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Job Accessibility, Commuting Time and Travel Complexity in the Mexico City
Metropolitan Area (MCMA)

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Abstract

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Transportation equity is an important dimension of urban sustainability. Specifically, the journey to work, which is still the main source of intra-urban trips in many cities around the world, is a key issue of urban transportation policy (Rode et al., 2014). This research aims to understand the relationship between urban structure and commuting patterns using the Mexico City Metropolitan Area (MCMA) as case study. Two complementary approaches are followed, one at Traffic Analysis Zone (TAZ) level and the other at individual-level analyzing the commuting trip patterns in a weekday. The first approach analyzes spatial variation in job accessibility in MCMA using two indicators (Gravity-based accessibility and the indicator developed by Shen, 1998) to determine the relative impact of location and mode choice of transportation (Chapter 2). Spatial regressions are applied to determine the relation between one-way Average Commute Time (ACT) and Job accessibility (Chapter 3). In the second approach, the unit of analysis is the

traveler to work, aiming to understand how the relation of commute on travel complexity is driven by urban structure (Chapter 4). Overall, the results of this project offer evidence to support the identification of priority areas and groups of people to target specific transport policies to improve equity. They also offer insights to better understand the driven forces of trip chaining patterns of commuters in the context of the Global South.

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DEDICATION

To my mom, thank you for all your love and your example in fighting adversity.

Chapter 1. INTRODUCTION

1.1 PROBLEM STATEMENT. RESEARCH MOTIVATION AND SCOPE.

In response to the increasing evidence of the negative environmental and social externalities, during the last decades transportation planning has shifted from a predominantly mobility-oriented paradigm to an accessibility-oriented paradigm (Rode et al., 2014). This has allowed to link transportation problems with important social policy issues such as urban poverty, unemployment, exclusion, etc. Under the new paradigm, the issue of equity between transportation modes, and its socioeconomic and spatial dimensions, have become a big concern on the agenda of accessibility planning (Jaramillo et al., 2012; Lucas, 2012).

In the Global South, where the most unequal cities are located, equity in transportation planning has special challenges and opportunities. In Latin America, as in most parts of the developing world, there was in the second half of the last century an intensive process of urbanization triggered by a demographic boom and a rural-urban migration that accompanied the industrialization of their economies. Nowadays with the labor's declining share in manufacturing, and with the conversion to tertiary economies, governments have been unable to integrate a large part of the working class to the formal economy. Thus, metropolises in the developing world have shown socioeconomic segregation, where poverty concentrates in slums with different degrees of consolidation that are partially and indifferent ways integrated to the urban metropolis. In Latin American transportation systems comprise both formal and informal schemes. An equity planning perspective should evaluate these systems in terms of their capacity to meet the needs of socially excluded people (Delmelle & Casas, 2012; Stanley & Lucas, 2008). The journey to work as

primary purpose of intra metropolitan trips is a valuable approach to evaluate the role of urban structure in the inclusion of people, through its role in travel patterns.

The Mexico City Metropolitan Area (MCMA), as my case study, has social inequality typical of the region, where historical, natural, and economic processes have produced a characteristic urban landscape that includes formal and informal urban peripheries, as well as neighborhoods with different socioeconomic status in the inner city, there is an overall pattern of wealthy areas in the west and the center together with low-income areas in the east. Transportation is a big concern in the city, putting its economic competitiveness at risk given that it takes the top spot as the metropolis with the worst traffic condition in the world (Tom Tom 2017). The evolution of the urban structure has been the cause of documented differences in commute experiences between those living in the periphery and those resident of the inner city with special impact on extensive peripheral low-income neighborhoods (Isunza & Soriano 2008; Suárez y Delgado 2009; Casado 2102). Furthermore, it is recognized that in MCMA there is a shortage in the geographical coverage of mass Transit systems such as the subway, comparing with other metropolises of similar size in the world (Murata, et. al., 2017). Bus Rapid Transit (BRT) systems have been considered as a cost-effective solution resulting in a rapid increase in its coverage in the last decade comparing with a negligible extension of the subway system. For this reason, it is critical to evaluate the evolution of commute patterns as impacted by those infrastructure changes in order to understand the differential social impacts of transport policies. Finite financial resources should mandate to allocate to serve for the disadvantaged under a perspective of equity planning (Manaugh, et al., 2015), in terms of geographical areas and/or groups of people. Thus, the overall objective of this research is to assess transport disadvantage conditions related to geographic

location, its social dimension identifying vulnerable groups of people and its relationship with the urban structure.

I would like to acknowledge that this research approach is grounded in a research framework primarily formed by a Northern Hemisphere perspective. A translation to the Global South context deserves carefully considerations which are discussed in the corresponding sections of analysis of the results.

1.2 CONCEPTUAL FRAMEWORK: BACKGROUND

1.2.1 *Urban Structure*

Overall, the concept urban structure refers to the spatial distribution of residents and economic activities in a city. Researchers describe the urban structure of a city using categories such as “monocentric”, referring to cities with an easily identifiable Central Business District (CBD) with low-density residential rings set up around in a concentric way, or “polycentric”, for cities with more than one employment center spread over the metropolitan area formed as part of a process of employment decentralization. In practice, these two categories are not mutually exclusive, since cities can show a myriad of intermediate development patterns (Figure 1.1). Thus, there is not a single urban structure indicator so researchers tend to approach this characterization in different ways.

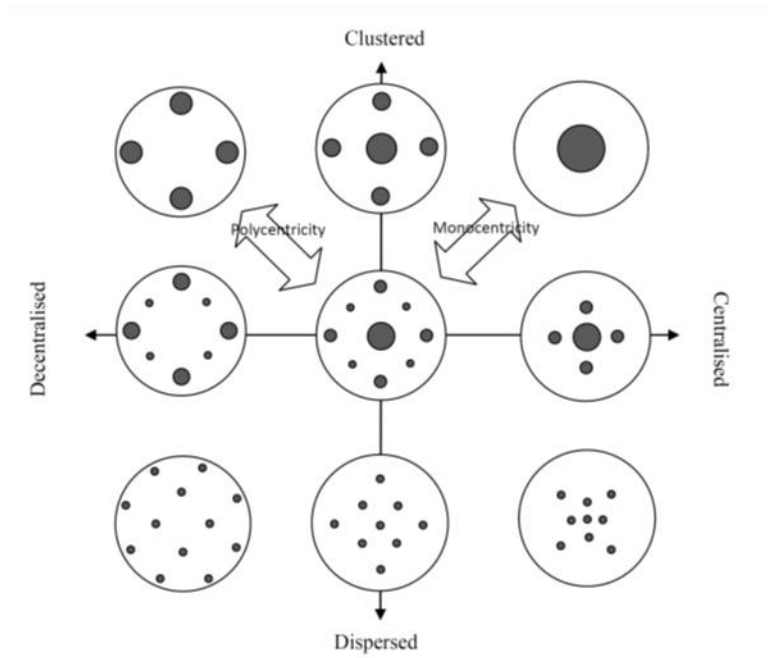


Figure 1.1. Different metropolitan structures according to the level of clustering and centralization (Taken from Smith, D.A. (2011); pp: 173).

Determining empirically the urban structure is not a straightforward task. The difficulty for an objective response lies in the fact that in terms of methodology there is no consensus for determining subcenters given that there is certain degree of bias when determining points of reference. There are several statistical approaches to identify subcenters evaluating dispersion and clustering of activities, however they lack any obvious connection to behavioral models explaining how city structure develops. Urban economists have developed idealized models in which the allocation of different land uses is determined by their corresponding bid-rent functions (Anas et al., 1998).

1.2.2 *Research on the relationship between urban structure and commute*

In Journey-to-work literature, there are three broad sub-research areas that investigate the effect of social and spatial structure on access (Kawabata & Shen, 2007) (Niedzielski & Boschmann, 2014). In the first, social inequalities and exclusions stem from uneven levels of access, empirical studies have examined differences in job access among different groups considered as being in risk (age, gender, socioeconomic condition, disabilities, etc.). The other two areas of journey-to-work research examine the relationships between commuting and land use as impacted by urban form. One asks how the proximity between locations of housing and jobs affects both journey-to-work times and distances, this is done either through studying the effect of job-housing balance or comparing with theoretical modeled minimum commute. The third research area debate historically how metropolitan US regional densities of employment and population have affected average commuting times. This dissertation covers the first two sub-research areas, which overlap with another research area called transport disadvantage as explained below.

The effect of spatial urban structure on travel behavior, specifically commute time and distances, has attracted the attention of researchers since many decades ago confronting contesting views. Urban economists and planners usually hold contrasting views on the effect of spatial changes on commuting times at the metropolitan level. Most urban economists consider the spatial transformation of cities from monocentric to polycentric structures as an adjustment process that mitigates some of the negative externalities that accompany urban growth, including traffic congestion, and suggest that many individual households and firms “co-locate” in order to reduce commuting times. They also suggest that these spatial adjustments can be more easily carried out in spread out metropolitan areas that have many alternative employment centers and residential location choices (Gordon & Lee, 2015). On the other hand, many urban planners blame excessive

decentralization and sprawl for the increase in traffic congestion and commuting distances and times (Gordon & Lee, 2015). Bertaud (2002) described four models of trip patterns according to different urban structures (Figure 1.2), being a monocentric city where strong links exist between the center and the external areas, while in a polycentric city strong links exist between each subcenter and its local residents. The other two additional models in between represent variations of these conditions. According to Ma and Banister (2007), a monocentric model represents less dispersal of land use in comparison with a polycentric city, while the trip length would be in the midpoint between two conditions of polycentricity, one in which short trips goes to the closest subcenters and other where random movements between subcenters are predominant (Figure 1.2).

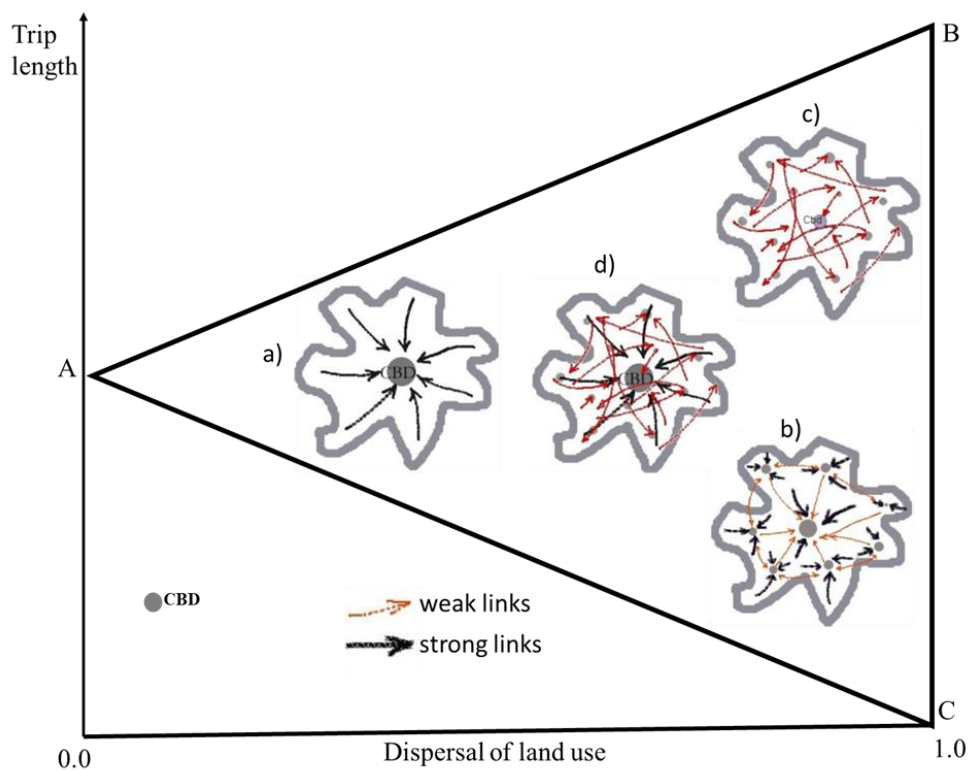


Figure 1.2. Conceptual models of Travel patterns affected by urban structure.
 Source: Ma and Banister (2007), diagrams of urban structure and trips flows are from Bertaud (2002).

Notes: In the figure, four different trip patterns within a metropolitan area are taken from Bertaud (2002). Bertaud described city (a) as the monocentric model, city (b) as the polycentric model (the urban-village version), city (c) as the polycentric model (the random-movement version), and city (d) as the mono-polycentric hybrid model (simultaneous radial and random movement), respectively

In practice, there are different approaches that operationalize the concept of spatial structure, such as considering the straight-line distances to urban centers, jobs density, jobs-to-housing ratios, employment accessibility, the pattern of streets network, etc. This variety of approaches explains in part the mixed empirical evidence that has accumulated in this academic debate. In this sense, the concept of spatial mis(match) between residents and activities emerged to explain different effects of urban structure on commuting but as explained in the next section there have been also difficulties to operationalize it.

The way in which urban structures affect travel behavior is conceptualized through the theory of utilitarian travel demand, which sees travel as a ‘derived demand’, since the demand for travel does not derive its utility from the trip itself, but from the need to reach the locations where certain activities take place. Thus, the demand for travel depends, on the one hand, on the utility of the activity, and on the other, on the aggregate costs of reaching that destination, which includes monetary costs, time and effort, all which are called Generalized Transport Costs (GTC). Urban structures determine many dimensions of these GTC such as the quality of the transport system and the characteristics of land-use in the locations where the corresponding activities take place (Boarnet & Crane, 2001; Boarnet 2011). Urban structure variables such as population density and mix land use categories would affect travel behavior by changing the distances between destinations (Wee, 2011). The study of the relationship between travel behavior and the built environment is often operationalized through regression models, where covariates represent

differential gains of utility, so an individual make his/her transportation decisions taken the one that maximize it. Here, trip costs (economic cost, time or distance) are seen as possible indirect effects of the built environment. Methodological debate revolves around the issue of isolation of the direct effect of the built environment controlling for different covariates and indirect effects, assuming that people make rational decision of location (Boarnet, M. 2011).

1.2.3 *Spatial mismatch and urban structure*

In the US, a parallel research field on job accessibility has been linked to the study of the so called “spatial mismatch hypothesis”. Kain (1968) defined this hypothesis stating that the distribution of employment for African-Americans, most of whom live in central urban areas, is affected by segregation in the housing market, which reduces the number of accessible employment opportunities that are available to them, while employment suburbanization aggravates the problem. Research results are mixed, both supporting and contradicting this claim. One group of urban researchers supported this view as some empirical evidence was generated (such as: Khattak A et al 2000). Among them, Kasarda (1995) argued that in low-income neighborhoods of the central city lives a high percentage of less-educated workers notwithstanding that jobs suitable for them are increasingly decentralized due to a fundamental industrial transition in U.S. metropolitan areas where the central-city economy is becoming more and more information intensive. According to Kasarda these two general trends have caused both spatial mismatch and skill mismatch, which together have put less-educated workers who reside in the central city at a disadvantage with respect to job access. Thus, the public policy implication originated by this view is that low-income households should be offered the opportunity to relocate from the central city to the suburbs through promoting affordable suburban housing.

