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Urban form, transit supply, and travel behavior in Latin America: Evidence from Mexico's 100 largest urban areas

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ABSTRACT

This paper examines the relationship between urban form, transportation supply, and individuals' mode choice across Mexico's 100 largest urban areas. After documenting variation in mode choice, urban form, and vehicle ownership, we fit a multinomial logit model to data from 2.5 million commuters who reported a work commute on the 2015 Intercensus. We estimate whether a person commutes by transit, car, or walking/biking as a function of commuters' gender, age, employment status, household income, and seven measures of urban form and transportation supply. Across urban areas, commuters are less likely to drive in dense urban areas where jobs are spatially concentrated jobs and near population centers. Commuters are also less likely to drive in areas with better public transit supply and less roadway. Collectively the measures of urban form are as strongly related to the probability someone commutes to work by car as household income. Population density plays a particularly strongly role with an estimated elasticity four times as strong as recent studies from US urban areas. Taken together, our findings suggest that land use planning and transportation investments can and do influence commute patterns. Recent public policies have almost certainly contributed to increased, rather than decreased driving and associated congestion, pollution, and traffic fatalities.

1. Introduction

Between 1990 and 2010, Mexico's largest 100 urban areas added 23 million new residents, a 53% increase. Nearly all of this new growth has been in densely populated suburban neighborhoods, comprised of informal housing or — more recently — large, dense, publicly-subsidized, and peripherally-located commercial housing developments.[1] The most central neighborhoods have lost population but jobs have become more centrally clustered, partially as a result of the overall shift from manufacturing jobs to services. While urban sprawl is generally characterized by low-density, fragmented, leapfrog, single-use development (Hamidi et al., 2016; Tsai, 2005; Galster et al. 2001), Mexico's recent sprawl is dense and spatially concentrated. Even in single-use development, moreover, residents quickly convert housing units into shops and local businesses.

Shifts in urban spatial structure have likely contributed to the rapid increase in vehicle fleets and vehicle travel in Mexico. Across cities, neighborhoods, and individuals, higher density neighborhoods with better access to jobs are associated with lower rates of motorization (Newman and Kenworthy, 1989; Holtzclaw, 1990; Levinson and Kumar, 1997; Ingram and Liu, 1999; Bento et al., 2005; Ewing and Cervero, 2010; Stevens, 2017). National and local government agencies have attempted to contain sprawl and its associated costs — such as pollution, long and expensive commutes, congestion, and traffic fatalities. For example, the National Housing Commission (Comisión Nacional de Vivienda, CONAVI) recently developed an Urban Growth Containment Program to promote more centralized construction of publicly subsidized housing (for an overview, see Monkkonen and Giottonini (2017)). The Federal government's recently approved 2016 New Human Settlements Law will allow for higher densities and mixed-use development throughout Mexican neighborhoods starting in 2018. Nonetheless, between 1990 and 2010, the vehicle fleet tripled in Mexico's largest 100 largest urban areas.

To inform academic understanding of this issue and contribute to

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[1] Since reforms enacted in the early 1990s, INFONAVIT, a subsidized housing provident fund for employed low-to-middle-income households, has sparked a shift from primarily incremental, self-help construction housing market to one based on speculative building and mortgage finance (Monkkonen, 2011).

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policy debates in Mexico, we examine whether and to what extent measures of urban form and transportation supply correlate with travel behavior across Mexico's 100 largest urban areas. Although there is a large and growing body of literature on the relationship between urban form and travel behavior (see for example (Ewing and Cervero, 2001, 2010; Boarnet, 2011; Stevens, 2017)), little empirical evidence is from Mexico or Latin America. What studies do exist tend to be from large capital cities with metropolitan household travel surveys, such Mexico City (Guerra, 2014b), Santiago de Chile (Zegras, 2010), or Bogota (Cervero et al., 2009). The relationship between urban form and travel behavior may vary substantially in smaller cities and urban areas. For example, even metropolitan Mexico City's most peripheral neighborhoods have high enough population densities to support high-capacity transit like subways or metros (Guerra and Cervero, 2011; Newman and Kenworthy, 2006; Pushkarev et al., 1982). As in other low- and middle-income countries, however, nearly all of Mexico's recent and projected population and economic growth is now occurring outside of its largest cities (United Nations Population Division, 2014). How smaller cities grow will help determine national car ownership levels, total vehicle travel, pollution levels, and traffic safety records. Despite the rapid growth in vehicle fleets, Mexico's urban areas remain highly multimodal, with 49% of residents commuting to work by transit, 28% by car, and 23% commute by foot or bicycle.

This paper is the first to examine the relationship between individual travel behavior and urban form across multiple Mexican cities. To do so, we rely on Mexico’s 2015 Intercensus, which provides the first national snapshot of how residents commute to work. We match the data to measures of urban form for Mexico's 100 largest urban areas. Together, these 100 cities and their suburbs account for 64% of the national population and 86% of the employed population. Due to the spatial resolution of the data, we rely on metropolitan level measures of urban form, as in Bento et al.’s (2005) study of the relationship between urban form, mode choice, and vehicle travel in US metropolitan areas in 1990. While this approach misses some of the nuances of how local neighborhood form influences travel behavior, it likely prevents biased parameter estimates from residential self-selection.

We organize the remainder of this paper as follows. Section 2 summarizes and describes the study's data and modeling approach. We pay particular attention to describing the construction of urban form metrics used in the analysis and their expected relationship to travel behavior. Section 3 presents the results of our mode choice models and Section 4 examines the strength of relationship between our measures of urban form, transit supply, and commute mode choice. Section 5 discusses implications for public policy and Section 6 concludes.

2. Data and modeling approach

We estimate whether someone commutes to work by transit, active modes (i.e., walk or bike), or car, as a function of age, income, education, and information about the urban area where the commuter resides. We use the Mexican National Population Council's National Urban System definition of urban areas, which includes all major cities and surrounding suburbs (Consejo Nacional de Población, 2018). As in Bento et al. (2005), commuter information like age and gender vary at the individual level while measures of urban spatial structure like population density and jobs-population balance vary at the metropolitan level.

