That is, the specific kind of urban expansion in large, peri-urban housing developments for working class households was expected to lead to a larger scale of segregation among low-income households. While it is possible that the time-period does not capture enough of the housing boom, which was primarily after the year 2000, the results of the subsequent models are similar. More research on the particularities of centralization and the increasing scale of segregation is needed.

Table 26 reports the results of regression models using four different measures of segregation by education. In this case the time-period is longer than that of assessing segregation by income, consisting of two decades (1990–2010) rather than one. More of the urban form variables are significantly associated with changes in segregation over this longer period, though Discontiguity is not. Cities that became more compact (as measured by the Proximity Index), saw an increase in the segregation of less educated households, but a decrease in the scale of that segregation, meaning that homogenous neighborhoods were smaller.

Table 26: OLS Regression Results: Changes in Urban Form on Education Segregation

	Segregation			
Variables	Overall education	Low-education	High-education	Macro-micro ratio
Area (ln hectares)	0.013***	0.024***	0.016*	-0.065*
	-0.004	-0.005	-0.010	-0.037
Proximity Index	-0.003	0.016**	-0.016	-0.120**
	-0.007	-0.007	-0.015	-0.057
Discontiguity	0.004	0.006	0.009	-0.024
	-0.003	-0.003	-0.007	-0.028
Centrality Index	0.008*	0.009*	0.003	0.125***
	-0.004	-0.005	-0.010	-0.039
Constant	-0.057	-0.189***	-0.054	0.737**
	-0.036	-0.039	-0.080	-0.307
Observations	200	200	200	200
R-squared	0.28	0.58	0.12	0.11
Number of cities	100	100	100	100
F-statistic	7.35***	26.23***	2.69**	2.35**

Notes: *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.

Urban land expansion is again the most important correlate with segregation. However, unlike previous tests, the strong connection between urban expansion and increasing segregation is driven more by the segregation of low-education households. As with compactness, greater amounts of urban expansion are associated with a decrease in the scale of segregation. As with income, more centralization is associated with a larger scale of segregation, as well as more segregation itself. These counterintuitive findings are notable and merit further study.

Summary and Discussion

In this section, we assess changes in urban growth, urban form, and segregation by income and education for the 100 largest cities in Mexico between 1990 and 2010, using a new data source for 1990 and cutting-edge measures of urban form and spatial segregation. We find rapid urban growth with small increase in population densities, increasing centralization, increasing levels of socioeconomic segregation, and an increase in the geographic scale of that segregation.

The most consistent finding is a strong, positive connection between urban growth (in terms of land area not population) and socioeconomic segregation. There is a negative correlation between urban expansion and the scale of segregation, meaning faster growing cities have smaller pockets of homogeneity. Additionally, we find that greater increases in a Centrality Index, which measures how concentrated population is closer to the center of the city, are positively associated with changes in segregation and the scale of segregation. These last results are intriguing because they run counter to what is expected, based on research from other countries (e.g. Le Goix 2005; Nechyba and Walsh 2004;), as well as a conceptual model developed from the Mexican experience and observed changes across the country.

Clearly, understanding the form of urban expansion and its relationship to the socio-spatial distribution of people in cities in Mexico requires further research and theorization, as well as new data and metrics. Fortunately, the provocative findings presented here offer some guidance as to next steps not only in understanding how Mexican cities are changing, but also the role of housing finance as well as other policies in exacerbating/mitigating the changes.

V. Conclusions and Future Research

Urbanization, especially rapid urbanization without sufficient investment in infrastructure, creates a host of negative externalities, such as congestion, pollution, environmental damage, and the threat of social problems. At the same time, urban expansion is intimately connected to economic growth in most places, and individual productivity is enhanced by living in larger cities (Bertinelli and Black 2004; He and Sim 2015). This relationship, between economic productivity and urban expansion has been little examined outside of high-income countries. The negative byproducts of urban growth are often the primary focus of research and policy. It is important to recognize the benefits—and costs—of urban expansion to inform sensible urban policy.

In this study, we focus on the major benefit or urbanization (economic productivity) and two of the most significant costs (transportation and social segregation). We examine the way in which urban spatial structure—sprawl vs. dense—shapes these three outcomes. Mexican cities grew dramatically between 1990 and 2010, in a relatively sprawling manner. This urban growth model has led to higher commuting costs; increases in socio-economic segregation (Monkkonen, 2012), and higher greenhouse emissions (CTS-Embarq, IMCO and Centro Molina 2013; ONU-Hábitat, Sedesol 2011). However, it has also supported the country's growing manufacturing sector, which mostly relies on the peri-urban development of large factories. We seek to make the tradeoff between these costs and benefits explicit.