On the other hand, other groups of urban researchers claim that when compared with comparable workers living in suburbs, less-educated workers living in the central city have no significantly disadvantage in job access. Along the same lines, Shen (1998) shows that low-income workers living in the central Boston Metropolitan Area still have some advantage in job access. However, he found that this location advantage is relatively modest in comparison with the advantage of private Car ownership. Thus, many researchers share the view that transportation mobility, rather than residential location, is the key determinant of low-income workers seeking job opportunities. This is particularly important since not considering travel mode is actually quite common in the journey-to work literature, particularly when the research question is focused on group comparisons.

According to Shen (2001) such disagreement may be attributed in part to the different ways in which economic opportunities are measured. Thus, some researchers use employment changes (growth, decline, and relocation) as the basis for analyzing spatial distribution of job opportunities and spatial variation in job accessibility (Kasarda 1995, Raphael 1998), while others as Shen (1998) use employment levels instead. According to this author, the latter approach is better if the objective is to understand variations in access for all less-educated workers, while if the objective is to understand variations in access for only those less-educated workers who are unemployed and are seeking jobs, neither approach will be entirely appropriate. Instead, Shen proposed “job openings” as the suitable measure, which is a function of new jobs (positive number with employment growth or negative number with employment decrease) and turnover jobs from pre-existing employment.

Grengs (2010) analyze the possible reasons that decades of empirical tests have resulted in widely divergent results with contradictory evidence that both supports and refutes the existence

of spatial mismatch. According to him this is because the meaning of “spatial mismatch” has not been well defined where there is a wide range of measures commonly used in studies, including straight-line distance, jobs density, jobs-to-housing ratios, residential segregation indices, and commute time.

Generally speaking, it is considered as evidence of spatial mismatch when commute distances or times are larger for one particular group, in comparison with others groups. However, this would be misleading unless the travel mode is controlled for in the comparison. Spatial mismatch language is predominant in the US literature, and given that original hypothesis refers to the location (central vs suburban areas) and group (low-income Blacks vs middle-income Whites) aspects this scholarship has been focusing in these; however, few studies have taken a broader perspective focusing on other groups, and/or other areas. According to Khattak, A et. al., (2000), commute distance is considered as arguably the best measure of spatial mismatch because it indicates the separation of location of work and residence. Mercado & Páez (2009) consider trip distances an important indicator of sustainable transportation and a useful indicator of quality of life. However, comparison of commute experiences between groups lack of a standard of reference which highlight the relative nature of the concept, benchmarking is difficult since the gross measure of trip distance or time is not very informative by itself of the social impact of transportation. Researchers often focus into identify long commutes as a way to determine the upper limit in the range of commute experiences, however it is not clear what should be considered a “good” lower limit, even very little is known about the minimum commute people would want to take since some psychological advantages of “some” commute.

Thus, to what point we can talk about acceptable or good commute? Comparing commute experiences between groups reveal the relative nature of the concept, i.e. considering with “respect

to the other”, while larger the number of groups in the comparison more internal validity of your concept in the specific metropolitan area of your interest. Furthermore, the study of commute times controlling for transportation mode seems a necessary approach which could give a totally opposite picture that considering only distances. As will be explained in the next section, as long as divergences in commute experiences are related to employment outcomes, this can be a sounded interpretation of existence of spatial mismatch (Gobillon et al. 2007), where however the accessibility concept seems a more appropriate concept to evaluate transport disadvantage and its link with social policy issues.

1.2.4 *Accessibility Planning*

Grengs (2010) identify four shortcomings in scholarship to illustrate how policy making is misguided by empirical studies of spatial mismatch: 1) Scholars have been vague in defining the relevant dependent variable in spatial mismatch studies, the problem is one of accessibility rather than distance itself; 2) Ignoring the substantial difference between Cars and Transit, and 3) Studies are typically focused narrowly on an specific groups (unemployed or low-wage African Americans living in the inner-city) and 4) The use of surprisingly simplistic geographical categories – e.g. dichotomy “central city” and “suburbs”. This author support for recent calls for reconceptualizing spatial mismatch, to rethink the meaning of spatial mismatch by using the concept of accessibility.

Often researchers advocating in favor of the SMH, as in the case of Gobillon et al. (2007), present as empirical evidence of SMH those works that show relationship between job accessibility of inner-city Black residents and its poor employment outcomes. However, this can be misleading since they don't specify how accessibility was measured while when referring to distance do not give a benchmark and focus narrowly in the case of Black community. Physical match is a very

narrow perspective, conversely accessibility as a broader concept can shed light about other dimensions that can be playing a role such as economic (unaffordability of Transit), transportation system service and comfortability, etc.

The SMH narrowly conceptualized can bring some errors in the implementation of public policies. For SMH advocates two policy implications are important (Gobillon et al. 2007): encouraging moving Blacks from the center to the suburbs, or to encourage moving employment opportunities to the center. To move inner city Blacks residents to suburban areas I think would worsen their situation. In many big metropolitan areas Transit systems are concentrated in the traditional downtown connecting suburban centers through direct routes. It can be an error to generalize that all US suburban areas are job accessible, then if the moving to the suburbs result in a disadvantage zone then new residents could get trapped in the middle of nowhere. Additionally, subsequent urban transformation can change initial expected advantage in a certain suburban area of moving destination. The nature of jobs has changed to being now more oriented to the service sector rather than to the manufacturing industry. Gobillon et al. (2007) recognize that spatial mismatch can be happening for other ethnicities and other urban schemes, i.e. not only inner city-suburban since there are also central city workers disconnected from some corresponding central-city jobs, as well as suburban workers disconnected from job opportunities in the suburbs. Ong & Miller (2015) call this a myopic focus on minority neighborhoods that ignores a much larger urban process. According to these authors, spatial mismatch, defined simply as physical separation, is not confined to just the inner city of a modern metropolis. Furthermore, most researchers measure only the number of jobs within a reasonable distance and disregard differences in the levels of transportation access. These authors conclude that, although spatial separation is not a groundless concern, Car access outweighs any disadvantage of simple spatial

separation (“transport mismatch”). This makes clear that if we would want to translate the SMH to other international context this cannot be possible in the way it is framed for US studies.

Grengs (2010) and Ong & Miller (2015) agree that if we are looking at the social outcomes of transportation policies spatial mismatch is not the correct way to approach this given the above-mentioned difficulties to establish acceptable parameters. Accessibility concept, instead, captures the interplay of land use and the transportation system. For this reason, under my perspective it is more compelling the concept of transport-related-social exclusion and transport disadvantage with no reference to spatial mismatch but to Accessibility. A group of Australian researchers go beyond proposing that well-being should be the final outcome of transport policy (Currie, 2011). Then, Accessibility works as the link between what we can measure as commute patterns and social outcomes of these conditions. For example, some empirical evidence has showed that job accessibility can actually have an important negative correlation with unemployment rates (Merlin & Hu 2017, gravity-based models not just physical distance). There is a certain consensus in the academic literature about accessibility planning and equity as a main guidance for transportation policy (Rode et al. 2014; Boisjoly & El-Geneidy 2017; Manaugh et al. 2015). Thus, there is no explicit reference to advocate for “matching” activities, or advocating ex ante for certain urban structure, even in some cases the reduction of private Car use is taken to a second level priority below the accessibility issue.

The advantage of considering accessibility is that this concept embraces together the dimensions of land use and the transportation system and allow for an intra-metropolitan comparison. Evidently normative guidance of accessibility could subsequently have implications in urban structure changes or on changing levels of “match” between economic and residential land uses. Thus, accessibility concept allows for a context specific evaluation for every place while

still having a universal theoretical background. Accessibility can be improved through reconfiguring land uses and increasing travel speeds. While neither approach would affect the average automobile commuter dramatically, they may help disadvantaged groups that have various housing and mobility constraints. According to Wee B. (2011) even if land use planning only minimally, if at all, results in a reduction in Car use (or motorized transport) despite the theoretically possible reduction in GTC, this is not a reason to advise negatively about such planning concepts. This is because there must also be relatively large additional accessibility benefits for the travelers not accounted in such models.

Accessibility planning has its own opportunity areas as is evaluated by Manaugh et al. (2015), mainly in the inclusion of indicators that concretely embrace these social equity and environmental aspects. Boisjoly & El-Geneidy (2017) assesses 32 recent metropolitan transport plans from North America, Europe, Australia and Asia with respect to their goals, objectives and performance indicators. Their results suggest that there is a trend toward a greater integration of accessibility objectives in transport plans, yet few plans have accessibility-based indicators that can guide their decision-making processes.

1.2.5 *Transport Disadvantage*

A branch in the built environment- travel behavior research has been focused on trip costs as variable of interest. Often, these measures have been linked, either explicitly or implicitly, to social outcomes of transportation policies using concepts such as transport disadvantage, mobility inequality, social exclusion, segregation, etc. This concern has increased given evidence that marginalized people often overlap with those people identified as facing some challenges of mobility (Delbosc & Currie, 2011), however theoretical frameworks are still incipient. In practice,

most studies evaluate different trip experiences under an equity framework, i.e. comparing either different population groups (vertical equity) or different geographic areas within a region (horizontal equity). Accessibility is a key concept whose multiple ways of measuring include inputs from trip costs. Thus, the focus on social outcomes of transportation policies has marked a different approach given that traditional planning methods for urban transport systems are aimed principally at satisfying demand and not considering aspects related to socio-economic or spatial equity (Jaramillo et al., 2012).

The methodological approaches in the Transport disadvantage literature these can be grouped as (Currie, 2011): 1) identifying the gap transport needs- transport supply, this latter measured as Transit system coverage or accessibility; 2) Measurement of the activity-space polygons, i.e. tracing trips routes or 3) simply describing and testing how variables such as time, trips complexity and/or distance differ significantly among different groups of interest.

The first area of the Journey-to-work literature is similar with the third approach in the transport disadvantage literature. This is clearly the main overlap between these two fields. In fact, it can be said that these two fields raised as different geographical contexts of the same phenomena given that the first one comes from US literature, while the second one comes mainly from European and Australian literature. In the Journey-to-Work literature commute distance is considered the best measure of spatial mismatch because it indicates the separation of location of work and residence (Khattak et al., 2000), while in transport disadvantage literature trip distance is considered as a proxy of cost burden of commute and related to social inclusion and quality of life. According to Stanley & Vella (2009) the language of social exclusion is rare in discourse from the United States and Canada. Thus, although not operating from a social exclusion theoretical framework and language, however, it would appear that there is a widespread interest in mobility

issues faced by particular transport disadvantaged groups in North America (e.g. seniors and people with a disability) (Burkhardt et al., 2003). Ideas about social exclusion, and particularly about its use in urban transportation field, started in UK and have extended beyond, according to Stanley & Lucas (2008) there is a great need to better research and understand the informal transportation system in both developed and emerging economies.

1.3 RESEARCH GOALS

The overall objective of this research is to assess transport disadvantage conditions related to geographic location, its social dimension identifying vulnerable groups of people and its relationship with the urban structure. This general objective can be broken down to three specific objectives that together achieve the overall goal of the project. These specific objectives are tackled in each empirical chapter.

The first specific objective (Chapter 2) is to study the role of location and transportation mode on accessibility. The unit of analysis is the Traffic Analysis Zones (TAZs) from the 2017 Household Origin-Destination Survey (HODS17). I estimate two models of accessibility using two sources of travel-time data (HODS17 and TRANUS) and two types of employment data (formal and total). The two transportation modes considered are Car and Transit. I did a comparison of job access in relation with the urban center and made a geographic overlap with the urban structure reported in the literature, specifically with the reported Central Area.

The second specific objective (Chapter 3) is to analyze differences in the pattern of Average Commute Time (ACT) with respect to the urban center between the use of Cars and the use of public Transit. Then, this research aims at testing the urban structure determinants of ACT as well as to identify possible groups in disadvantage.

The third specific objective (Chapter 4) is to determine the effect of urban structure on trip generation besides the role of transportation mode. Individual characteristics are also tested in the models. Trip generation and the shape of the travel tour by commuters are the important dependent variable of interest.

1.4 RESEARCH SETTING - CASE STUDY MCMA

The official geographical delimitation of the Mexico City Metropolitan Area (MCMA) comprises three states: Mexico City (CDMX, formerly called The Federal District), and some areas of the State of Mexico and the State of Hidalgo (Figure 1.3). In terms of municipalities, the MCMA comprises 16, 59 and 1, from each state, respectively.

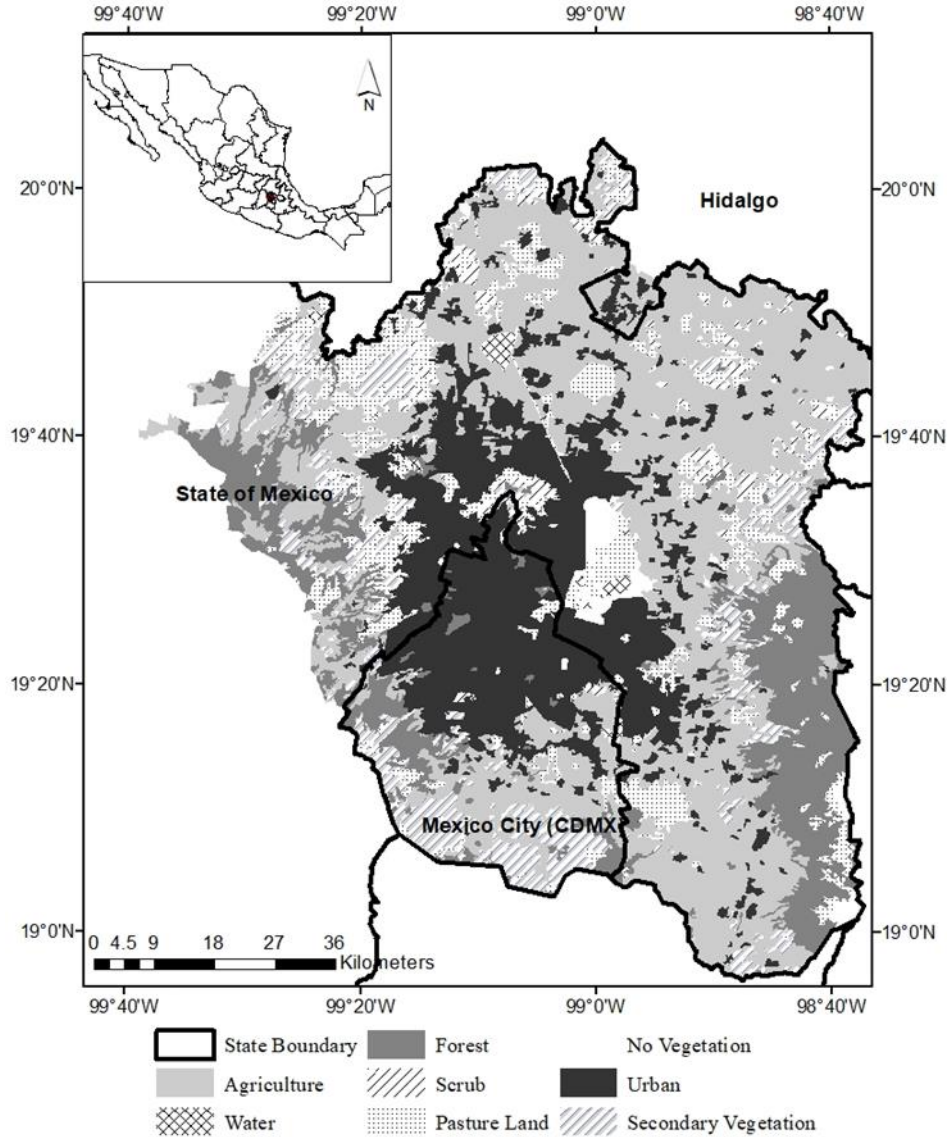


Figure 1.3. Land Cover in the MCMA (Source data: INEGI 2017).