The Intercensus does not provide information on the neighborhood where respondents reside or work.[2] Thus this analysis ignores the way that differences in the built environment influence travel behavior at the neighborhood level, as in the studies reviewed in recent meta-analyses (Ewing and Cervero, 2010; Stevens, 2017). This limitation has one substantial benefit, however, in that estimates of the relationship between urban form and travel behavior are unlikely to be biased by residential self-selection (for a review of the self-selection problem, see (Handy et al., 2005; Cao et al., 2009; Mokhtarian and Cao, 2008)). Residents may choose to live in a neighborhood that suits their travel preferences but are much less likely to change metropolitan areas based on preferred travel behavior. Nineteen in twenty adults in our sample lived in the same metropolitan area in 2010 as in 2015 and just 2% had moved from one metropolitan area to another (authors' calculation using INEGI (2015)).

The 2015 Mexican Intercensus provides the first-ever national data detailing how Mexicans commute to work and school. Prior to 2015, 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 at all. Although data are available at the household level, spatial resolution is only available down to the municipality and more populous localities. The largest urban area, Mexico City, includes nearly 80 municipalities. Most small metropolitan areas include just one. In Mexico's 100 largest urban areas, the sample includes data collected from 7.2 million individuals, including 2.5 million commuters, in 1.9 million households collected in March 2015. We exclude respondents who did not report commuting to work from our sample, as well as 408,756 respondents who did not report their mode of travel.

Table 1 summarizes the variables used in the models and the expected relationship to commute choices. In the following sections, we provide additional details on mode choice, car ownership, transit supply, and our measures of urban spatial structure in Mexico's 100 largest urban areas. According to the Intercensus, 63% of commuters were men, with an average age of 38 and a monthly household income of 12,800 pesos (around $1000 USD in 2015). Roughly a third of commuters had completed junior high school, with another 23% having completed high school, and 22% having completed college or a higher degree. Just over half of the sample work in the informal sector, according to Suárez, Murata, and Campos's (2016) estimation procedure. This multi-criteria approach characterizes informal workers as those who are: self-employed or day-laborers; not professionals; not involved in healthcare, finance, telecommunications, government-owned industries, or other heavily regulated sub-sectors; and not benefitting from employer-sponsored healthcare or retirement funds.

For the 114,461 residents who did not report household income and 1364 who did not report age, we set income or age to zero and added a dummy variable to indicate missing data. Unreported educational attainment is included with lower educational attainment in the reference category.

2.1. Mode choice to work

In Mexico's largest urban areas, 49% of residents commute to work by transit, 28% commute by car, and 23% commute by foot or bicycle. Fig. 1 plots the distributions of mode share across the 100 urban areas as three kernel-smoothed histograms. Public transit is the most common way for people to access work and accounts for between 12% and 67% of trips in each urban area. Public transit mode share includes buses, minibuses, microbuses, minivans, workplace shuttles, and all types of taxis (shared or unshared), in addition to trains, metro, and bus rapid transit (BRT). In some cities, such as Tijuana, shared taxis are particularly important to the public transportation system. In northern cities with a high share of employment in large factories, such as Juarez and Chihuahua, worker shuttles are particularly important and support around a quarter of all work commutes. Only 1% of commuters relied entirely on a mass rapid transit (MRT) system like BRT or rail. Another 3%, mostly in Mexico City, relied on a combination of MRT and some other transit mode, such as a bus or minibus.

Driving (including cars, light-duty trucks, and motorcycles) is the next most common mode and accounts for between 9% and 62% of

[2] The national statistics agency (INEGI) turned down our request for neighborhood-level geographic data.

Table 1
Summary data and expected relationships with mode choice (N = 2.46 million).

Predictor variables	Mean	Std. Dev.	Expected relationship
Metropolitan measures			
Population per hectare	61.4	21.5	Dense urban areas are more likely to support transit than walking, biking, or driving.
Jobs-population imbalance	0.24	0.08	Better balance is likely to support short, non-motorized trips.
Spatial compactness	0.65	0.15	Transit use and active modes will be more likely in urban areas where neighborhoods tend to be closer together.
Spatial concentration of jobs	0.47	0.04	Transit use will be higher in urban areas where jobs cluster in fewer locations.
Kilometers of MRT per hundred thousand residents	0.71	0.88	Urban areas with better transit are likely to have higher transit use.
Share of employment as drivers or in transit	8.7	6.4	Transit use will be higher in areas with more overall transit supply
Meters of roadway per hectare	144.1	36.9	Urban areas with more roadway will tend to have higher rates of driving.
Individual measures			
Male	0.64	0.48	Men are more likely to commute by car.
Works in informal sector	0.51	0.50	Informal jobs are closer to home and likelier to be accessed by foot or bike.
Age	38	13	The young are more likely to bike, walk, or use transit, while the middle-aged are more likely to drive.
Household income (pesos per month)	12,886	17,176	The lowest income households are likely to rely on walking and biking. The wealthiest households on cars.
Highest educational attainment			
Junior high school (*Secundaria*)	0.32	0.47	The lowest levels of education are likeliest to be associated with higher rates of walking and biking. The highest with car use.
High school	0.23	0.42	
College degree or higher	0.23	0.42	

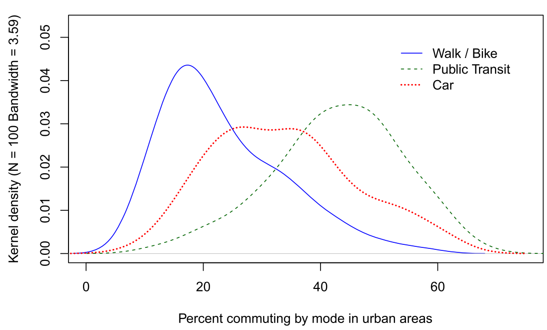

Fig. 1. Distribution of commute to work by mode across 100 largest urban areas.
Note: Kernel density function uses R's default kernel estimation procedure.

commutes across the 100 largest urban areas. Even in the most car-reliant city, La Paz, 38% of commuters walk, bike, or take transit. The proportion of non-motorized trips ranges from 9% to 57%. The majority of commuters walk or bike to work in three of Mexico's 100 largest urban areas, while the plurality does so in six additional cities. While most non-motorized travel is by foot (80%), bicycling makes up 10% or more of the commute mode share in nearly a fifth of Mexico's hundred largest urban areas. In short, Mexico's cities are highly multimodal with substantial variation in modal importance.