In part, the motivation for this report is the urban policy program recently initiated by the federal government that seeks to promote compact growth, mixed land use, and polycentric urban structures. These principles are being applied without much study or consideration of their possible negative impacts. Additionally, we see that different strains of the academic literature focus on the negative impacts of urbanization and the benefits, and seek to bring these literatures into conversation.

One of the principal findings is that the benefits of urbanization are strong, and unexpectedly, urban compactness is not associated with economic productivity in Mexico. On the contrary, more sprawling cities are more productive. This result is robust across several model specifications and raises provocative questions about the federal government's urban policy.

The analysis of transportation outcomes finds that urban density and size matter as much to transportation outcomes as income or regional GDP. Sprawl, however, is complex to measure and, when measured, not necessarily associated with travel in ways that we might have originally hypothesized. Some of this may relate to the unit of analysis and aggregation bias. While outside the scope of this analysis, a next step to better understanding the relationship between urban form, household income, demographics, and travel behavior would be to use disaggregate household-level micro data on commute times and mode choice to work and more spatially refined measures of urban form, where possible.

The relationship to segregation is clearer. There is a strong, positive connection between urban growth and socioeconomic segregation, and a negative correlation between urban expansion and the scale of segregation. Cities that are growing faster have smaller pockets of homogeneity. We also find that greater centralization is positively associated with increases in segregation and the scale of segregation. This last finding runs counter to research from other countries, as well as a conceptual model developed from the Mexican experience and observed changes across the country.

The report also shows the need for urban researchers to develop a set of metrics and data sources better suited to measuring the particularities of urban form in Mexico. For example, the Discontiguity Index we use to measure leapfrog development lacks precision because of the need to rely on census data, and the use of a standard Centralization Index in cities with a prevalence of high-density peri-urban developments is imperfect. Additionally, a multi-scale approach might be useful in the effort to assess changes in urban form and their relationship to social dynamics. An effort to measure sub-city/neighborhood form dynamics, and then create city-level indexes based on these measures of a smaller geography has the potential to capture the transformations wrought by new, formal housing developments. In terms of data, we need to create a database of state and municipal regulations and planning codes in Mexico, so that we might start to match changes in urban form to policies other than housing finance. Additionally, better data on transit and road infrastructure, not to mention housing prices, are important for more convincing models.

Finally, in a larger sense, urban scholars in Mexico could usefully focus efforts on understanding and testing whether, how much, and in what ways changes in urban form matter for people's lives. Research on spatial inequality in the United States and other countries has demonstrated the importance of neighborhood residence through the quality of public services, social networks, and personal safety, for example. In the case of Mexico, one's neighborhood likely also matters in these ways, but we must build an evidence base demonstrating this. This research is important for prioritizing and guiding policy efforts to change spatial structure, which are currently made without much research to support them.

As the first section of this report demonstrates, we cannot take for granted that the relationship between urbanization and other elements of the economy and society are the same across countries. Therefore, we must build an independent evidence base for Mexico and Latin America on neighborhood effects, segregation (such as the work of Prieto 2015; Quintanar and Sabate 2014; or Caudillo and Torche 2014), congestion, and other diseconomies of scale, rather than relying on studies from the United States and Europe.