Mexico City has been historically the political, economic and social hub of the country. Since the second half of the last century there was a rapid process of urbanization due to primarily by a demographic boom and an extensive migration from the country side to the metropolitan peripheries (Aguilar and Ward, 2003). The period of major urban population growth rate was 1950-1970, during which the capital was the center of the national process of industrialization by

import substitution taking advantage of the agglomeration economies (Garza,1985) (Isunza, V. G. & Soriano C. V. 2008).

However, for the 80s a process of absolute and relative deindustrialization related to the global economy started in the metropolis, the causes of this are multiple and complexly intertwined but the implantation of the economic neoliberal model of development played a key role (Pradilla, 2016). Factories were obligated to settle down beyond the limits of the Federal District, thus the tertiarization of the economy lead to commercial and services activities to begin to dominate the economy. Since 1980s predominant land uses in the central city and first urban ring have shifted towards a service economy (Delgado, 1988). According to Montejano, Caudillo, & Silván (2016) this has not meant an overall disappearance of manufacturing, but a consolidation of light manufacturing, especially within the metropolitan periphery where the majority of industrial activity is now located. Thus, old industrial clusters and sectors in the central city had evolved into service, commerce or residential areas. Within these changes there were also internal migration flows given a residential decentralization that caused a depopulation of central areas, additional caused of this has pointed to a severe economic crisis in the early 80s, the big earthquake that beat the city in 1985 as well as changes in the priorities in the federal public investment to other places in the country (Isunza, V. G. & Soriano C. V. 2008). In terms of physical growth of the periphery, the urban sprawl was particularly intense in the period 2000-2010 (ONU-Habitat 2018), additionally to the previous causes, promoted by a policy that encouraged private companies to build housing in the outskirts (Pradilla, 2016). The tertiarization also has been linked to the emergency of the informal economy predominantly for low-income workers. According to Suárez & Delgado (2009) over 40 per cent of the jobs in the city are informal and do not appear in the

economic census data. As we will see later, the effect of this urban structure has provoked serious differences in intra metropolitan job accessibility putting in disadvantage many low-income areas.

1.4.1 *Metropolitan urban structure in MCMA*

There is an official structure of MCMA based on urban ring configuration, which determine what municipalities correspond to the central city and those to subsequent four urban rings (COMETAH, 1998; Delgado 1988) (Figure 1.4). On the other hand, since last two decades research has been devoted to assess the MCMA urban structure in more detail, however a definitive response has been elusive. Thus, starting from the model of a monocentric city the debate has been directed to determine the extent polycentricity has emerged. The difficulty for an objective response lies in the fact that in terms of methodology there is no consensus for determining subcenters given that there is certain degree of bias when determining points of reference.

A straightforward idea is to consider thresholds of employment or other related economic indicators at census tracts level; however, the subjectivity of such threshold often causes that the assessment of the urban structure vary according to that point of reference, moreover criteria used to joint adjacent tracts to identify subcenters is also a debatable issue. In this sense Aguilar and Alvarado (2005) defined sub-centers for MCMA as those tracts that had at least 5500 jobs, this study found 35 subcenters located mainly in the central city and the first ring, concentrating 25 per cent of the Jobs in the city, which was interpreted as evidence of polycentric structure.

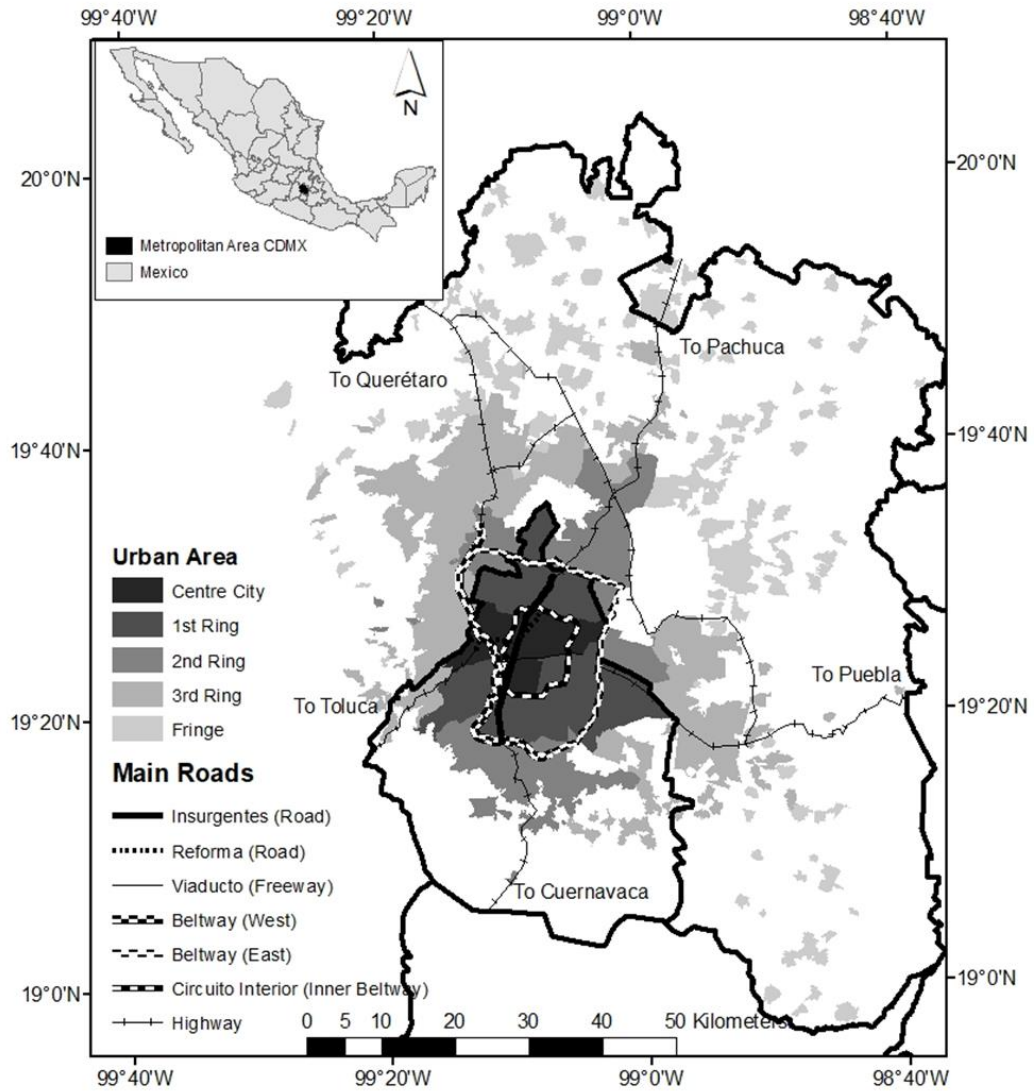


Figure 1.4. Main Roads and Urban Rings.

Commute data has also been used into the analysis of urban cores for MCMA. Graizbord and Acuña (2005) analyzing flows of commuting (number of trips) between pairs of municipalities and comparing an expected number of trips estimated with the use of contingency tables found 14

centers, eight primary centers and six secondary centers. As noted by Suárez & Delgado (2009), this approach is problematic since a significant chi-squared tests only suggest that a distribution is not probabilistic so destinations with above the expected number of flows does not mean that they are actually centers, furthermore the structure identified by Graizbord and Acuña (2005) and Aguilar and Alvarado (2005) vary given that economic centers do not match. Nava (2011) applying dominant associations methodology using data of the 1994 Household Origin Destination Survey (HODS94) travel survey and including trips for all purposes, identified 24 primary centers out of the 135 TAZs studied, which is interpreted as a signal of polycentric structure although recognizing as the more important functional relationship the Zócalo (historic center) with the east area. González-Arellano (2010) in an exploratory analysis using the HODS94 travel survey use an approach that incorporates the temporal dimension explicitly. They analyze 24 hrs. of trips and activities done in ZMVM identifying the daily dynamic of polycentrism. They identified the period of time between two contiguous activities for the same traveler (duration of activity), the former trip purpose for each activity (the actual activity), and the destination of the former trips to each activity (activity location). With this approach was possible to locate in any moment were the activities are being done in the metropolis. They found that work activities represent 62 percent of the total of no residential activity-persons hours. They found that between 7:00 am and 9:00 am the historical center is clearly a centrality of commerce and service, joined to this they identified two corridors north-south (Insurgents roadway) and to the west (Reforma avenue). Other sources that suggest a polycentric condition in MCMA are Garrocho (1996) & Graizbord (2008).

On the other hand, in the last decade researches have contested the polycentric condition of MCMA. Suárez & Delgado (2009) assess the urban structure using a trip attraction capacity approach, based on both employment and working population concentration dynamics throughout

the city. Their proposal uses a threshold that is dynamic in space and can be set for each location in relation to its capacity for attracting work trips from other places in the city, the concentration of working residents in nearby areas is also considered. This methodology uses a jobs to working residents ratio to identify “attraction areas”, two separate exercise were considered one for formal jobs and other for an estimation of informal jobs. In terms of mapping they use GIS generated neighborhoods of 1.6-km (1 mile) radii in order to provide focal statistics for each urban hectare of the city. They found that most jobs are concentrated in a large central agglomeration (CA) which is predominantly tertiary, within this are found inner nodes and corridor-like structures that had been identified in previous research as sub-centers. Thus, in the center of this CA, there is what they call the CBD that elongates from east to west, then the rest of the CA elongates to the north and south of the CBD and which turns into three corridor-like shapes situated along main roads of the city. According to the results, there are eight areas that may qualify as sub-centers. Considering only formal employment, the areas identified as CA, including adjacent corridors and CBD, account for 10.9 per cent of the metropolitan area and hold 53 per cent of formal Jobs, while considering informal employment the area correspond to 21.5 per cent and the share of Jobs reach 70 percent. There are no specific data about what they call CBD probably due to is considered only as inner node in the complete CA. It is concluded that Mexico City has a hybrid, although still predominantly monocentric, urban form, the CA is considered as a dispersed center.

Casado (2012) using the concept of local labor markets (LLM), and the HODS07 travel survey set two basic criteria for urban cores, i.e. number of resident workers and the degree of self-contained. Using a specific algorithm designed to delimit self-contained areas, he identified 12 LLM, the most important called Zócalo (historic center) contain 55% of the metropolitan employment, inside this the author identify a great CBD that include the central city and an

extension to certain north-south axis and east-west axis. The rest of the subcenters locate close to that CBD which reinforce the centralized structure of the MCMA.

Montejano, Caudillo & Silván (2016) examine Mexico City's urban structure based on land use data, specifically they proposed a composite index by combining the Reach centrality measure (derived from the Urban Network Analysis tool in the ArcGis toolbox), that specifically measure how many destinations each point reaches within a given network radius, with an Entropy Index which represents the mixed land-use degree. They use disaggregated data at buildings level as units of analysis (using only economic units with 11 or more jobs per unit). For all points in the system the proposed Composite Centrality Index (CCI) range from 0 (less centrality) to 1 (more centrality), based on assigning more importance to the entropy variable. They conclude that despite the signs of an emergent polycentric structure in both the MCMA and CDMX, it seems to be in its first stages, mainly because of a lack of formal jobs in those subcenters and because of a considerable size difference between them and the CBD.

Over the last three decades research has been devoted to assessing the MCMA urban structure that began with the monocentric model, but the debate has now been directed towards determining the extended polycentricism that has emerged. As we can see there is a consensus for considering the polycentric evolution of the MCMA and even though it is in its early stages, this is being undertaken using the employment-resident ratio (Suárez and Delgado, 2009), the trips-flow approach (Casado, 2012), and the land use approach (Montejano, Caudillo and Silván, 2016). The sub-centers identified by Aguilar and Alvarado (2005) are mostly contained within the identified formal CA in Suárez & Delgado (2009), in the same way Casado (2012) state that that general speaking all subcenter are similar to those found by Suárez & Delgado (2009), with some minor differences given more restrictive criteria and a broader geographical scale. Thus, we can

conclude that most of the subcenters found in seminal research in the polycentric evaluation of the MCMA have been considered in subsequent research as corridors and extension of the central area, while the appearance of more external cores depends in great extent on the point of reference for which the analysis was based.

It is important to know the area delimitation of this very influential CBD in MCMA. In the same way with the methodological difficulty to define sub centers, fixing the spatial boundaries of a CBD is also an arbitrary exercise. In the case of MCMA there is no any official delimitation of its CBD, research also produce different delimitations according to the methodological approach. Thus, for example if we take the four municipalities commonly considered as the central city, we have 139.48 km². Taken Casado (2012) approach CBD is defined by 19 HODS07 TAZs which correspond to a 121.50 km². According to the analysis of Suarez & Delgado (2009) the 10.9 per cent of the CA (adjacent corridors and CBD) for formal employment represent an approximate of 134.04 km², while for informality 21.5 per cent represent 264.4 km², in this case they don't give statistics and definition of what they strictly call CBD probably because adjacent corridors are a direct extension of this.

Comparing urban structures among cities can be difficult given the variety of contextual features that impede a general standard for benchmarking. However, if we take a look at the empirical evidence it can be notorious that what is conceptualized as the CBD in MCMA is a relative huge area where instead of subcenters emergence across the metropolitan area what we see is a centrality that grow scattered along main highways. For example, Glendening K. S. (2012) with the goal to delimit the center of Los Angeles use a score under the union analysis array, the analysis was also performed on two cities with widely-acknowledged centers as controls: Chicago and New York. According to him the central area in Los Angeles, commonly considered

polycentric, under the union analysis is 94 km² in area, significantly larger than either Chicago's or New York's central areas: 25 km² and 51 km² respectively. Thus, the Los Angeles metropolitan area is about twice as populous as that of Chicago but its central area is nearly four times as large in area, New York's metropolitan population is significantly larger than Los Angeles's despite its smaller central area. The greater area of Los Angeles's center indicates less concentration of amenities in Los Angeles. Glendening K. S. (2012) analysis is a loose estimation of Los Angeles CBD that includes not only the downtown but a corridor that goes from here to Santa Monica. Even a conservative estimation of the central area in the MCMA is 121.50 km² (Casado, 2012), which is approximately 27 km² larger than the Los Angeles central area and 2.5 times larger than the central area of New York City (Glendening, 2012), this latter a city with similar population. In terms of the metropolitan share of employment, MCMA's Central Business District identified by Casado (2012) includes 32.7 % of the metropolitan employment, which is superior to the employment share of the Central Business Districts in New York City, which in 2000 was 21.2%, and that in Los Angeles was 13% (Lee, 2007).

The influential but dispersed central area in the MCMA could be said to have two effects on metropolitan accessibility, one being that economic activity is not as agglutinated and concentrated as it would be in a contained focal area. The other is that, regionally speaking, the MCMA is an extremely large and powerful central area, which signals a lag in the economic conditions of peripheral metropolitan areas, a typical situation in the developing world. This latter is part of an exacerbation of socioeconomic segregation between the center and the periphery (Monkkonen, 2012). There is a consensus that in comparison with the decentralization of residencies, the corresponding decentralization of employment has been much slower, and this has

caused a continuing demand for commuting to work from the periphery to the central area (Suárez, 2007; Suárez and Delgado, 2009; Casado, 2012).