Despite relatively low rates of driving to work, 48% of commuters live in a household that has one or more cars. In households with a car, 51% of commutes to work occur by car compared to just 6% in households without a car. We do not include car ownership in our models of mode choice since it is endogenous to travel decisions. Models predicting car ownership as a function of urban form, transportation supply, and household characteristics — available on request — do not add substantively to our mode choice analysis.

2.2. Transportation supply

We generate two variables to serve as proxies for the quality and quantity of transit supply in Mexico's urban areas. The first is an estimate of the total kilometers of high-capacity transit — metro, light rail, commuter rail, and BRT — per capita in each urban area. Just seven Mexican metropolitan areas had a high-capacity transit system in March of 2015. We exclude one potential system in Villahermosa because this system is missing various BRT features. Since then, additional lines have opened in Acapulco, Pachuca, and Tuxtla Gutiérrez. The three largest (Mexico City, Guadalajara, and Monterrey) have a rail and/or metro system in addition to BRT.

Table 2
Mode split by type of transit used in urban areas with high-capacity transit.
Sources: Global BRT Data n.d.; UrbanRail.Net n.d.; INEGI, 2015

City	Public transit	1.Bus/taxi/ minibus	2. High-capacity	1. and 2.	System km
Valle de México	60.3	37.6	4.3	10.5	413
Guadalajara	50.4	40.6	0.8	0.6	40
Monterrey	49.7	36.5	1.7	1.0	73
Puebla-Tlaxcala	53.9	46.6	0.2	0.0	32
León	42.1	34.5	0.2	0.1	32
Juárez	50.9	20.8	0.0	0.1	25
Chihuahua	37.2	22.1	0.4	0.6	22

Notes: 1. Bus/taxi/minibus indicates that no high-capacity transit use was reported; 2. High-capacity indicates that only high-capacity transit use was reported; 1. and 2. Indicates that both high-capacity transit and bus, taxi, or minibus use were reported. The total public transit mode share also includes worker shuttles, which capture substantial mode share in Juárez and Chihuahua.

Table 2 lists information about transit systems and transit mode share in each urban area with a high-capacity transit system. The Mexico City Metropolitan Area (Valle de México) has the largest and oldest transit system in the country, as well as the most substantial BRT network. The seven BRT systems have opened over the past decade, while the rail systems are older. Together Mexico City's metro, BRT, and other rail lines provided over 400 km of high-capacity transit service and supported about 15% of all commutes in Mexico City in 2015. Two-thirds of these transit commutes, however, also relied on a bus, minibus, minivan, or taxi. Residents used the next most important system, Monterrey's light rail and BRT, for less than 3% of all commutes. The BRT systems in three of the four smallest cities serve less than 1% of trips to work. No respondents reported using Juarez's BRT or the system in Villahermosa.

Transit supply is likely endogenous to city-level transit use but exogenous to any particular individual's commute choices. That is, unlike household car ownership, urban-level transit supply is unlikely to be correlated with systematic variance in error terms due to a given individual's unobserved preference for transit or other modes.

Since so much transit occurs on buses, minibuses, worker shuttles, vans, and taxis, we also wanted to construct estimates of the quality and quantity of lower capacity transit supply. We were unable to find consistent data on fleet size by urban area. Instead, we rely on an estimate of the share of workers employed as drivers, transportation operators, or drivers' assistants using the Intercensus. These estimates include truck drivers as well as minibus drivers and transit firms. Parameter estimates should therefore be interpreted with caution.

2.2.1. Roadway density

We also estimate the total amount of roadway per hectare of urbanized land using OpenStreetMap road network data (OpenStreetMap Wiki contributors 2017) and the amount of urbanized land estimated from the 2010 Census tracts. In general, we expect higher rates of driving in urban areas with a greater density of roads. We also expect lower rates of walking and biking. Again, we expect urban-level measures of road supply to be exogenous to individual commuters' travel decisions.

2.3. Measures of urban form

We generated a dozen measures of urban spatial structure, using road network and Census tract data from the 2010 population Census and 2009 economic Census.[3] We estimated the number of jobs by Census tract using the mid-point method and data on the number of firms by firm size in each Census tract. The largest category firm has 250 or more employees. These estimates also exclude employment in the informal sector (INEGI, 2009) and therefore tend to underestimate employment in tracts and urban areas where jobs are in large firms or the informal sector. Due to the small number of observations (100 urban areas) and high correlation across measures of urban form, we drop multiple measures of urban form from our final reported models. These are available in a Lincoln Institute of Land Policy working paper (Montejano et al. 2018). Below we describe the measures included in the final models.

2.3.1. Population density

Population density is perhaps the most common and simplest measure of urban spatial structure. We estimate metropolitan population density as the total population divided by the total urbanized land area in each Census tract. This is a fairly gross measure of urban density and substantially lower than average neighborhood densities or the residential densities where most people reside. For example, Mexico City has a metropolitan population density of 91 people per hectare, but the average neighborhood density is 135 people per hectare, and the average person lives in a neighborhood with 161 people per hectare. Aguascalientes has 64 people per hectare, but the average metropolitan resident lives in a neighborhood with 105 people per hectare. In addition to being one of the strongest predictors of travel behavior, population density was strongly correlated with other measures of urban structure, such as the total population (0.79 correlation), estimates of fragmented growth patterns (0.69 correlation), and measures of centrality (0.59 correlation).

2.3.2. Spatial compactness

To estimate spatial compactness, given a fixed density, we use Angel, Parent, and Civco's (2010, 446) Proximity Index, which measures 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 points in the urban footprint. The Proximity Index takes the value of one when urban form is a circle, and zero under perfect linearity. To improve the measure, we exclude non-developable land, such as bodies of water or steep hills.