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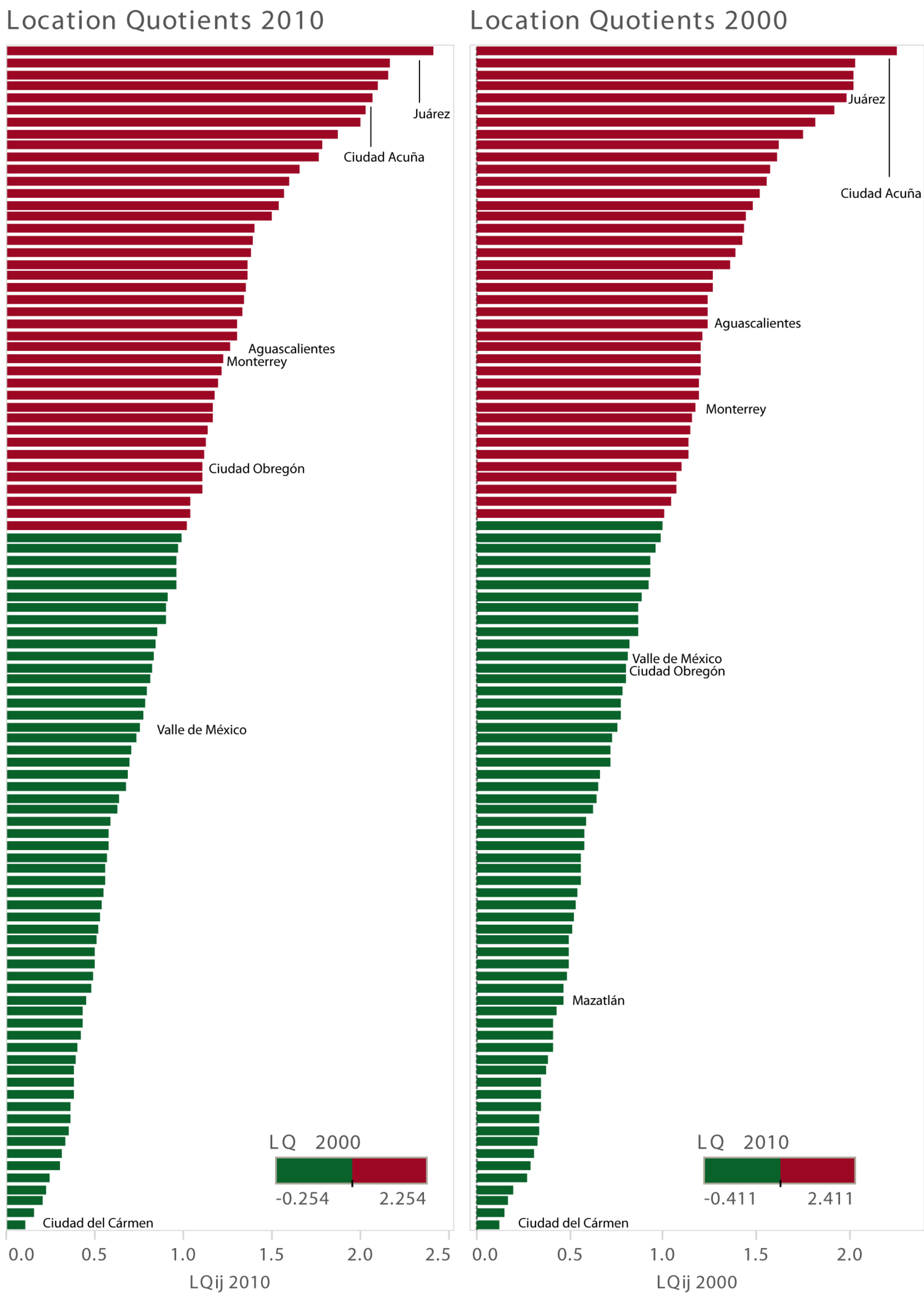
Appendix A: Location Quotient of Manufacturing Jobs in 2000 and 2010

Figure 1: Location Quotient of Manufacturing Jobs in 2000 and 2010



Appendix B: Detailed Modeling Strategy

The Longitudinal Mixed Model or Growth Curve Model

The most common mixed models are those which structure with individuals at level 1 and some grouping at level 2. A special case of mixed models are longitudinal studies where measurements on individuals are repeated at multiple points in time. In this kind of structure, the measurement occasions form the level 1 units, and individuals are level 2. These models, where the predictor of major interest is some measure of time, are also known as growth curve models. These models control for non-independence among the repeated observations for each individual, but in a conceptually different way than conventional panel data analysis. Rather than estimating the correlation among an individual's repeated observations, it actually adds one or more random effects for individuals to the model (Finch, Bolin, and Kelley 2014; Steele 2014). The model equation thus includes extra parameters to contain any random effects. They take the form of additional residual terms, each of which has its own variance to be estimated.

Random intercept mixed models

The basic growth curve model, or the random intercept model, controls for the fact that some individuals always have higher values than others. By controlling for this variation, we take it out of the original residual. It takes the following form:

$$y_{ij} = \beta_{0j} + \beta_1 t_{ij} + e_{ij}$$

$$\beta_{0j} = \beta_0 + u_{0j} \qquad (1)$$

Where:

β_{0j} is the overall intercept (averaged across individuals), interpreted as the expected value of y at $t_{ij} = 0$.

β_1 is the slope of the regression of y on time, commonly referred as the growth rate. In a random intercept model, the growth rate is assumed to be the same for all individuals.

$u_{0j} \sim N(0, \sigma_{u0}^2)$ is an individual-specific random effect, capturing the effects on y of unmeasured individual characteristics with values that are fixed over time. The intercept for individual j is $\beta_{0j} = \beta_0 + u_{0j}$, so u_{0j} represents the difference between an individual's value on y (at any occasion) from the overall mean β_0. The variance of u_{0j} (σ_{u0}^2) is the between-individual variance in y after accounting for the linear effect on time.