Figure 1.5 shows the metropolitan geography of possible determinants of observed commuting patterns. Based on 2010 census data, indicators are calculated at aggregated level of HODS17-TAZ. These indicators are: Employment density (trips to work attracted per TAZ/ha), EAP density (Economically Active People/ha), Marginalization index (higher value means greater socioeconomic deprivation) and Percentage of households owning a Car (Households with at least one vehicle per TAZ/Total households per TAZ). Employment density, as noted by previous studies, remains highly centralized, with some emerging peripheral centers still in their early stages. In addition to few central TAZs with high concentration of employment opportunities, the international airport is also an area of high concentration of employment; however, there are ongoing plans to move the airport out of the metropolitan area, to the northeast of its actual location.

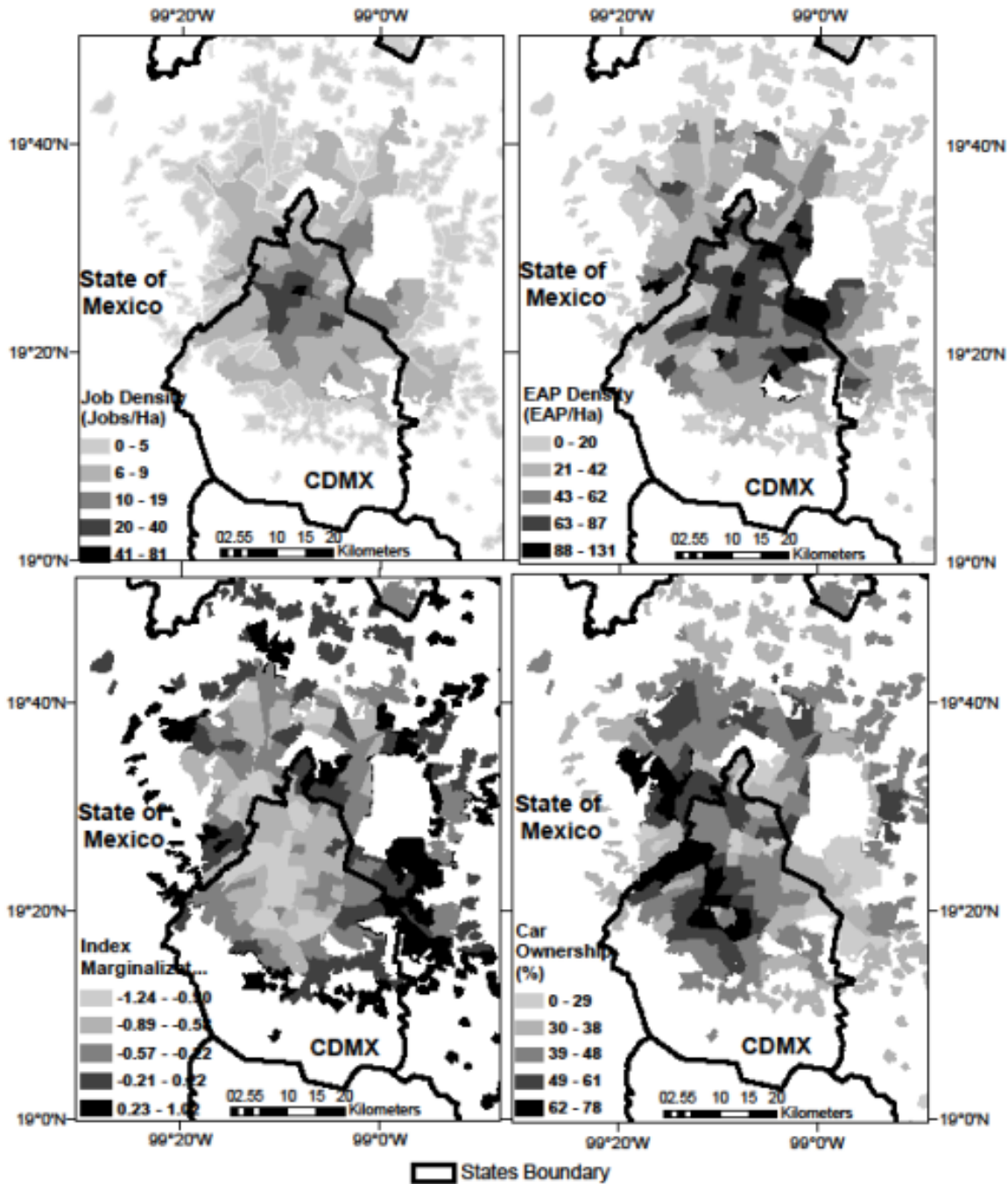


Figure 1.5. Socioeconomic geography in the MCMA at HODS17-TAZs level.

Geographic distribution of Employment density (trips to work attracted-top left), EAP density (top right), Percentage of households owning a Car (bottom left), Marginalization index (bottom

right). Source: Authors' calculations using data from INEGI (2010). Map classes are defined using Natural Breaks (Jenks) classification.

1.5 DISSERTATION STRUCTURE

This dissertation is structured into five chapters, the first is this introduction which includes a statement of the motivation of the study, the conceptual framework, the general research goals as well as an overall description my case study. Chapters 2, 3 and 4 are closely-related empirical studies, below there is the description of each one. Finally, in Chapter 5 there is a summary of the main findings of this dissertation, remarking the contributions in the state of the art of the knowledge of these urban processes in MCMA. Furthermore, policy implication and possible future research lines are discussed.

1.5.1 *Chapter 2: Location based Accessibility in MCMA*

In Chapter 2 a location-based accessibility assessment is taken for the MCMA which offer new insights about this urban process in the metropolis. The unit of analysis is the Traffic Analysis Zone (TAZ) delimited in the Household Origin-Destination survey (HODS17), which will allow intra-metropolitan comparison of accessibility and the identification of transport disadvantage condition at a geographical resolution close as possible to neighborhoods. Furthermore, splitting the analysis by transportation mode will allow accessibility comparison by these means.

1.5.2 *Chapter 3: The effect of Accessibility on ACT*

In Chapter 3 one-way Average Commute Time geography in the metropolis is analyzed to determine the extent of unequal travel experiences, then the effect of the urban structure through the previous accessibility indicators is explored. Together with the accessibility analysis, it is expected to identify specific zones where commute entail an excess burden and where public policies should be directed.

1.5.3 *Chapter 4: Individual Level Analysis*

In Chapter 4 an individual-level analysis is taken to determine activity patterns of commuters analyzing their travel routes. A link is explored with the previous area-based accessibility on activity patterns of commuters, which can give preliminary insights of social impacts of transport disadvantage conditions.

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Chapter 2. DIFFERENCES OF JOB ACCESSIBILITY AMONG FORMAL AND TOTAL EMPLOYMENT AND AMONG CAR AND PUBLIC TRANSIT IN THE MCMA.

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Abstract

The present project studies the pattern of spatial variations of employment accessibility in the Mexico City Metropolitan Area. The question is to assess differences in employment accessibility according to the transportation mode (Car or Public Transit) used and between the formal employment sector and total employment (formal + informal sectors). I explored two indicators: gravity-based job accessibility and the indicator developed by Shen (1998); and two data sources of travel time: the 2017 Household Origin Destination Survey and the region's travel demand model TRANUS. The resulting accessibility landscape was compared with the urban structure cited in the literature. Results show that the areas with the highest employment accessibility are within the central agglomeration and the associated corridors along main highways at its perimeters, according to the urban structure reported by Suárez and Delgado (2009). Total employment greatly increased employment opportunities, thereby increasing accessibility. Commuting by Car reduces travel time, and although this increases accessibility overall, the increase is negligible when comparisons are made with the increment of accessibility between formal and total employment or with the difference between the higher and lower ends of job accessibility by public Transit in the Traffic Analysis Zones. These comparisons have shown that as opposed to travel time, locations of residence and employment were the primary factors affecting access to employment.

2.1 INTRODUCTION

Transportation planning has been changing to an employment accessibility-oriented paradigm in response to negative environmental and social externalities ascribed to the mobility-driven paradigm that predominated in the second half of the last century (Rode et al., 2014). Mobility approach focused into improve the levels of service of transportation infrastructure with a clear bias toward the private Car use. Conversely, accessibility while still recognizing the aspect of easiness of mobility in different transportation modes it also stresses the issue of land uses policies as a mean to decrease distances and/or times of travel. Thus, an accessibility indicator that include these two aspects, easiness of mobility by transportation modes and traveled times, works as an appropriate benchmarking of transport policies. Moreover, accessibility indicators have allowed to link transportation problems and important social policy issues such as urban poverty, unemployment, exclusion, etc. Under the new paradigm the issue of equity in transportation modes, along with socioeconomic and spatial dimensions, have become primary concerns on the agenda of accessibility planning (Jaramillo et al., 2012; Lucas, 2012). Assessing the benefits of transportation projects and policies based on improving employment accessibility (referred to hereafter as accessibility) in the metropolitan landscape has become a necessary practice (Foth et al., 2013), and to accomplish this, frameworks have been proposed to assess equity in terms of spatial and social disparities (Martens et al., 2012).

Commuting to work is the main source of intra-urban trips in many cities around the world, and is a key issue of urban transportation policy (Rode et al., 2014). Different metrics have been proposed to assess accessibility. However, it has been shown that some of these metrics produce

different geographic assessments, which has hindered the identification of the effect of unequal commuting experiences and of their relationship with other important aspects of social policy (Merlin and Hu, 2017). Thus, the development of proper metrics is essential to establish a link between the concept of accessibility and the development of urban policies and their implementation (Manaugh et al., 2015; Boisjoly and El-Geneidy, 2017). To establish this link, Shen (1998) developed an indicator that has proved to be robust in its application in cities with different spatial structures. In his methodology, Shen includes the competition for opportunities and travel times for Car drivers and public Transit (hereinafter Transit) users, unveiling important nuances in the patterns of metropolitan accessibility.

Using Shen's indicator it has been shown that in highly automobile-oriented metropolitan areas of the United States the number of accessible job opportunities is considerably lower for Transit users compared to those who drive Cars, by far outweighing any location advantage that residents living near the central areas of a city or in suburban sub-centers may have. Thus, although location is important, the key factor for low-income workers seeking job opportunities is their transportation mode (Shen, 1998). Kawabata and Shen (2007) state that to be able to make a systematic international comparison of the relationship between accessibility and commuting time, we first need to understand the nature of the commuting inequality between driving a Car and using Transit in metropolitan areas that have differing transportation systems and urban spatial structures.

Latin America encompasses vast socioeconomic inequalities where transportation systems are made up of both formal and informal schemes that must be evaluated in terms of their capacity to meet the needs of those who are socially excluded (Delmelle and Casas, 2012; Stanley and Lucas, 2008). Although specific urban form varies for different US cities (where Shen's indicator

have been widely used), there are some features that distinguishes MCMA from them. For example Firstly, there is a relatively high level of intra-metropolitan Transit ridership in MCMA, which is 66.51% of all trips, while 38.7% for trips to work in CDMX (Mexico City, formerly the Federal District), and 51.1% for trips to work in the rest of the municipalities (2017 Household Origin-Destination Survey (HODS17)). On the other hand, in US the average of Transit use was only 5.1% of all trips in 2011 (US Department of Transportation, 2011), whereas commuter Transit ridership in all US cities but New York, New Jersey and Philadelphia is lower than in CDMX (Gilbert 2017), additionally Transit ridership has fallen in many of the top 50 Transit markets (Mallet, 2018). Secondly, in MCMA there has been a process of urban sprawl driven by extensive migration from the countryside over the past century and residential decentralization of affluent areas due to the fear of the instability of infrastructures in the inner-city during earthquakes (Aguilar and Ward, 2003; Isunza and Soriano, 2008; Pradilla, 2016). Thirdly, comparing MCMA with other metropolitan areas of similar population size such as Los Angeles and New York, what is called the central area is a relatively large geographical area with a high share of the metropolitan employment which is an indication of this highly influential inner city in the jobs market. This issue will be taken up in more detail in the following section.

This research addresses a question that can be divided into two parts. In the first part I assess whether there are substantial differences in accessibility depending on transportation modes (Cars and Transit) and the differences between the formal sector and total employment (formal + informal). The strength of these differences was analyzed using two models of accessibility and two sources of travel-time data. The second part of the research question was to learn whether the accessibility geography resembles the urban structure reported in the literature.

Compared to previous research on accessibility in the MCMA, the present work incorporates three aspects that have not previously been approached in conjunction: 1) analysis at a more detailed geographical level instead of on the municipal level; 2) considering the demand side of the labor market; and 3) disaggregating travel-time data by transportation mode. According to Merlin and Hu (2017), all of these aspects are significant in achieving a realistic overview of accessibility.

2.2 LITERATURE REVIEW / BACKGROUND.

2.2.1 *Urban spatial structure and commute inequity*

The concept of urban structure refers to the spatial distribution of residencies and economic activities in a city. There have been contrasting views in academic scholarship as to the effects of urban structure changes on commuting ever since the seminal works in this debate appeared some 30 years ago. Since then, diverse evidence has been reported in the literature. For some, land use patterns play a fundamental role in determining travel behavior, and therefore associated initiatives should be applied to reduce congestion, air pollution, dependence on automobiles, and such issues as the ‘job-housing balance’ (Cervero, 1989; Cervero, 1996). On the other hand, some researchers dismiss the relevance of physical planning in favor of market-driven policies (Giuliano, 1991). In the US, a parallel research field on accessibility has incorporated the study of what is called a ‘spatial mismatch hypothesis’, which, according to Kain (1968), shows that the distribution of employment for African-Americans, most of whom live in central urban areas, is affected by segregation in the housing market. This reduces the number of accessible employment opportunities available to them, and employment suburbanization aggravates the problem. Research results are disparate, both supporting and contradicting this claim. The varying and inconsistent manners of operationalizing the urban structure could be the source of this

disagreement (Gobillon et al., 2007; Grengs, 2010; Ong and Miller, 2015). Given that transportation disadvantages can arise from various factors (location, transportation system, individual characteristics, etc.), authors such as Grengs (2010) claim that these debates should be reconceptualized with the inclusion of the concept of accessibility.

2.2.2 *Location-based accessibility and metropolitan inequities*

In this paper I follow the definition of accessibility given by Merlin and Hu (2017) as the measure of the ease in reaching employment opportunities distributed across distances from different residential locations. Geurs and Wee (2004) argue that accessibility has four elements that are theoretically important for such a definition – land use, transportation, time and individual characteristics – and that the concept of accessibility involves an irreducible relationship between these elements. Geurs and Wee identified four basic perspectives of the measurement of accessibility: infrastructure-based, location-based, person-based and utility-based. Of these categories, location-based indicators represent the most appropriate manner of measuring intra-metropolitan variability, often at the Traffic Analysis Zones (TAZ) level, because these allow for a clearer understanding of the role of location as a causal factor in the formation of disadvantageous transportation patterns (Farrington, 2007). With an accurate knowledge of the spatial patterns of accessibility researchers could contribute to the design and implementation of improved accessibility programs that are often based on location (Shen, 2000).