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2.3.3. Jobs-population imbalance

Following Bento et al. (2005), we estimate jobs-population imbalance using a Gini coefficient, based on the percentage of residents and percentage of jobs in each Census tract. A score of zero indicates perfect balance with an equal distribution of jobs and people across all tracts, while a score of one indicates perfect imbalance. The Gini coefficient is a common measure of inequality and frequently applied to measure urban spatial structure (Tsai, 2005; Burt et al., 2009). Urban areas with a better balance of jobs and residents across neighborhoods are likely to facilitate short, non-motorized trips by foot or bike.

2.3.4. Spatial concentration of jobs

We also used the Gini coefficient to estimate how concentrated jobs are in specific neighborhoods. A score of one indicates a perfectly monocentric city with all jobs located in a single Census tract, while a score of zero indicates an even spread of jobs across Census tracts. We expect an uneven distribution of jobs to support transit use since transit tends to work best in places with concentrated destination patterns that are conducive to fixed-route services.

2.4. Model specification

We fit our mode choice data with a multinomial logit model (for specification details, see (Train, 2009 or Ben-Akiva and Lerman, 1985)). To facilitate model convergence and make parameter estimates more comparable, we demean all of our continuous predictor variables and divide them by the standard deviation. Table 2 provides the standard deviations for each predictor variable and can be used to convert parameter estimates back to their original numerical values. For ease of interpretation and comparison with other studies, we also provide elasticity estimates using sample enumeration (Train, 2009, 37; Ben-Akiva and Lerman, 1985, chap. 6). These account for non-linearity in the estimator, as well as the data. We estimate clustered standard errors using clustered bootstrapping and the procedures provided in Liang and Zeger (1986). The two methods produce similar results, with a number of urban form variables losing statistical significance due to the larger standard errors. Finally, due to the large size of the sample, we estimate a separate model excluding respondents from the Mexico City metropolitan area. This model — available on request — produces parameter estimates so similar to those reported in Table 3 that we opt not to report them below.

3. Mode choice model

Table 3 presents the results of the multinomial logit model predicting whether a commuter travels by transit or active modes instead of by car. Urban spatial structure plays a strong and statistically significant role in commuter mode choice in Mexico's 100 largest urban areas. A one standard deviation increase in population density (21.5 people per hectare) is associated with a 0.32 increase in the utility of commuting to work by transit or by an active mode. For an average resident, this 35% increase in population density corresponds with a 38% increase in the odds of choosing transit over a car and a 38% increase in the odds of choosing walking or biking over a car.

Other measures of urban form are less strongly or consistently associated with mode choice than population density. Residents in urban areas with more imbalanced jobs and people across neighborhoods are less likely to walk or bike than to drive or take transit. A one standard deviation increase in jobs-population imbalance corresponds with an 8% decrease in the odds of commuting by non-motorized modes. Presumably imbalance tends to increase commute distances, making travel by bike or foot more difficult. An increase in imbalance is also associated with higher transit use but the relationship is not statistically significant at the 90% confidence level. By contrast, a standard deviation increase in the concentration of employment in a small number of Census tracts corresponds with a statistically significant 12% increase

[3] For convenience, we translate Área Geoestadística Básica (AGEB) as Census tract, its equivalent geographic unit.

Table 3
Multinomial logit model predicting commute mode to work (reference category: commute by car).

	By transit		By foot or bike	
Population density	0.319	***	0.321	***
	(0.066)		(0.073)	
Jobs-population imbalance	0.017		−0.078	*
	(0.040)		(0.042)	
Spatial compactness	0.002		0.060	
	(0.048)		(0.042)	
Spatial concentration of jobs	0.117	***	0.016	
	(0.041)		(0.042)	
Roadway density	−0.190	***	−0.317	***
	(0.044)		(0.044)	
Kilometers of MRT per capita	0.091		−0.085	
	(0.059)		(0.061)	
Proportion of jobs in transportation	0.143	***	0.119	***
	(0.044)		(0.045)	
Male	−0.572	***	−0.444	***
	(0.026)		(0.046)	
Works in informal sector	−0.127	***	0.827	***
	(0.033)		(0.062)	
Monthly household income (natural log)	−1.034	***	−1.367	***
	(0.043)		(0.051)	
Income data missing	−4.870	***	−6.166	***
	(0.230)		(0.253)	
Age	−1.233	***	−1.663	***
	(0.035)		(0.049)	
Age squared	0.883	***	1.362	***
	(0.031)		(0.039)	
Age data missing	−2.283	***	−2.918	***
	(0.088)		(0.109)	
Junior high school (Secundaria)	−0.265	***	−0.554	***
	(0.020)		(0.018)	
High school	−0.720	***	−1.279	***
	(0.040)		(0.035)	
College degree or higher	−1.734	***	−2.527	***
	(0.067)		(0.050)	
Northern region	−0.245	**	−0.368	***
	(0.121)		(0.123)	
Southern region	0.164		−0.085	
	(0.109)		(0.131)	
Intercept	2.212	***	1.160	***
	(0.063)		(0.047)	
McFadden R^2: 0.144				

Notes:*p < 0.1; **p < 0.05; ***p < 0.01; all continuous variables demeaned; Cluster robust standard errors in parentheses.

in the odds of commuting by transit. Transit does a good job of a good job of carrying large numbers of passengers along fixed routes, and appears to thrive in areas with concentrated job centers. A more spatially compact urban area — as measured by circularity relative to linearity — is not strongly associated with mode choice. Although a standard deviation increase in circularity is associated with a 6% increase in the odds of using non-motorized modes for an average commuter's journey to work, there is only about an 85% probability that this estimate is statistically different from zero.

In terms of transportation supply, increases in roadway correspond almost as strongly with reduced transit use, walking, and biking as similar increases in population density. For the average commuter, 26% more roads per hectare corresponds with 17% lower odds of getting to work by transit and 27% lower odds of getting to work by foot or bike. In terms of transit supply, residents are more likely to commute by transit and non-motorized modes in urban areas with a higher share of employment in the transportation sector — a proxy for the quality and quantity of bus, minibus, and taxi service. An average commuter has 12%–15% higher odds of walking/biking or taking transit to work in urban areas with 6.4 percentage points more workers in the transportation sector. With an average of 9% of workers in the transportation sector, however, this represents a fairly sharp increase in estimated service.