$e_{ij} \sim N(0, \sigma_e^2)$ is an occasion-specific (time-varying) residual, capturing the effects on y of unmeasured time-varying characteristics. The variance σ_{0j} (σ_e^2) is the within variance in y adjusting for linear growth.

The model is easily extended to account for both time-varying and time-invariant explanatory variables. The basic condition for the suitability of mixed models are high values of the intraclass correlation (ICC), which is the ratio of the between-individuals variance (σ_{u0}^2) and the total variance ($\sigma_{u0}^2 + \sigma_e^2$).

Random slope mixed models

A more realistic growth model allows for variation between individual in the rate of change in y (the slope of t_{ij}) as well as in their level of y at any occasion (the intercept). The random intercept model can thus be extended to:

$$\begin{aligned} y_{ij} &= \beta_{0j} + \beta_1 t_{ij} + e_{ij} \\ \beta_{0j} &= \beta_0 + u_{0j} \\ \beta_{1j} &= \beta_1 + u_{1j} \end{aligned} \tag{2}$$

In a single-equation form, it can be written as:

$$y_{ij} = \beta_{0j} + \beta_1 t_{ij} + u_{1j} t_{ij} + e_{ij} \tag{3}$$

The individual variation in the slope is indicated by the j subscript on the slope parameter β_1 (common to all individuals) plus a random amount u_{1j} specific to individual j. Again, the model can account for both time-varying and time-in variant explanatory variables as marginal fixed effects. We used the lmer (Bates et al. 2015) and nlme (Pinheiro et al. 2016) packages available for the R software (R Core Team 2016).

Linear regression panel models

In a linear regression panel model, the continuous dependent variable is linearly dependent on a set of predictor variables, and individuals (cities) have measures at two or more points in time. The model can be written as:

$$y_{it} = \mu_t + \beta x t_{it} + \gamma z_i + \alpha_i + \varepsilon_{ij} \tag{4}$$

Where μ_t is an intercept term that can be different for each time period, x stands for the independent variables whose values can vary across time, time-varying variables, z stands for the independent variables whose values do not change across time, time-invariant values that measure stable characteristics, and β and γ are the coefficients for the xs and zs. The model assumes that these effects are time-invariant. Interactions with time can be added if the effects of the independent variables are thought to vary with time, α_i and ε_{ij} are both error terms. ε_{ij} is different for each individual at each point in time. α_i only varies across individuals but not across time. We can think of α_i as representing the effects of all the explanatory variables that have not been included in the model.

There are two kinds of panel models. The assumptions about α_i help to determine what panel model one should estimate. One basic assumption is that error terms should be uncorrelated with the explanatory variables; this assumption can be violated if relevant variables are omitted form the model. If we believe that α_i is correlated with the xs (time-varying explanatory variables) then we can estimate a *fixed effects model*. The fixed effect model controls for time-invariant variables that have been not measured but have an effect on y. If α_i is uncorrelated with the xs then a random effects model can provide unbiased estimates of both βs and γs.

There is a special case when the measurement occasions T=2, the equations for the two periods can be written as:

$$y_{i1} = \mu_1 + \beta x_{i1} + \gamma z_i + \alpha_i + \varepsilon_{i1}$$

$$y_{i2} = \mu_2 + \beta x_{i2} + \gamma z_i + \alpha_i + \varepsilon_{i2} \tag{5}$$

If we subtract the first equation from the second, we get:

$$\begin{aligned} y_{i2} - y_{i1} &= (\mu_2 - \mu_1) + \beta(x_{i2} - x_{i1}) + (\gamma z_i - \gamma z_i) + (\alpha_i - \alpha_i) \\ &\quad + (\varepsilon_{i2} - \varepsilon_{i1}) \\ &= (\mu_2 - \mu_1) + \beta(x_{i2} - x_{i1}) + (\varepsilon_{i2} - \varepsilon_{i1}) \end{aligned} \tag{6}$$

Which can be rewritten as:

$$\Delta y_i = \Delta\mu + \beta\Delta x_i + \Delta\varepsilon_i \tag{7}$$

Where Δ indicates a difference score. Note that both α_i and γ_i cancelled out, because whatever effect the time-invariant variables have, it is the same at both time 1 and time 2. For fitting the panel data models, we will use the plm package (Croissant and Milo 2008) for the R software.