The Shen (1998) equation is a location-based indicator that takes into account primarily land use and the transportation aspects of accessibility. Land use is taken into account by considering the urban geography of employment opportunities, while the transportation aspect involves an assessment of travel-times that sums up the existing transportation alternatives of a

certain location. When disaggregating data by travel mode (Car or Transit), location-based indicators provide insights into the relative importance of each travel mode in an urban spatial structure (Kawabata, 2009).

A common approach for measuring accessibility is the gravity-based model, which was initially developed by Hansen (1959). This model involves calculating the number of job opportunities available depending on a given travel cost that includes travel distance and time. In its initial form, this simple model lacks two aspects that are rarely considered in the literature: 1) the incorporation of both the supply and demand sides of the labor market and 2) disaggregation by travel modes. Shen (1998) addressed these limitations, and his solution yields fruitful insights, because jobs and workers are not equally distributed within metropolitan areas, and differentiating between Car and Transit users provides very different images of accessibility. In US cities this index has shown that, when compared with workers living in the suburbs, less educated workers living in the central urban area are not significantly disadvantaged with respect to accessibility.

There is strong evidence that suggests that commuting by Car largely determines the accessibility to jobs; thus, not having a Car for commuting can be a major barrier to participation in economic activities (Shen, 1998; Kawabata and Shen, 2007). This evidence suggests that the inequality in accessibility between Car and Transit users is particularly acute in low-density, highly automobile-oriented urban spatial structures. In cities such as Hong Kong and Tokyo with high population densities and substantial Transit coverage, accessibility has been found to be much higher for Transit users than for Car users (Kwok and Yeh, 2004). Kawabata and Shen (2006) also found that accessibility for Transit users is much lower in US Car-oriented cities like Boston and Los Angeles than in Tokyo.

2.2.3 *Previous location-based methods for job accessibility assessment in MCMA*

Suárez and Delgado (2007) used the gravity-based model with an inverse power impedance function for the distance network at the municipality level, and accounted for the labor demand (disaggregating the data by sector of occupation and income level) by considering the proportion of each population group living in each tract, but without considering the possibility of people commuting from other parts of the city to compete for the same jobs in a given tract. Caudillo (2017) used a variation of the gravity-based accessibility indicator applying the squared inverse distance as an impedance function at the census tract level. He tested two different measures of distance (Euclidean and Manhattan), but his methodological approach did not consider the demand side. In these two examples the general pattern of accessibility in the MCMA shows only slight differences from the previously reported highly concentric pattern of the employment geography in the MCMA.

Casado (2012) and Suárez and Delgado (2007) used a trips-attraction capacity approach at the TAZ level aimed at assessing the urban structure, and with this it is to be expected that assessing accessibility also based on travel data will result in finding similarities within such an urban structure. In other words, it could be interpreted that the accessibility landscape has a direct effect on in such an urban structure. However, it is important to point out that under the conceptual framework of accessibility, an accessibility-rich area is not necessarily an urban employment core if travel time is sufficiently short.

2.3 RESEARCH OBJECTIVES AND HYPOTHESIS

Objectives

- To determine job accessibility using travel time as impedance factor and compare two methodologies to evaluate the robustness of the outcome
- To determine differences in job accessibility between to employment data sources (formal and total) and between two transportation modes (Car and Transit)
- To compare the accessibility results with the reported monocentric urban structure in the MCMA

Hypothesis

- The Shen's indicator of job accessibility will have more consistent results than the basic gravity-based model
- In the interplay of travel time and land use as determinants of job accessibility, it is expected that in MCMA this last factor will be more important being the difference in job access more prominent between employment data (formal and total) than between transportation modes.
- Proving land use as main determinant of job access, it is expected that the resulting access landscape in the MCMA will be similar to the monocentric dispersed structure.

2.4 METHODOLOGY AND DATA SOURCES

2.4.1 *Data*

HODS17 split the MCMA into 194 TAZs, and this geographic scale is used for the present analysis. Four types of data are needed for the expected accessibility estimation. Firstly, using time matrices by transportation mode (Car or Transit) that captures travel times between each pair of TAZ are key inputs. Thus, for travel-time matrices I used two data sources. One was the HODS17 that provides time information for 64,494 intra-metropolitan work trips, and based on these data, two matrices (one for Car and another for Transit) were extracted using the factor expansion to weight each trip as a representative sample of its corresponding TAZ. However, not all cells from the 194x194 matrix were filled, so estimations for the empty cells were constructed using a simple regression model of time versus distance to the centroid for each HODS17-TAZ. The reason for using travel-time matrices is that they reflect the intra-metropolitan differences in the levels of service of the transportation infrastructure for both Car and Transit, thus using a specific time-distance relationship for each TAZ was used to capture such location transportation characteristics. This can be considered to be a time-distance hybrid approach.

The other source of trip-time information was obtained from the region's travel demand model, TRANUS (model 2013, modeling date 25-02-2014) provided by the Institute of Policies for Transportation and Development (ITDP, 2014). The calibrated trip matrices include travel times at peak morning hours between the region's 978 TAZ; however, these times were applied to the HODS17-TAZ by associating each HODS17-TAZ with the TRANUS-TAZ that contains the HODS17-TAZ centroid in order to maintain congruency with the geographical unit of analysis selected for the present study. In the case of the peripheral HODS17-TAZ in which the geographic centroid did not lie in an urban area, I made a correction to place the point of reference in its

corresponding central urban area. I selected two matrices for this study, Transit and Car, and the two sources of travel times, HODS17 and TRANUS, were used to check the consistency of the results. Therefore, I based the analysis of accessibility on four time-matrices: 1) Car time from TRANUS; 2) Transit time from TRANUS; 3) Car time from HODS17; and 4) Transit time from HODS17.

Secondly, the supply side of the jobs market is represented by employment data for which two approaches were followed, one for formality and the other for total employment (formal + informal). In the case of the formality approach, I got the data from the TEPA database provided by the Mario Molina Center for Strategic Studies on Energy and the Environment (2016) that contains the estimated number of jobs per block. These employment data are estimations based on the number of economic units reported in the 2013 economic census and the corresponding numerical range of workers in each of those units. I added the values of the TEPA database that lay within each of the HODS17-TAZ. Aggregating spatial data may introduce some errors in the spatial analysis (known as the modifiable areal unit problem), but the HODS17-TAZ included the smallest area units for which all the necessary data were available. In the case of the total employment approach, I considered total trips to work attracted to each HODS17-TAZ as a proxy of total employment, an approach used previously by Suárez and Delgado (2009), who estimate that economic informality represents over 40 per cent of total employment.

This work considers these two useful and feasible scenarios for job accessibility evaluation, formal and total employment. On one hand, total employment (formal plus informal) considers that all job seekers compete for all available job positions, this offers a first and general depiction of job accessibility. On the other hand, the second scenario considers accessibility only to the formal sector, it is assumed that these jobs are the priority for those job seekers, this scenario

represents the main objective of any urban policy aimed at integrate to the formality to all the labor force. I consider that to evaluate job accessibility only to informal employment (total employment minus formal employment) is an unreal scenario given that for all job seekers informality is not the first option, on the contrary it is assumed they go to informality once that the formal sector is no longer achievable due to a lack of opportunities. Moreover, if I consider evaluation of job access only to informal jobs, I would have to extract the share of the Economically Active People (EAP) available to match those jobs adding a difficulty the fact that some of them go back and forth from the informality.

Thirdly, I extracted the working population for each census tract from the 2010 census (INEGI, 2010) under the variable Economically Active People (EAP), this variable represents the demand side of the jobs market. The MCMA contains 5,648 census tracts; so, in this case I added the values of the 2010 census tracts that lay within each of the HODS17-TAZ. Finally, trips to work matrices that capture the commute flow between each pair of TAZ were extracted from the HODS17 in a similar manner as that used for time matrices.

2.4.2 *Employment Accessibility*

I estimated two accessibility measurements: the gravity-based model (GBM) and the Shen indicator. The gravity-based indicator is modeled with a negative exponential impedance function:

$$A_i = \sum_j E_j f(C_{ij}) \quad (2.1)$$

Intra-zonal travel time was assumed to be 0.7 times the minimum travel time observed for each TAZ. The travel impedance function is specified as $f(C_{ij}) = e^{-bC_{ij}}$, where b is an

empirically determined parameter. Based on an ordinary least squares (OLS) regression (log of trips to work vs travel time), the estimated value for TRANUS time matrices was -0.4 (TRANUS time was converted into minutes) and the value for the HODS17 matrices was -0.01. Thus, TRANUS b parameter is 40 times higher than for HODS17, this means that accessibility estimations of TRANUS will be always higher than the accessibility counterpart for HODS17. It is expected a difference in this parameter since time data was obtained with a different approach in both types of matrices. TRANUS provides travel times based on a transportation model which use information inputs of several sources not only from travel surveys but also use levels of services of transportation infrastructure. On the other hand, HODS17 represent average observed traveled times from each recorded trip in the survey. For our analysis of accessibility this is not necessarily an issue when comparing results between both matrices given that for this aspect, I am not comparing absolute values but the pattern of relative differences among TAZs, i.e. the ranking of inter TAZs accessibility. In the next section there is an explanation of this.

The approach of assessing accessibility using the formula developed by Shen (1998) is a variation of the Hansen Accessibility Index. This indicator captures the ‘demand side’ of accessibility, that is, the spatial distribution of workers. The final equation is as follows:

$$A_i^{auto} = \sum_{i=1}^j \frac{E_j f(C_{ij}^{auto})}{\sum_k [\alpha_k W_{kf}(C_{kj}^{auto}) + (1-\alpha_k) W_{kf}(C_{kj}^{transit})]} \quad (2.2)$$

$$A_i^{transit} = \sum_{i=1}^j \frac{E_j f(C_{ij}^{transit})}{\sum_k [\alpha_k W_{kf}(C_{kj}^{auto}) + (1-\alpha_k) W_{kf}(C_{kj}^{transit})]} \quad (2.3)$$

Where E_j is the number of relevant employment opportunities in location j ; A_i^v is the accessibility available for people living in location i and traveling by mode v ; C_{ij} is travel time from i to j ; W_{km} is the number of people living in location k and traveling by mode m to seek the relevant job opportunities; $f(C_{ij}^v)$ and $f(C_{kj}^m)$ are the impedance functions for transportation modes v and m , respectively, which measure the spatial separation between i and j , and k and j , respectively. For an urban or regional system with M transportation modes, $v, m = 1, 2, \dots, M$, and k locations, $k = 1, 2, \dots, N$. The travel impedance parameter is the same than the used for GBM.

The general accessibility index proposed by Shen (1998) is as follows:

$$A_i^G = \alpha_i A_i^{auto} + (1 - \alpha_i) A_i^{transit} \quad (2.4)$$

Where A_i^G is the general accessibility for all groups of people living in location i ; α_i is the percentage of households with Cars in location i . In this case I used the actual percentage of commute trips by Car in each TAZ according to the HODS17. The number of workers corresponds to the EAP, while jobs were estimated based on the total of jobs available in all economic sectors. The inequality in accessibility between Cars and Transit in zone i (X_i) was calculated based on the following equation (Kwok and Yeh, 2004):

$$X_i = \frac{A_i^{car} - A_i^{transit}}{A_i^{car} + A_i^{transit}} \quad (2.5)$$

Equation (5) standardizes the difference between accessibility by Car and accessibility using Transit in a range from 0 to 1. The inequality in accessibility increases as the disparity measure approaches 1.

The population-weighted regional averages of accessibility by Car (A^{car}), accessibility by Transit ($A^{transit}$), and the disparity of accessibility between using Cars and Transit (X) were calculated as follows (Kawabata, 2009):

$$A^{car} = \sum_{i=1} \left(\frac{W_i}{W} \right) A_i^{car}, \quad A^{transit} = \sum_{i=1} \left(\frac{W_i}{W} \right) A_i^{transit} \quad (2.6)$$

$$X = \frac{A^{car} - A^{transit}}{A^{car} + A^{transit}} \quad (2.7)$$

2.4.3 Comparisons of job access evaluations

Thus, there are four basic aspects of comparison in this evaluation of job accessibility in MCMA. These are between sources of travel time data (Tranus vs HODS17), between methods (Shen vs GBM), between type of employment data (total vs formal) and between transportation modes (Car vs Transit) (Figure 2.1). Note that when doing each comparison, the rest of the aspects are kept constant. In the first two, absolute values of accessibility are not comparable. Both sources of travel time data followed different approaches in gathering the data, modeled times from TRANUS tend to be higher than HODS17 times for the travel among every TAZs pair. Likewise, GBM and Shen's type equations have different units as well as upper and lower limits. For this reason, when comparing job access results between sources of time data or between methods the objective is to

determine the consistency and robustness of the results in base of the job access ranking among TAZs. Thus, the Spearman Rank Correlation (SRC) is the appropriate indicator to check the consistency in the accessibility estimations. For example, a value close to 1 when comparing job access results between the two sources of travel time data would mean that the method is consistent and robust regardless such different sources of travel times data, which would be a desirable outcome. Moreover, a value close to 1 when comparing job access results between methods would mean that the job access estimation is convergent, here there is not any a priori expectation for some value, however when looking the variation of such indicator through other aspects of comparison can give us insights of how the accessibility estimation of each method is affected and therefore tell us which methods is more informative.

Then, in the other two aspects of comparison (Total employment vs formal employment; Car vs Transit) absolute values and rankings of accessibility are relevant. These two aspects represent direct variables embedded in both accessibility equations and therefore offer insights about how these factors impact accessibility. Overall, the purpose of analyzing the importance of these variations was to select those estimations with the highest consistency between travel-time sources but included further differences according to employment-type data and transportation modes. This information offers insights into the nuances of these aspects in the disparity of intra-metropolitan accessibility.

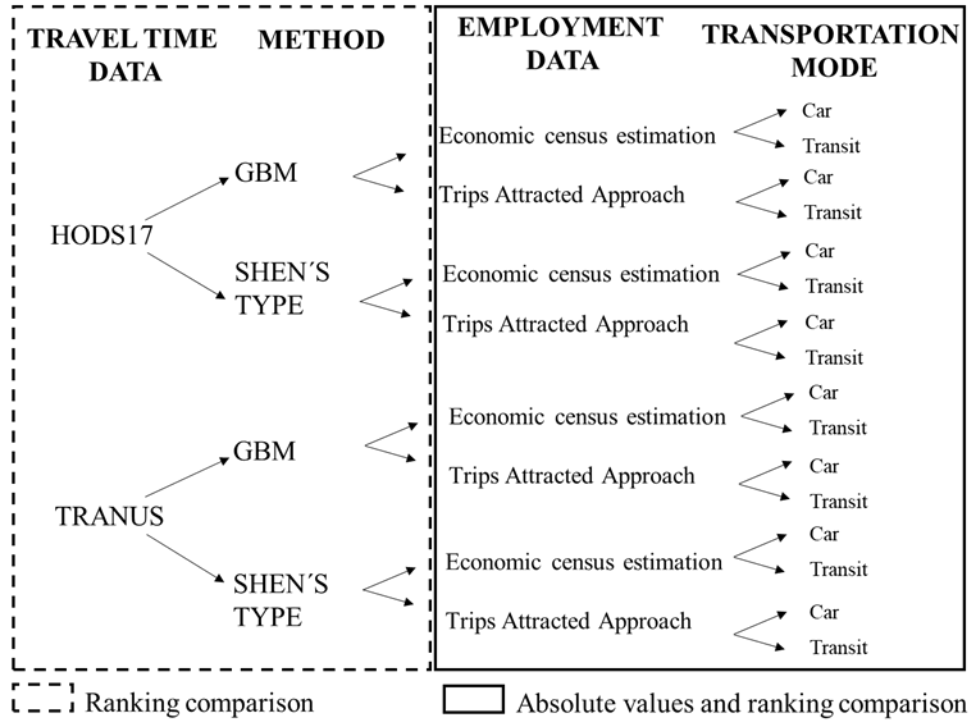


Figure 2.1. Four aspects of job accessibility comparison

2.5 RESULTS AND DISCUSSION

Spearman Rank Correlations can be seen in Table 2.1. This section presents the main findings by methods, starting with GBM.