High-capacity transit appears to have a weaker and less consistent relationship. A standard deviation increase in the amount of high-capacity transit per residents corresponds with a 10% increase in the odds of an average resident commuting by transit. Much of this increase, however, comes from a corresponding decrease in non-motorized modes. Neither relationship is statistically significant at the 90% confidence level, however. Moreover, a standard deviation increase would require 185 new kilometers of service in Mexico City and around 40 km in Guadalajara or Monterrey.

In summary, Mexico's urban commuters are much more likely to travel by transit in dense cities, with spatially clustered job centers, limited roadway, and good transit supply. Urban areas with similar features, but a more even balance between jobs and population and perhaps also a compact, circular shape, tend to favor commuting by foot or bike. Low-density cities with poor transit service and substantial amounts of roadway almost certainly and unsurprisingly favor driving. Overall, population density, roadway density, and local transit supply are more strongly and consistently related with mode choice than the other measures of urban form.

In terms of demographics, men are less likely to use transit than to drive or to walk/bike. Commuters with higher income tend to drive more. For an average commuter, a one standard deviation increase in the natural log of monthly income corresponds with an absolute increase in income from around 6,000 to 50,000 pesos, a 64% decrease in the odds of commuting by transit, and a 75% decrease in the odds of commuting by foot or bike. Education, which may reflect differences in preferences, current wealth, or future earnings not captured well by the monthly income variable, follows a similar pattern. As residents get older, they are more likely to use cars than transit up to 44 years old when they become less likely. Residents are more likely to use cars than non-motorized modes up to 44 years-old.[4]

People working in the informal sector are a bit more likely to drive than take transit, but substantially more likely to walk or bike than to use either motorized mode. Informal workers often minimize travel costs by choosing workplaces close to home (Suárez et al., 2016). The higher rates of driving may relate to the substantial number of day laborers, drivers, and self-employed retailers who may use private cars to access remote sites or move people and goods.

4. The relationship between, urban form, transportation supply, and car travel

Table 4 presents the estimated strength of the relationship between urban form, transportation supply, and the probability that individuals commute to work, based on sample enumeration (Train, 2009, 37; Ben-Akiva and Lerman, 1985, chap. 6). We also include an estimate of aggregate elasticities. These aggregate elasticities tend to be weaker than individual estimates since the average probability of commuting to work by car is less than 50%. For example, an increase in the probability of commuting to work from 1% to 3% implies a strong elasticity but has a small influence on aggregate mode choice. Average individual elasticities range from a very weak 0.005 to a much stronger but still inelastic −0.198. For comparison, we also include an estimate of the income elasticity of commuting to work by car, which is stronger than each built environment variable, but still inelastic.

Population density is five times more strongly related to the probability of commuting to work by car than any of the other measures of urban form. Although still inelastic, the relationship is also substantially stronger than the roughly −0.05 elasticity found in recent meta-analyses (Ewing and Cervero, 2010; Stevens, 2017). The next most strongly related variable is the spatial concentration of jobs. A

[4] The demeaned quadratic term makes the age coefficients somewhat difficult to interpret although the interested reader can calculate values with the additional information that the mean squared age is 1569.

Table 4
Elasticity with respect to the probability of commuting to work by car.

	Individual elasticity	Aggregate elasticity
Population density	−0.198	−0.142
Jobs-population imbalance	0.005	0.002
Spatial concentration of jobs	−0.038	−0.035
Spatial compactness	−0.010	−0.007
Roadway density	0.108	0.088
Proportion of jobs in transport	−0.047	−0.037
Kilometers of MRT per capita[1]	−0.038	−0.036
Household income	0.346	0.260

[1]Elasticity estimates exclude residents living in the 93 urban areas without a rail or BRT system since any percentage increase from zero kilometers of high-capacity transit remains zero.

doubling in the concentration of jobs corresponds with around a 4% decrease in commuting by car, with a corresponding increase in transit use and almost no change to non-motorized modes. In addition to weak statistical relationships, spatial compactness and jobs-housing imbalance have weak absolute associations with driving rates. According to the model estimates, a doubling in spatial compactness or metropolitan jobs-housing imbalance would change driving rates to work by less than 1%.

At an elasticity of 0.1, road supply has the second strongest relationship to commute choice of the seven metropolitan-level measures presented in Table 5. Holding the metropolitan land area constant, a 10% increase in roadway corresponds with a roughly 1% increase in residents' probability of commuting to work by car on average. This conforms to general findings that greater road supply increases the amount of driving (Ingram and Liu, 1999; Cervero and Hansen, 2002; Downs, 2004; Duranton and Turner, 2011). Increasing the amount of high-capacity transit or the number of workers employed in the transportation sector — a rough proxy for the supply of buses, minibuses, minivans, and taxis — has about half of the effect on the probability of driving as increases in road supply. Since 93 out of the 100 urban areas do not have any high-capacity transit, we also simulated the estimated response of adding 10 km of high-capacity transit to all 100 urban areas. This resulted in an estimated 4% reduction in the number of people commuting to work by car. These results fit well with findings that new high-capacity transit investments can have important but localized impacts on transit use and attract most of their riders from local buses and minibuses (Baum-Snow and Kahn, 2000, 2005; Cervero and Landis, 1995, 1997; Guerra, 2014a). As seen in Table 3, however, the relationship is not statistically significant at the 90% confidence level.

Finally, to give a better sense of how measures of urban form and transport supply work together, we simulate aggregate mode choice if all commuters lived in urban areas with the 25th percentile, 50th percentile, and 75th percentile measures of car-friendly urban form and transportation supply (Table 5). In a car-friendly urban area — as estimated using the 75th percentile values of the metropolitan measures associated with a higher probability of commuting by car — we expect 37% of work commutes to be by car, compared with 29% in a typical city, and 18% in an urban area more suited to transit, walking, and biking. Most of the shift in mode share comes from transit, which varies from 57% to 42% of work commutes in the 25th percentile and 75th percentile car-friendly urban areas. That a 75th percentile car-friendly city has twice the expected driving rates as a 25th percentile one suggests that changes in urban form and transportation supply have the potential to result in economically, socially, and environmentally important shifts in driving rates over time.