Appendix C: Characterization of Travel Mode Aggregation

Table 1. Categories Included in Mode Choice Aggregations

Original category	Group
5 Bicicleta	Non-motorized
6 Caminando	
1 Camión, taxi, combi o colectivo	Public transit
2 Metro, metrobús o tren ligero	
4 Transporte laboral	
3 Vehículo particular (automóvil, camioneta o motocicleta)	Driving

Appendix D: Additional modeling

Table 1: OLS Models Predicting Driving to Work Mode Share

	(1)	(2)	(3)
Average household income	0.006***	0.007***	0.005***
	(0.001)	(0.001)	(0.001)
Average years of schooling	-1.211	-2.399	-1.678
	(1.758)	(1.717)	(1.425)
Total population (log)		0.234	-2.011**
		(1.218)	(1.005)
Clustering index		4.168	5.029**
		(3.166)	(2.518)
Proximity index		4.729	9.477**
		(5.709)	(4.480)
Discontiguity (log)		-8.522***	0.224
		(3.168)	(2.937)
Border region			14.277***
			(2.215)
Northern region			10.192***
			(2.692)
Southern region			-2.218
			(2.301)
Constant	3.131	4.613	26.751**
	(10.835)	(14.987)	(12.579)
Observations	100	100	100
R^2	0.349	0.471	0.691
Adjusted R^2	0.336	0.437	0.661

Note: Std. err. in parentheses. *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.

Table 2: OLS Models Predicting Public Transit to Work Mode Share

	(1)	(2)	(3)
Average household income	-0.003**	-0.004***	-0.003***
	(0.001)	(0.001)	(0.001)
Average years of schooling	6.636***	8.009***	7.530***
	(1.888)	(1.720)	(1.638)
Total population (log)		3.193**	4.370***
		(1.220)	(1.155)
Clustering index		-5.936*	-4.877*
		(3.170)	(2.894)
Proximity index		-15.063***	-17.644***
		(5.717)	(5.149)
Discontiguity (log)		2.124	-1.921
		(3.172)	(3.375)
Border region			-5.804**
			(2.546)
Northern region			-9.639***
			(3.094)
Southern region			5.115*
			(2.644)
Constant	5.420	-24.850	-37.954**
	(11.638)	(15.006)	(14.457)
Observations	100	100	100
R^2	0.114	0.374	0.519
Adjusted R^2	0.095	0.333	0.470

Note: Std. err. in parentheses. *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.

Table 3: OLS Models Predicting Non-Motorized Transportation to Work Mode Share

	(1)	(2)	(3)
Average household income	-0.004***	-0.003***	-0.002***
	(0.001)	(0.001)	(0.001)
Average years of schooling	-5.426***	-5.611***	-5.853***
	(1.211)	(1.178)	(1.117)
Total population (log)		-3.428***	-2.358***
		(0.836)	(0.787)
Clustering index		1.769	-0.152
		(2.172)	(1.974)
Proximity index		10.340***	8.173**
		(3.917)	(3.511)
Discontiguity (log)		6.399***	1.700
		(2.174)	(2.301)
Border region			-8.472***
			(1.736)
Northern region			-0.552
			(2.109)
Southern region			-2.896
			(1.803)
Constant	91.449***	120.236***	111.203***
	(7.462)	(10.283)	(9.857)
Observations	100	100	100
R^2	0.588	0.667	0.747
Adjusted R^2	0.579	0.646	0.722

Note: Std. err. in parentheses. *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.

Appendix E: Additional Modeling of Traffic Fatalities

Table 1: OLS Model Predicting Natural Log of Traffic Fatalities

	Dependent variable:		
	Log of traffic fatalities		
	(1)	(2)	(3)
Average household income	0.0001	0.0001^{*}	0.0002^{**}
	(0.0001)	(0.0001)	(0.0001)
Average years of schooling	0.121	0.020	-0.056
	(0.105)	(0.107)	(0.114)
Total population (log)	0.664^{***}	0.673^{***}	0.648^{***}
	(0.060)	(0.076)	(0.080)
Clustering index		0.235	0.196
		(0.198)	(0.201)
Proximity index		0.920^{**}	0.950^{***}
		(0.356)	(0.357)
Discontiguity (log)		0.096	0.244
		(0.198)	(0.234)
Border region			0.067
			(0.177)
Northern region			0.409^{*}
			(0.215)
Southern region			0.226
			(0.184)
Constant	-6.018^{***}	-6.338^{***}	-5.720^{***}
	(0.885)	(0.935)	(1.004)
Observations	100	100	100
R^2	0.642	0.675	0.690
Adjusted R^2	0.630	0.654	0.659

Note: Std. err. in parentheses. *, **, and *** indicate statistical significance at the 0.1, 0.05, and 0.01 levels.