Table 2.1. Spearman rank correlations between different estimations of accessibility according to the method, travel time source, employment data and transportation mode.

Comparing	Accessibility Method	
	GBM	Shen-type
Travel time source (TRANUS vs HODS17)	0.56 (For-Car)	0.76 (For-Car)
	0.69 (For-Tra)	0.81 (For-Tra)
	0.64 (TA-Car)	0.80 (TA-Car)
	0.74 (TA-Tra)	0.83 (TA-Tra)
Employment data (Formal vs Total)	0.97 (HODS17-Car)	0.97 (HODS17-Car)
	0.97 (HODS17-Tra)	0.97 (HODS17-Tra)
	0.99 (TRANUS-Car)	0.97 (TRANUS-Car)
	0.99 (TRANUA-Tra)	0.99 (TRANUA-Tra)
Transportation Mode (Car vs Transit)	0.71 (HODS17-For)	0.99 (HODS17-For)
	0.78 (HODS17-TA)	0.99 (HODS17-TA)
	0.92 (TRANUS-For)	0.91 (TRANUS-For)
	0.91 (TRANUS-TA)	0.92 (TRANUS-TA)

Note: In parenthesis are the constants in the comparison. (For: Formality employment data; TA: trips attraction capacity approach for total employment; Car: Car time; Tra: Transit time).

Gravity-based model maps show an important variation in the patterns of accessibility, this can be showed with the comparative lower values of spearman correlation in the GBM than in Shen's type in the comparison between travel time sources (Table 2.1). However, total employment gives more consistent accessibility results between travel-time sources than does formal employment, with a correlation coefficient of 0.64 for Car and 0.74 for Transit. The GBM estimations using the HODS17 data offers slightly larger accessibility differences (0.97 SRC) between employment data in comparison with estimations using TRANUS (0.99 SRC). Thus, gravity-based models using the HODS17 database and total employment are presented in Figure 2.2.

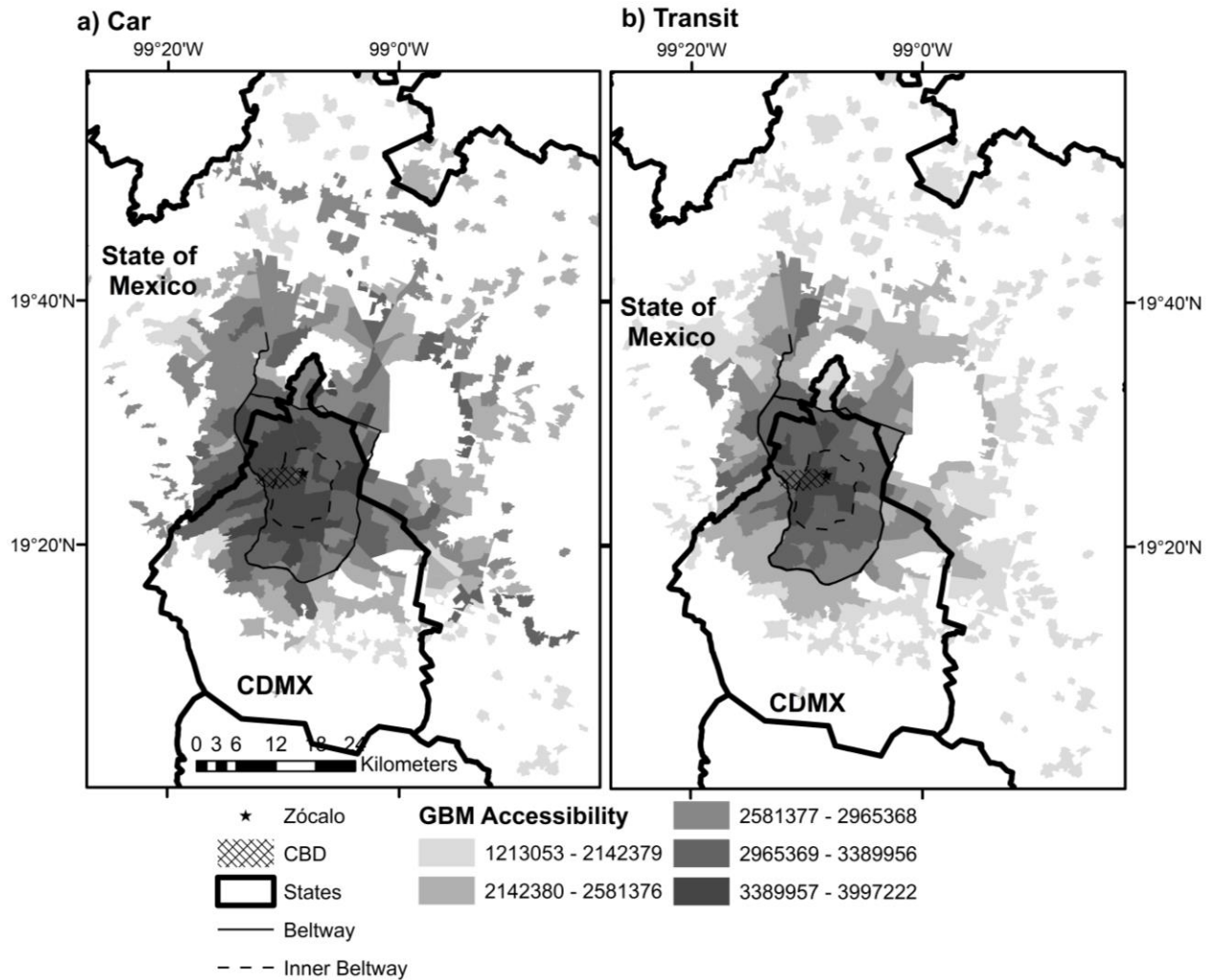


Figure 2.2. Accessibility with the GBM using the HODS17 database, accounting for total employment and both Car (a) and Transit (b).

Accessibility by Car expand areas with the highest category outside the beltway (Figure 2a), while for Transit areas with this highest category remain mostly within the beltway polygon (Figure 2b) because of the prominent subway transportation system coverage in the inner city, as well as its high concentration of opportunities. Central areas in the west side within the beltway polygon have the highest accessibility values with the GBM since this model focuses on the supply side of the jobs market, therefore jobs-rich areas have the highest accessibility scores, then there

is a decrease toward jobs-poor areas in the periphery, this can be noticed for every GBM model (Figure 2.3 a). This negative relationship is not as clear as in the Shen's type model.

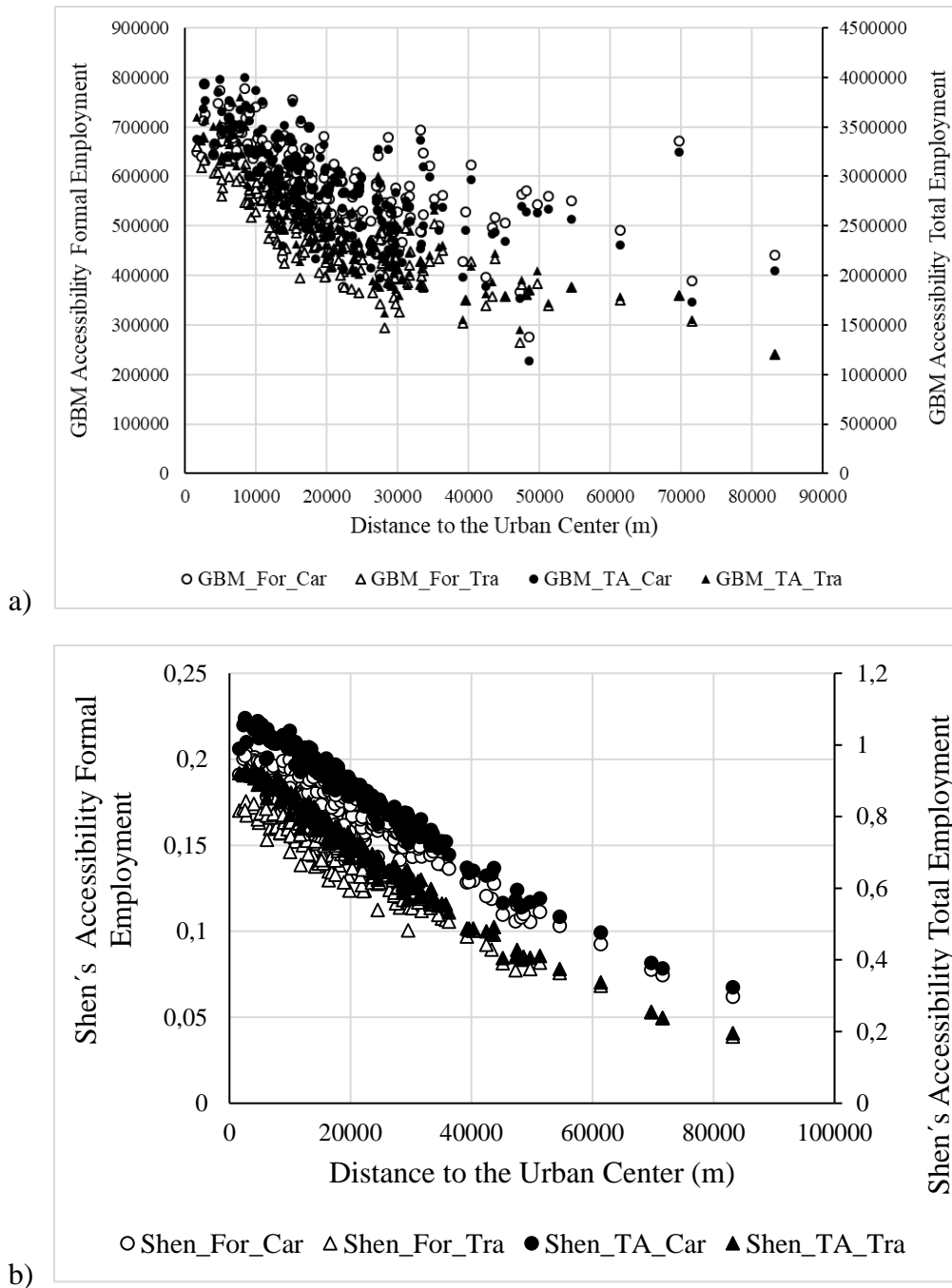


Figure 2.3. Accessibility vs Distance to the metropolitan center using the HODS17 database with GBM Accessibility (a) and Shen's type Accessibility (b).

(For: Formality employment data; TA: trips attraction capacity approach for total employment; Car: Car time; Tra: Transit time).

Overall, using the gravity-based model I find two main differences in accessibility according to the data used as input. Firstly, considering total employment considerably increases accessibility for all TAZ reflected in the magnitude of the accessibility indicator, however the spatial patterns (i.e. the ranking of the TAZ) is very similar, as we saw above. Secondly, with the TRANUS data accessibility is always higher for Car users over Transit users, but this is only generally true with the HODS17 data, because there are a few TAZ with no identifiable spatial patterns where accessibility is higher for Transit users than for Car users.

The Shen's indicator shows a more consistent spatial pattern of accessibility between travel-time sources with a Spearman Rank Correlation of 0.81 for formal employment accessibility and 0.83 for total employment accessibility (Table 2.1). This gives credence to the results of the Shen's indicator in which, unlike the GBM accessibility results we saw above, there was a lower correlation coefficient in the comparison between travel-time databases. With the Shen's indicator employment data was shown to produce little dissimilarities with a correlation coefficient of approximately 0.97. Likewise, with the GBM these coefficients were approximately 0.98. With regard to the differences in accessibility between transportation modes, when using Shen's indicator these are minimal, as we can see that the correlation indicator is 0.99 with the HODS17. For GBM the correlation indicator is 0.78 with the HODS17 and total employment. Using TRANUS the correlation indicators comparing transportation modes are very similar between GBM and Shen's indicator, with values of 0.92. With these findings, the first part of the research question is answered. Then, the details of these differences are described in conjunction with the

overall accessibility metropolitan landscape in relation to the urban structure, thereby addressing the second part of the research question.

The pattern of Shen's accessibility in relation to the urban center is a well-delineated line with a negative slope (Figure 2.3 b), showing the clear difference in access between the inner city and the periphery. There is no official delimitation of a specific Central Business District, but various authors refer to this as an area similar to the one represented in Figure 4, and from there it extends from north to south through Insurgentes Avenue in CDMX (Figure 5) in what Suárez and Delgado (2009) call a Central Agglomeration (CA). Then, extending from the CA we can identify what Suárez and Delgado (2009) call Adjacent Segmented Corridors (ASC), which are formed along the highways to Querétaro and Toluca. In Figure 4 the ASC is shown to correspond to areas extending into the State of Mexico from CDMX. The employment centers' polygon of the CA and the ASC as a whole (hereafter called CA polygon) is represented in Figure 2.4 for formal jobs (a and c) and for total jobs (b and d), the latter being a geographical extension of the first.

Overall, we can see that inside this CA polygon many of the TAZs with the highest metropolitan accessibility are located, which is consistent with any transportation mode and employment data. However, there are specific cases where this pattern is not followed. Using natural jenk breaks there are some TAZ inside the polygon with similar accessibility scores to some of those outside of the polygon, and this is more evident in the polygon that considers informality, principally those at the edge of the polygon. This means that some TAZ in the inner city could show medium accessibility regardless of their geographical inclusion in the polygon of the CA, probably due to factors such as a high workforce population that increases competition for opportunities, local problems of mobility caused by the urban structure, or infrastructure deficits.

In any case, these results help to identify such problematic areas so that local problems can be addressed.

Surprisingly, there are several TAZs outside the polygon that have similar accessibility by Car to those inside the polygon. Shen's indicator does not necessarily coincide with employment centers, for example areas with low employment opportunities do not necessarily have low accessibility if either the competition for those employment opportunities is not significant or if there is sufficient capacity for mobility with direct road connections for those driving a Car or efficient Transit connections for others.