Table 5
Predicted commute mode share based on type of urban form and transportation supply.

Urban form	Car	Public transit	Non-motorized
Typical (median)	28.9%	46.6%	24.5%
25th percentile car-friendly	18.2%	57.2%	24.6%
75th percentile car-friendly	37.4%	42.2%	20.4%

5. Policy implications

As more households purchase cars, the potential shift from transit and non-motorized modes to private cars presents numerous environmental, social, and economic challenges in urban Mexico. Increased pollution, traffic fatalities, and congestion loom large. Based on the analysis of the relationship between urban form, transportation supply, and commute patterns, we draw three broad policy conclusions.

5.1. Urban form shapes transportation choices

Land use plays an important role in commute patterns in Mexican cities. This role may be as important as household income or structure. Although no single measure of urban form is as strongly related to mode choice as household income, the seven measures of urban form and transportation supply collectively have an elasticity about 25% stronger than household income (Table 4.) Aggregate population density is particularly important. Within urban areas, differences in urban form likely also matter, with higher rates of transit, walking, and biking in dense neighborhoods with good access to jobs and other opportunities. Examining the strength and significance of these relationships, however, is outside of the scope of this research design or available data on commute patterns in any but the largest of Mexican cities.

Despite this research limitation, current trends suggest that many Mexican cities will become less well suited to transit, walking, and biking over time without proactive changes in public policy. Not only are cities spreading out, but residents are becoming increasingly more concentrated in dense suburban neighborhoods, further from job centers. Although shaping growth patterns through public policy is challenging, Mexico's principal housing policy — mortgage finance and construction loans through INFONAVIT — presents a missed opportunity.

INFONAVIT funds more new housing construction than the private financial sector and informal sector combined (Monkkonen, 2011), but has concentrated low-to-medium income households in single-use, peripheral neighborhoods with poor transit access and disconnected street networks. Despite the low car ownership rates of residents, INFONAVIT-financed developments are designed around cars with ample parking and an intentional separation from neighboring street networks and bus stops. One result is that households in commercial housing developments are more likely to own a car and drive twice as much on average as similar households in neighboring informal settlements (Guerra, 2015). Although the federal government has enacted some urban policy reforms in the wake of the Great Recession, INFONAVIT has not changed its general approach or succeeded in shifting development patterns towards more centralized, infill housing construction (Monkkonen and Giottonini, 2017).

5.2. Transit investments

Transit investments have the potential to have small, but important impacts on mode share. We estimate that doubling the supply of high-capacity or conventional transit corresponds to 4%–5% fewer commutes by car. Similarly, adding 10 km of new high-capacity transit to each urban area corresponds with a 4% reduction in the proportion of people commuting to work by car. Since high-capacity transit tends to attract fewer riders in smaller cities (Shyr et al., 2017) and only the largest urban areas like Mexico City and Guadalajara currently have high-capacity transit, however, these estimates may be biased upwards. There are also almost certainly increasing and decreasing returns to transit investments at different scales. Estimating these is beyond the scope of this study, but doubling transit supply or adding new BRT lines would almost certainly be challenging.

Nevertheless, our findings suggest that local and national governments should put additional emphasis on improving local bus service. Not only are the elasticity estimates stronger and more convincingly statistically significant for local transit supply than for high-capacity transit investments, high-capacity transit investments are relatively expensive and slow to materialize. With a kilometer of BRT costing between $2 million and $10 million dollars per kilometer in Latin American cities (Global BRT Data n.d.), for example, adding just 10 km of BRT to the 93 urban areas without any form of high-capacity transit would likely absorb between 0.5% and 2% of annual GDP generated in those urban areas. To put that number in perspective, the government spent roughly 3.7% of GDP on education and 0.7% on defense in 2013 and 2015 (The World Bank n.d.). While initial lines may cover operating costs, moreover, system expansions, flat fares, and free transfers will almost certainly lead to operating subsidies. Mexico City's flat fare metro has long absorbed most local government transportation expenditures (Davis, 1994, 249; Crôtte et al., 2011; Islas, 2000, chap. 7). Applying the rate of BRT construction of the past decade (379 km), it would take nearly three decades to build these starter lines.

The data on high-capacity transit presented in Table 2 also suggest that even with extensive investments in high-capacity transit, commuters will continue to rely primarily on conventional buses, minibuses, minivans, and shared taxis. Even in Mexico City, which has the most substantial high-capacity transit network by far, workers only use high-capacity transit for 15% of trips. Moreover, 71% of the commuters using high-capacity transit also use a bus, minibus, or minivan. A transit policy focused entirely on high-capacity transit will be expensive and time-consuming to implement and will ignore the majority of current and future transit riders. By extension, a transportation policy that seeks to improve conditions for the majority of transit users and stem increases in car ownership and driving rates needs to look beyond high-capacity transit investments, and couple them with land use planning and investments in conventional transit.

5.3. Road investments

Lastly, our findings suggest that investments in new roads and highways will continue to draw commuters into private cars. Despite this relationship and stated policies to increase the use of public transport and non-motorized modes, state and federal agencies spend most of their budgets on road investments and maintenance. Between 2011 and 2015, 80%–90% of transportation spending across 59 metropolitan areas in Mexico went into road investment and maintenance (ITDP, 2017). Over the same time period, only 7%–11% of investments went to public transit, pedestrian, or cycling infrastructure, with the remainder going to public space investments. These investment patterns are substantially out of step with the existing use of the transportation system and the promotion of environmentally sustainable or socially equitable outcomes.

6. Conclusion

In this paper, we examine the relationship between urban form, transportation supply, and mode choice to work across Mexico's 100 largest urban areas. Across the 2.5 million residents who reported making a work commute on the Intercensus, we found lower rates of driving in dense urban areas with jobs spatially concentrated in smaller areas near population centers. We also found lower rates of driving in areas with better public transit supply and less roadway. Collectively, the measures of urban form relate to commuting to work by car as strongly as household income. Taken together, our findings suggest that land use planning and transportation investments have a substantial influence on commute patterns. In a 25th percentile car-friendly urban environment, we predict half as many commutes by car as in a 75th percentile car-friendly urban environment. Due to a low spatial resolution of data, we are not able to measure how local variation in the built environment correlated with individuals' mode choices within cities. This limitation, however, also likely prevents biased parameter estimates from residents selecting into neighborhoods that suit their travel preferences.

In terms of public policy, we argue that coordinated land use planning and transportation investments have the potential to increase walking, biking, and transit use across Mexico's largest urban areas. However, existing land use and transportation policies are almost certainly contributing to the growth in car ownership and car travel. The most important land use policy of the past 20 years has publicly subsidized the creation of large low-to-moderate income housing developments on the urban periphery, far from existing job centers or transit supply. Meanwhile, public investments have strongly favored road infrastructure, with the occasional centrally-located high-capacity transit investment. Stemming the tide of rising motorization will require substantial shifts in public policy.

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References

Angel, Shlomo, Parent, Jason, Civco, Daniel L., 2010. Ten compactness properties of circles: measuring shape in geography. Can. Geogr./Le. Géogr. Can. 54 (4), 441–461. https://doi.org/10.1111/j.1541-0064.2009.00304.x.

Baum-Snow, Nathaniel, Kahn, Matthew E., 2000. The effects of new public projects to expand urban rail transit. J. Publ. Econ. 77 (2), 241–263. https://doi.org/10.1016/S0047-2727(99)00085-7.

Baum-Snow, Nathaniel, Kahn, Matthew E., 2005. Effects of urban rail transit expansions: evidence from sixteen cities, 1970-2000. Brookings-Wharton Papers on Urban Affairs 2005, 147–206.

Ben-Akiva, Moshe, Lerman, Steven, 1985. Discrete Choice Analysis: Theory and Application to Travel Demand, first ed. The MIT Press, Cambridge, MA.

Bento, Antonio M., Cropper, Maureen L., Mushfiq Mobarak, Ahmed, Vinha, Katja, 2005. The effects of urban spatial structure on travel demand in the united states. Rev. Econ. Stat. 87 (3), 466–478. https://doi.org/10.1162/0034653054638292.

Boarnet, Marlon, 2011. A broader context for land use and travel behavior, and a research agenda. J. Am. Plann. Assoc. 77 (3), 197–213. https://doi.org/10.1080/01944363.2011.593483.

Burt, James E., Barber, Gerald M., Rigby, David L., 2009. In: Elementary Statistics for Geographers, third ed. Guilford Press, New York, London.

Cao, Xinyu, Mokhtarian, Patricia L., Handy, Susan, 2009. Examining the impacts of residential self-selection on travel behaviour: a focus on empirical findings. Transport Rev. 29 (3), 359–395. https://doi.org/10.1080/01441640802539195.

Cervero, Robert, Hansen, Mark, 2002. Induced travel demand and induced road investment: a simultaneous equation analysis. J. Transport Econ. Pol. 36 (3), 469–490.

Cervero, Robert, Landis, John, 1995. Development impacts of urban transport: a US perspective. In: Banister, David (Ed.), Transport and Urban Development. E & FN SPON, London, pp. 136–156.

Cervero, Robert, Landis, John, 1997. Twenty years of the bay area rapid transit system: land use and development impacts. Transport. Res. Pol. Pract. 31 (4), 309–333. https://doi.org/10.1016/S0965-8564(96)00027-4.

Cervero, Robert, Sarmiento, Olga L., Jacoby, Enrique, Fernando Gomez, Luis, Neiman, Andrea, 2009. Influences of built environments on walking and cycling: lessons from Bogota. Int. J. Sustain. Transp. 3 (4), 203–226. https://doi.org/10.1080/15568310802178314.

Consejo Nacional de Población, 2018. Sistema Urbano Nacional. 2018. http://www.conapo.gob.mx/es/CONAPO/Datos_Abiertos_Sistema_Urbano_Nacional.

Crôtte, Amado, Graham, Daniel, Noland, Robert, 2011. The role of metro fares, income, metro quality of service and fuel prices for sustainable transportation in Mexico city. Int. J. Sustain. Transp. 5 (1), 1–24. https://doi.org/10.1080/15568310903050073.

Davis, Diane, 1994. Urban Leviathan: Mexico City in the Twentieth Century. Temple University Press, Philadelphia.

Downs, Anthony, 2004. Still Stuck in Traffic: Coping with Peak-hour Traffic Congestion (Revised). Revised. Brookings Institution Press.

Duranton, Gilles, Turner, Matthew A., 2011. The fundamental Law of road congestion: evidence from US cities. Am. Econ. Rev. 101 (6), 2616–2652. https://doi.org/10.