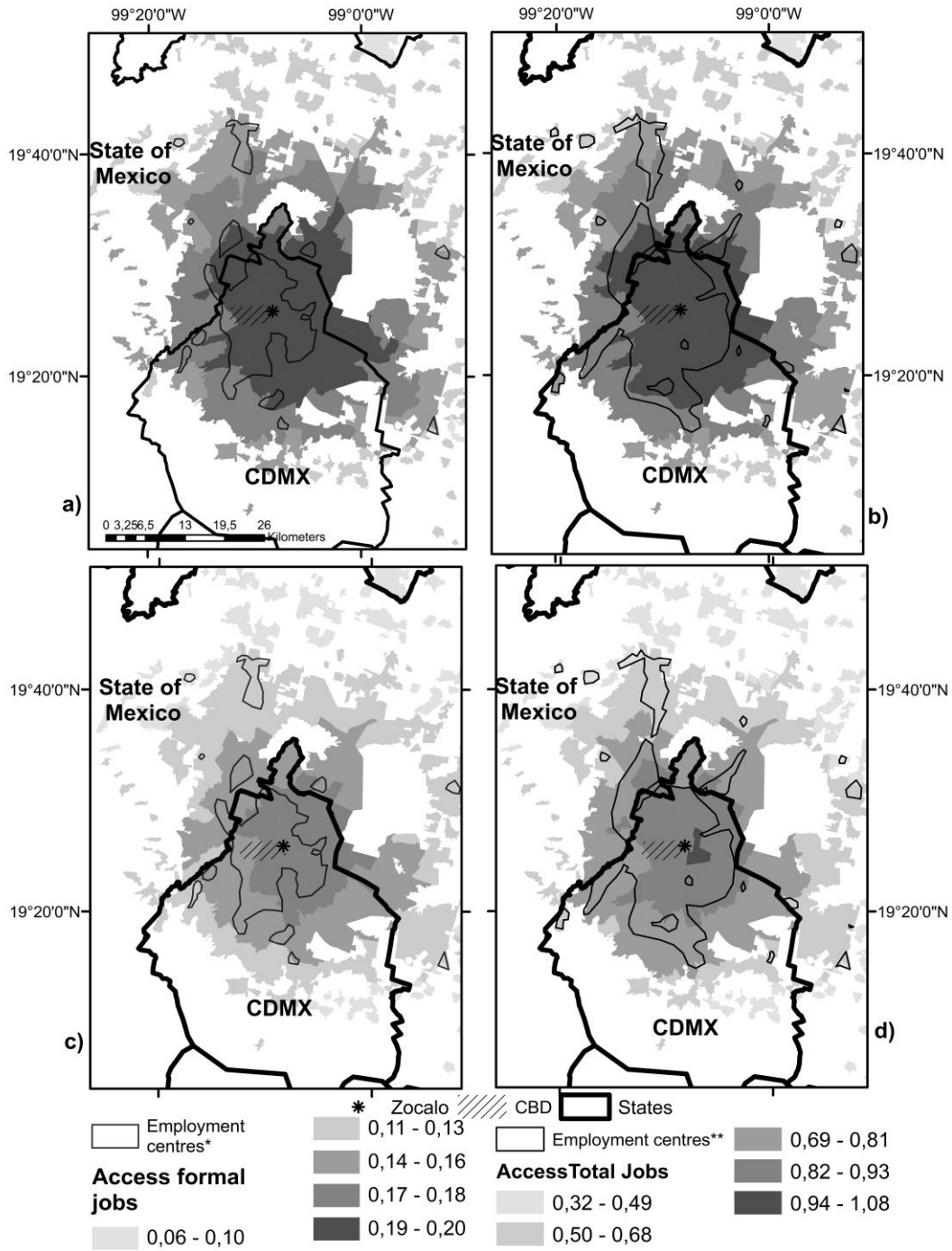


Figure 2.4. Shen-type models with HODS17 travel time data for formal employment by Car (a) and Transit (c) and for total employment by Car (b) and Transit (d). Note: *employment centres for formal jobs; **employment centres for total jobs

Using maps of the Shen's indicator, when informality is included this again is shown to be the primary factor in increased accessibility. Everything else being equal, accessibility by Car is higher than that for Transit, and none of the TAZ contradict this in any of the travel-time data sources employed (maps not shown). Regarding the effect of the time data sources, differences between accessibility by Car versus Transit (in favor of Car) are more prominent in the TRANUS database than in the HODS17 database, the gap being less in the HODS17.

Figure 2.5 shows the disparity in accessibility between Car and Transit for both HODS17 (b) and TRANUS (d). Overall, in central areas disparity in favor of Car usage is less than in peripheral areas, which is reasonable given that the main Transit infrastructure is concentrated in the central areas. In order to discuss the differences of accessibility by transportation mode and location I focus on the model that uses total employment, although similar arguments also apply to the model using only formal employment. Thus, the general disparity is only 0.09 in HODS17 and 0.18 in TRANUS (Table 2.2). It is useful to remember that the average accessibility in the region for total employment is the ratio between the number of jobs (total trips to work attracted 6,811,580) and the number of potential workers (EAP 8,966,847), which is 0.759. A property of Shen's indicator is that accessibility measures per TAZ and transportation mode are standardized, so this average can be taken as a reference for comparison, and the average of these indicators weighted by EAP should result in that same regional average, this relationship was demonstrated by Shen (1998).

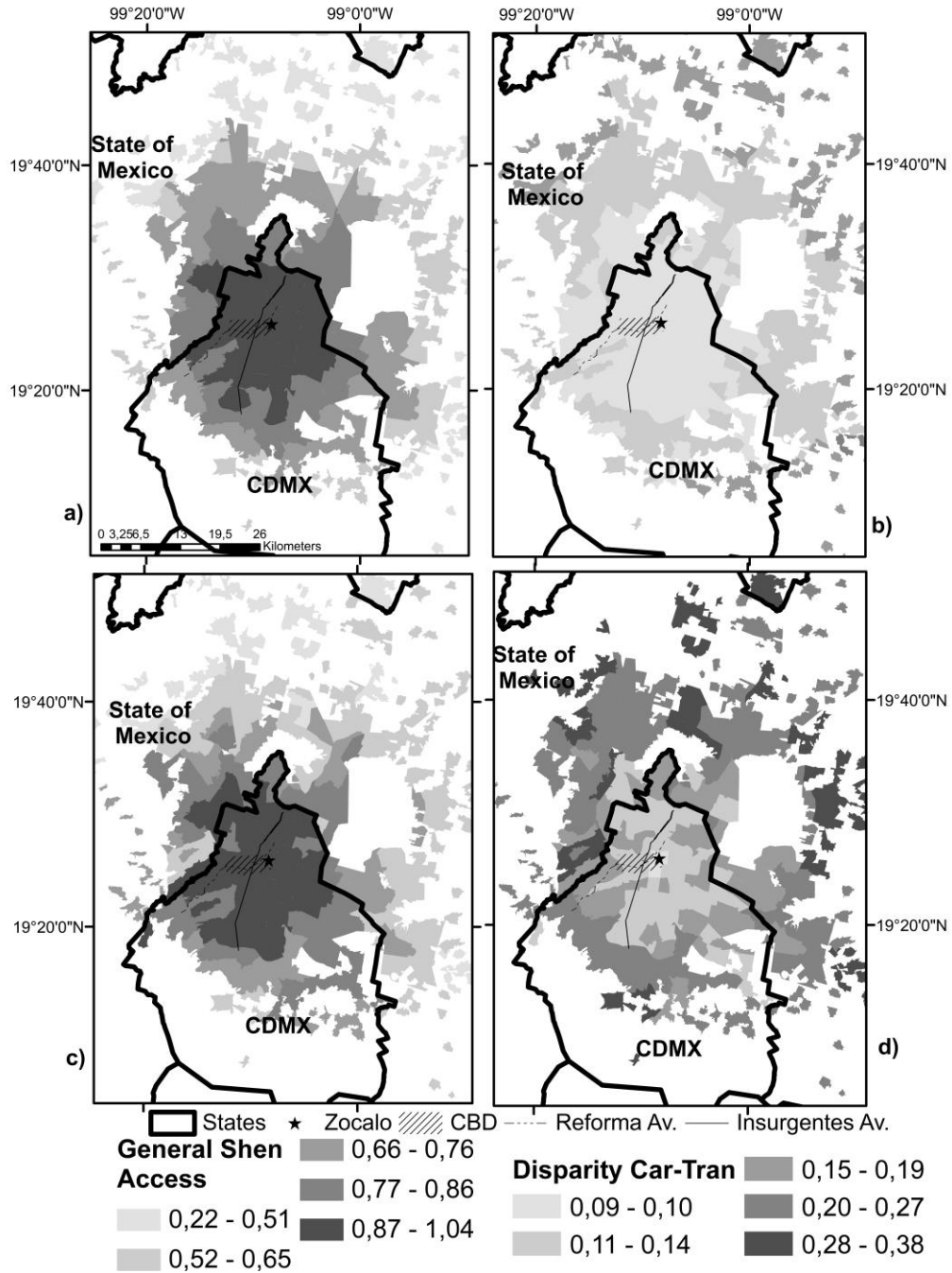


Figure 2.5. General Shen-type accessibility (left) using the HODS17 (a) and TRANUS (c) databases, and disparity in accessibility between Car and Transit (right) using the data of HODS17 (b) and TRANUS (d).

With the HODS17, Shen’s indicator for driving a Car goes from 0.32 to 1.07, while the range goes from 0.19 to 0.93 if using public Transit. Using TRANUS the ranges are a little narrower, being from 0.73 to 1.15 for Car drivers and from 0.34 to 0.94 for Transit users. For any TAZ the accessibility score is achieved primarily because of its location, since changing the transportation mode will impact the accessibility score only marginally, on average 0.18 (Table 2.2, Disparity index for TRANUS).

Table 2.2. Population-weighted regional averages of accessibility by Car (A_{car}), Transit (A_{tra}), and the general disparity of accessibility between Car and Transit (D).

Data source	A_{car}	A_{tra}	D
HODS17	0.88	0.72	0.09
TRANUS	0.99	0.69	0.18

In other words, accessibility for people living in the MCMA can be slightly greater if they drive a Car, however their real potential for getting to job sites depends on their place of residence in direct correspondence to their closeness to employment centres. Evidently areas near the main employment corridors have high levels of accessibility, leaving people that live increasingly further away from the CA at a greater disadvantage. This is contrary to the case of Car-oriented cities in the US where this same methodology demonstrated that Car accessibility outweighs any locational advantage (Shen, 1998). However, the MCMA doesn’t match the condition shown in some south Asian cities where it was found that accessibility is actually much higher for Transit users than for Car users (Kwok and Yeh, 2004), even when in the MCMA there are also large population densities and high Transit user rates. This reflects not only the inefficiency of the existing Transit systems in the MCMA but more fundamentally, the deficit in geographical coverage of mass Transit systems is apparent. The HODS17 reveals that in the central TAZ, where there are a number of subway stations, commute time by Transit is shorter than by Car, however

it is possible that when we move away from the CA the accessibility throughout the rest of the metropolis is greater for Car than for Transit.

The disparity between TAZ shows that the most opportunity-rich area has a General Shen's indicator (with HODS17) of 0.96 while the metropolitan average is 0.759, i.e. 26% higher. Therefore, the Shen's indicator shows important nuances of locational accessibility. Given that the core of the metropolitan area lies within CDMX, when making a comparison on a regional scope, the State of Mexico shows lower levels of accessibility. Many TAZ located in the State of Mexico are on the metropolitan periphery; however, those located on the eastern limit between the State of Mexico and CDMX have relatively good levels of accessibility. In CDMX, the areas that suffer from low levels of accessibility lie in the east and the south, with a small portion in the northern areas. If we look for the ten TAZs with the worst accessibility index and highest marginalization in both the State of Mexico and CDMX, priority areas are found (Figure 2.6), and for these, different strategies should be analyzed in conjunction such as public transportation investment and/or land use policies to encourage economic development in job-poor areas. These results offer straightforward area-level implications to guide the metropolitan transportation policy for planning how to mitigate locational disadvantages.

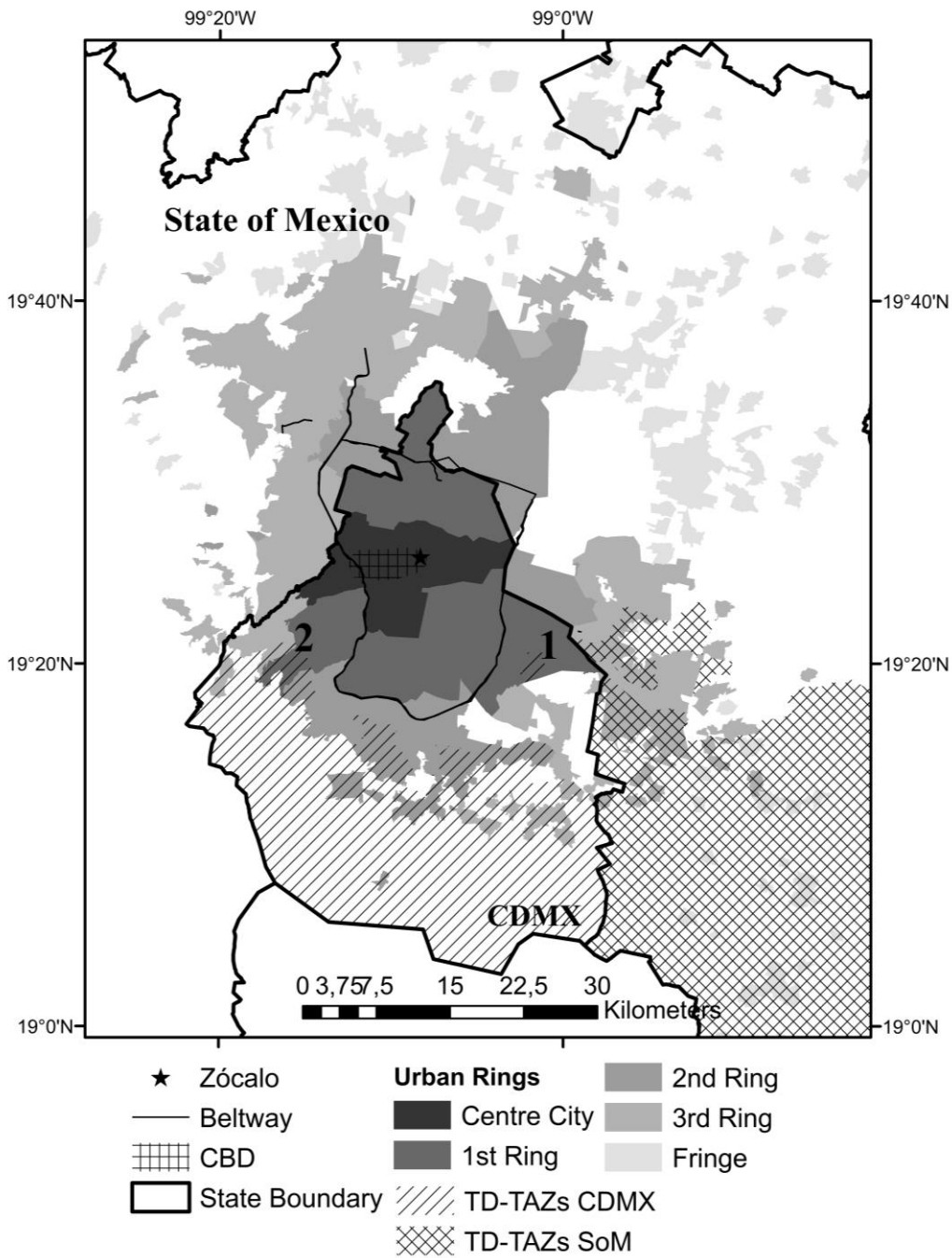


Figure 2.6. Potential priority areas for accessibility improvement, in the Southwest (1) and in the Southeast sides (2) of CDMX, both still in the 1st Ring.