1257/aer.101.6.2616.
Ewing, Reid, Cervero, Robert, 2001. Travel and the built environment: a synthesis. Transport. Res. Rec.: J. Transp. Res. Board 1780, 87–114. https://doi.org/10.3141/1780-10.
Ewing, Reid, Cervero, Robert, 2010. "Travel and the built environment: a meta-analysis. J. Am. Plann. Assoc. 76 (3), 265–294. https://doi.org/10.1080/01944361003766766.
Galster, George, Hanson, Royce, Ratcliffe, Michael R., Wolman, Harold, Coleman, Stephen, Freihage, Jason, 2001. Wrestling sprawl to the ground: defining and measuring an elusive concept. Hous. Pol. Debate 12 (4), 681–717. https://doi.org/10.1080/10511482.2001.9521426.
Global BRT Data. n.d. Accessed May 9, 2017.http://www.brtdata.org/.
Guerra, Erick, 2014a. Mexico City's suburban land use and transit connection: the effects of the line B metro expansion. Transport Pol. 32 (March), 105–114. https://doi.org/10.1016/j.tranpol.2013.12.011.
Guerra, Erick, 2014b. The built environment and car use in Mexico city is the relationship changing over time? J. Plann. Educ. Res. 34 (4), 394–408. https://doi.org/10.1177/0739456X14545170.
Guerra, Erick, 2015. Has Mexico City's shift to commercially produced housing increased car ownership and car use? J. Transp. Land Use 8 (2), 171–189. https://doi.org/10.5198/jtlu.2015.714.
Guerra, Erick, Cervero, Robert, 2011. Cost of a ride: the effects of densities on fixed-guideway transit ridership and costs. J. Am. Plann. Assoc. 77 (3), 267–290. https://doi.org/10.1080/01944363.2011.589767.
Hamidi, Shima, Ewing, Reid, Renne, John, 2016. How affordable is HUD affordable housing? Hous. Pol. Debate 26 (3), 437–455. https://doi.org/10.1080/10511482.2015.1123753.
Handy, Susan, Cao, Xinyu, Mokhtarian, Patricia L., 2005. Correlation or causality between the built environment and travel Behavior? Evidence from northern California. Transport. Res. Transport Environ. 10 (6), 427–444. https://doi.org/10.1016/j.trd.2005.05.002.
Holtzclaw, John, 1990. Explaining Urban Density and Transit Impacts on Auto Use. California Energy Resources Conservation and Development Commission, Sacramento.
INEGI, 2009. Metodología Censos Económicos 2009. Mexico City: Instituto Nacional de Estadística, Geografía e Informática. http://www.inegi.org.mx/est/contenidos/espanol/proyectos/censos/ce2009/metodologia.asp.
INEGI, 2015. Encuesta Intercensal 2015. http://www.inegi.org.mx/est/contenidos/Proyectos/encuestas/hogares/especiales/ei2015/.
Ingram, Gregory K., Liu, Zhi, 1999. Determinants of motorization and road provision. In: Gomez-Ibanez, Jose, William, B. Tye, Winston, Clifford (Eds.), Transportation Economics and Policy Handbook. Brookings Institution Press, Washington, D.C 325–56.
Islas, Victor, 2000. Llegando tarde al compromiso: la crisis del transporte en la ciudad de México. Distrito Federal: El Colegio de México, Centro de Estudios Demográficos y de Desarrollo Urbano, Programa sobre Ciencia, Tecnología y Desarrollo.
ITDP, 2017. Invertir Para Movernos: Diagnóstico de Inversión En Movilidad 2011-2015. Versión Revisada 2017. ITDP. http://mexico.itdp.org/noticias/invertir-para-movernos-2015-diagnostico-de-inversion-en-movilidad-2011-2015/.
Levinson, David M., Kumar, Ajay, 1997. Density and the journey to work. Growth Change 28 (2), 147–172. https://doi.org/10.1111/j.1468-2257.1997.tb00768.x.
Liang, Kung-Yee, Zeger, Scott L., 1986. Longitudinal data analysis using generalized linear models. Biometrika 73 (1), 13–22. https://doi.org/10.1093/biomet/73.1.13.
Mokhtarian, Patricia L., Cao, Xinyu, 2008. Examining the impacts of residential self-selection on travel behavior: a focus on methodologies. Transp. Res. Part B Methodol. 42 (3), 204–228. https://doi.org/10.1016/j.trb.2007.07.006.
Monkkonen, Paavo, 2011. The housing transition in Mexico expanding access to housing finance. Urban Aff. Rev. 47 (5), 672–695. https://doi.org/10.1177/1078087411400381.
Monkkonen, Paavo, Giottonini, Paloma, 2017. Repensar La Contención Urbana En México: del Control Del Crecimiento a La Promoción Del Crecimiento de Calidad. In: Montejano, Jorge, Camilo, Caudillo (Eds.), Densidad, Diversidad Y Policentrismo: ¿planeando Ciudades Más Sustentables? CentroGEO, Mexico City.
Montejano, Jorge, Monkkonen, Paavo, Guerra, Erick, Caudillo, Camilo, 2018. The Costs and Benefits of Urban Expansion: Evidence from Mexico, 1990–2010. Lincoln Institute of Land Policy Working Paper. .
Newman, Peter, Kenworthy, Jeffrey, 1989. Cities and Automobile Dependence : A Sourcebook. Gower Technical, Aldershot.
Newman, Peter, Kenworthy, Jeffrey, 2006. Urban design to reduce automobile dependence. Opolis 2 (1), 35–52.
OpenStreetMap Wiki contributors, 2017. Mexico Latest OSM. GeoFabrik Downloads. http://download.geofabrik.de/north-america/mexico.html.
Pushkarev, Boris, Zupan, Jeffrey, Cumella, Robert, 1982. Urban Rail in America : an Exploration of Criteria for Fixed-guideway Transit. Indiana University Press, Bloomington.
Shyr, Oliver F., Emanuel Andersson, David, Cheng, Yu-Hsuan, Hsiao, Yu-Hsuan, 2017. What explains rapid transit Use? Evidence from 97 urbanized areas. Transport. Res. Pol. Pract. 100 (June), 162–169. https://doi.org/10.1016/j.tra.2017.04.019.
Stevens, Mark R., 2017. Does compact development make people drive less? J. Am. Plann. Assoc. 83 (1), 7–18. https://doi.org/10.1080/01944363.2016.1240044.
Suárez, Manuel, Murata, Masanori, Delgado, Javier, 2016. Why do the poor travel Less? Urban structure, commuting and economic informality in Mexico city. Urban Stud. 53 (12), 2548–2566. https://doi.org/10.1177/0042098015596925.
The World Bank. n.d. "The World Bank Open Data." Accessed May 9, 2017. http://data.worldbank.org/.
Train, Kenneth, 2009. Discrete Choice Methods with Simulation, second ed. Cambridge University Press, New York. http://elsa.berkeley.edu/books/choice2.html.
Tsai, Yu-Hsin, 2005. Quantifying urban form: compactness versus sprawl. Urban Stud. 42 (1), 141–161. https://doi.org/10.1080/0042098042000309748.
United Nations Population Division, 2014. World Urbanization Prospects, the 2014 Revision. 2014. http://esa.un.org/unpd/wup/.
UrbanRailNet. n.d. Accessed May 9, 2017. http://urbanrail.net/.
Zegras, Christopher, 2010. The Built Environment and Motor Vehicle Ownership and Use: evidence from Santiago de Chile. Urban Stud. 47 (8), 1793–1817. https://doi.org/10.1177/0042098009356125.