2.6 CONCLUSIONS AND LIMITATIONS, FUTURE RESEARCH

My exploration of accessibility using the GBM shows an important variation in the Mexico City metropolitan pattern according to employment data, travel-time sources and transportation mode. As a general description, jobs-rich areas in the inner city have the highest accessibility with a decrease in accessibility with increasing distance from the urban center, however this negative relationship is not as clear as in the Shen's type model. This is an expected result with GBM since this model focuses on the supply side of the jobs market, i.e. employment urban cores are predominant areas of accessibility. Total employment increases accessibility and gives more consistent results between travel-time sources than does formal employment, probably due to the reinforcement of the role of land use in the estimation. Accessibility is always higher for Car drivers than for Transit users with TRANUS, while for HODS17 this remains true for the most part but with a few exceptions.

The Shen's indicator shows a more consistent spatial pattern of accessibility (spearman correlations close to 1) regardless of travel-time data and transportation mode with the HODS17, demonstrating the robustness of the method. In general, the spatial pattern of accessibility in relation to the urban center is a line with a clear negative slope. Again, as expected, the inclusion of informality increases accessibility. The Shen-type indicator allows us to see that Car user accessibility is slightly higher than accessibility by Transit, and the gap between the two using HODS17 data is less than that when using TRANUS data. This means that for any TAZ its accessibility score is achieved primarily because of its location. This disparity in terms of location means that accessibility in the TAZ with the highest accessibility record is 26% higher than the metropolitan accessibility average.

The policy implications of these results can be divided into three non-mutually exclusive approaches for improving accessibility: 1) developing affordable housing programs in job-rich areas, 2) intensifying investment in the subway system (While significant public-private investments have been made in the last few years to replace the informal bus-predominant transportation system with Rapid Transit Bus systems, although these systems have some merits they don't replace the need for mass-Transit systems such as subways), and/or 3) encouraging land use policies that attract and foster employment opportunities in location-disadvantaged areas (low accessibility levels) and in sub-developed corridors in high density population areas. Cervero (1996) explained in his seminal work how a considerable job/worker imbalance between communities creates the conditions for congestion problems, given the need for long travel distances, and he therefore argued for planning for more diverse communities. Controversy arose over this because critics against land use planning argued in favor of market policies for congestion relief. However, in the context of the MCMA many of the assumptions for such market alternatives cannot be realized, principally because mobility costs are a significant limitation in accessibility given that the rate of Car use for commuters is relatively low, 38.7% (HODS, 2017). Furthermore, the freedom to relocate to residences near workplaces is limited to a very small segment of the population who can afford to do so. The job/housing ratio clearly has limitations as a suitable indicator to guide transportation policy, as some of its critics have pointed out (Giuliano, 1991). I think that the Shen's indicator solves some of the important limitations of the job/housing ratio because distances, times, employment, residential geography and competition are explicitly integrated.

Decreasing distances to work for those workers who live in peripheral areas is also controversial. According to Guerra (2014), "households in low-diversity, inaccessible

neighborhoods are among the least likely to drive, but once they drive, they tend to drive a lot” (Ibid.: 13). Guerra states that policies encouraging suburban job accessibility, meaning reducing travel to work distances by increasing suburban job opportunities, would imply an increase of total Vehicle Kilometers Traveled (VKT) by encouraging a shift to Cars from other modes, which would thereby further endanger the urban traffic system. Thus, such a land use policy would be at odds with the environmental aim of reducing emissions from transportation in a metropolis with renowned problems of air pollution and traffic congestion.

Grengs (2010) has made a detailed analysis of this tradeoff between cleaner air and providing opportunities for the poor. His argument aims to change the terms of the debate by asking whether it is fair to require that poor people endure enormous disadvantages in terms of accessibility on behalf of the middle-class and the rich, who benefit not only from Car ownership and its mobility and accessibility but also would also benefit from improvements in air quality. In the case of the MCMA I can say that increasing local traffic at the expense of a decrease in regional mobility needs would certainly increase overall regional motor vehicular traffic but at the same would be a more equitable manner of distributing traffic costs.

Finally, it is important to point out two limitations that were encountered in this study that I suggest are worthy of further analysis. Of special importance is the precision of time matrices (Transit and Car), which should be properly calibrated and periodically assessed to allow for a longitudinal analysis of commute patterns in order to better identify transport-disadvantaged areas. I also noted that there are some remarkably contrasting differences in accessibility between contiguous TAZ. Some of these differences are well explained by the discontinuity of the local transportation infrastructure, which suggests that they would be priority areas for public investment; however, it is suggested that further studies should aim to recalibrate time matrices to

increase the validity of the data. It is further suggested that the metropolitan transportation agency (COMETRAVI) collect and maintain reliable information about all relevant aspects of transportation systems.

The other limitation I encountered in this study and suggest that should be considered in further studies is the reliability of the formal employment data, because the source that is presently available do not provide more than a rough estimate. This is suitable for representing the employment geography, but for an understanding of the specifics of employment it is limited. For example, for large economic units the estimation of jobs is based in the lower limit of the range recorded (i.e. over 250 workers or more), thus it is impossible to know the exact number of jobs in those units.

Another aspect that I suggest should be considered further is the possibility of analyzing accessibility by specific economic sectors, such as low-wage workers; unfortunately, no official data by job sector is currently available for the MCMA at the TAZ level. Having this information would be essential for an in-depth analysis of transportation disadvantages, and these should be properly understood as being the predominant objectives of the transportation policies in the MCMA in order to promote equality in accessibility.

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Chapter 3. COMMUTING INEQUALITY, ROLE OF URBAN STRUCTURE AND IDENTIFICATION OF DISADVANTAGED GROUPS IN THE MCMA.

Abstract

Cities in developing countries are undergoing a vigorous urbanization process marked by deep social and economic inequalities, which are reflected in transportation. This study analyzes one-way Average Commute Time (ACT) in the Mexico City Metropolitan Area, specifically regarding its spatial pattern in relation to the urban center, the differences between Cars and Public Transportation, and explores the drivers of its urban structure as well as the social dimension. Our results show that ACT is lower for Car drivers than for Transit users. The curve depicting the relationship between ACT and distance to the center differs between private and public Transit, being semi-flat for the former and an inverted U-shaped curve for the latter. There is a higher spatial correlation for Transit ACT than for Car ACT. Based on the results from OLS and spatial regression models, travel times from the transport model TRANUS show that job accessibility plays a significantly inverse role in determining ACT for Transit users and Car users alike. However, this response is not consistent according to observed travel times from the household travel survey. As regards population groups, migrants and indigenous populations display significantly longer commute times, especially when using public Transit, evidencing that these groups are in disadvantage.

3.1 INTRODUCTION

The study of the relationship between urban structure and commuting has produced a large body of research in the last few decades, driven primarily by concerns for the growth of negative social and environmental externalities involved in urban transportation. In the second half of the last century an academic debate began in the US over how land use affects travel behavior, including commute distances and times, and the extent to which minority groups have a locational disadvantage condition to access jobs. Costs of traveling are not homogeneously dispersed in the city having disproportionate impacts among localities and among different population groups, for this reason the concept of equity emerged as a key issue in urban transportation policy.

The debate about the relationship between the built environment and travel behavior contrast two main points of view. For some, land use patterns play a fundamental role in determining travel behavior, and therefore associated initiatives should be applied to reduce congestion, air pollution, and dependence on automobiles (Cervero, 1989; Cervero, 1996). On the other hand, some researchers dismiss the relevance of physical planning in favor of market-driven policies (Giuliano, 1991). In this context a consensus on the way urban structure influence commuting has been elusive. Guerra (2013) argues that the detection of the influence of land use on travel behavior has been difficult in US cities because of factors such as Car-oriented urban form, high Car use rates, low population densities and co-localization processes. If this is true, it is reasonable to expect that in cities in the developing world, the built environment exerts a stronger influence on travel behavior than in most US cities given the presence of more densely constructed environments and fewer Car drivers. In this sense, some aspects of travel behavior have been

tested, however, in order to define the relationship between commute time and urban structure, the evidence is still limited for cities in developing countries.

Regarding the social aspect of commuting, in US the hypothesis stated by Kain (1968) triggered an important academic debate, under this view housing market segregation and employment decentralization greatly increase the difficulty for low-income minorities, especially for African Americans who live in the central city to access jobs. In the case of social aspects of commuting in Latin America there has been especial interest in focusing mostly on evaluating area-level accessibility to certain opportunities. Although this has brought insights concerning transportation problems of the urban poor in the Global South, the urban structure determinants of such disadvantage remain to be analyzed. Specifically, the study of determinants of an observed mobility indicator such as travel time has been limited in the region. Moreover, the identification of population groups in disadvantaged are often limited to low-income groups and/or people living in the periphery, but the identification of other groups has not been explored with the same intensity. This is vital in order to establish a more inclusive policy.

The study of transportation problems of disadvantaged groups in the Global South is important because in today's increasingly urbanized world, developing countries are absorbing most of this urban growth. Here suburban expansion is dominated by poor and densely populated neighborhoods. According to Guerra (2017), many suburban residents of cities as diverse as Mumbai, Dakar, and Bogotá have to deal with long and costly trips on multiple modes of public transportation to reach centrally located jobs. Benevenuto & Caulfield (2019) argue that in the Global South low research production has failed to inform transport policy in its role to alleviate poverty. In this sense increasing efforts in research are needed to develop a more robust evidence about the interlinked association among urban form, mobilities and social deprived conditions.

What is still needed to understand in the developing world is how commute time varies at the neighborhood level beyond the dichotomy inner city/suburbs, as well as to analyze the relation between commute times and the urban structure. Without knowledge of spatial patterns from commuting at neighborhood level, researchers are less capable of contributing to the design and implementation of accessibility improvement programs, which are often based on location (Shen, 2000). To the extent of my knowledge in Latin America there is no paper which develops a statistical model exploring explanatory factors of one-way travel time to work. In US cities where travel times are significantly lower for those commuting by Car than for those who commute by Transit and where travel times is the most important factor for job access, it has been demonstrated that accessibility and one-way commute times are inversely associated (Shen, 2000). This association is considerably greater for public Transit users than for those using a Car for commuting (Kawabata and Shen, 2007). How this relation behave in a Latin America city, where location is more important than differences in travel time between Car and Transit to increase job access? what aspects of urban structure are most determinant of commute times? These findings will be relevant to the overall Global South context.

This research aims to address two primary questions. The first is whether there are differences in the Average Commute Time (ACT) pattern with respect to the urban center between Car use and public Transit use. Additionally, it will evaluate the extent to which periphery and inner city are heterogeneous in commuting experiences. To this end I calculated and visualized commute times for Car and Transit users separately, comparing the data of two sources. Furthermore, these values were graphed according to the distance to the urban center. The second question was whether the association between employment accessibility and commute time is negative and whether this is greater for public Transit users than for people driving alone. The

question was addressed using the ordinary least squares (OLS) model and two typical spatial regression models that take into account spatial autocorrelation, the spatial lag model (Lag-ML) and the spatial error model (Err-ML). The models were estimated separately for average commute times (ACT) by driving alone and public Transit. In order to address the social aspects of commuting, the specification of regression models included different social groups that could be in travel disadvantage.

This study offers an exploration of the complex urban structure in developing world cities as a determinant of commute times and develops an interpretation to understand this relationship in the specific case study. Additionally, this paper demonstrates that other important population groups are potentially in disadvantage with respect to commute times cost besides the common focus on income.

3.2 LITERATURE REVIEW/BACKGROUND

3.2.1 *Urban Spatial Structure and Commuting time*

In journey-to-work literature there are three broad sub-research areas that investigate the relationship between jobs and workers' housing locations and journeys-to-work. The first two inquire how the proximity between housing and job locations affects both journey-to-work times and distances. In the first area, the effect of job/housing balance and commuting was studied. Initial advocates of this measure to decrease the need for commuting include Cervero (1989 and 1996), though Giuliano (1991) was among his main critics. The study in the second sub-research area compared a theoretical minimum commute against an observed commute, given an actual distribution of jobs and housing, the difference was considered to be an excess of commute time and effort it required (Giuliano & Small, 1993). In the third sub-research area, the debate was about

how, in metropolitan cities in the US, regional densities of employment and population have historically affected average commute times because of jobs and people the decentralization in an emergent polycentric structure. Some researchers argued that commute times at the end of the last century were shrinking (Gordon et al., 1991), while others said it had increased at a modest pace (Rosseti and Eversole, 1993).

An important urban process in the journey-to-work literature is the co-location of jobs and people and the role of land use in encouraging this co-location. Some authors consider the spatial transformation of cities from monocentric to polycentric structures as an adjustment process that mitigates some of the negative externalities that accompany urban growth such as traffic congestion, and suggest that many individual households and firms ‘co-locate’ in order to reduce commute times (Gordon & Bumsou, 2015) as an alternative for these problems, thus avoiding government planning intervention in land use. Other authors argue that there are barriers that limit co-location process the influence (Cervero and Landis, 1992).

3.2.2 Travel disadvantaged populations and commute times

In the social dimension of commuting, the travel disadvantaged condition of certain groups has attracted attention. The first and most cited author in the US is Kain (1968), who developed the “Spatial Mismatch Hypothesis”, which states that employment distribution for African Americans, who mainly live in the central city areas, is affected by segregation in the housing market, which thereby reduces job opportunities accessible to them. Furthermore, employment suburbanization of aggravates the problem. Literature has debated this hypothesis. Shen (2000) argue than one of the reasons for which the literature brings contested finding is that analyses of intra-metropolitan

commuting are mostly based on the central-city/suburb dichotomy. Thus, this high level of geographical aggregation may conceal meaningful differences among commuters living in different neighborhoods. According to this author, when the magnitude of such variations is large using central-city and suburban averages researchers are probably overlooking important spatial and social dimensions of commuting. More specifically, the circumstances of more disadvantaged population groups have often been underestimated.

Grengs (2010) identified four shortcomings in the literature when illustrating how policy-making is misguided by empirical studies of spatial mismatch: 1) scholars have been vague in defining the relevant dependent variable in spatial mismatch studies, where the problem is accessibility rather than distance in itself; 2) ignoring the substantial difference between cars and public transit use for commuting; 3) studies typically are narrowly focused on specific groups (unemployed or low-wage African Americans living in the inner-city); and 4) the use of surprisingly simplistic geographical categories, e.g. the dichotomy central city/suburbs. Besides, only a few studies have addressed these shortcomings. In the journey-to-work literature, study of social inequalities and exclusions has been integrated into the research lines described above by assessing unequal levels of access or travel times, and empirical studies have examined the differences among various groups considered at risk because of age, gender, socioeconomic condition, disabilities, etc.

Shen (1998) demonstrated that although location is very important, the key factor for low-income workers seeking employment opportunities is their transportation mode. In other words, although inner-city living offers a locational advantage for job opportunities, most inner-city residents do not own Cars. This situation greatly limits available job opportunities for them in car-oriented US cities. Shen (2000) demonstrated that in the 20 largest US metropolitan areas,

commute times vary substantial and systematically among neighborhoods. This applies not only at a metropolitan level, but also for those located in the central city, demonstrating that commute times tend to be longer for low-income minorities than for other central city residents. Furthermore, in Shen's Boston case study (2000), he proved that urban structure measured as a job accessibility factor is strongly related to commute times. From their studies of the San Francisco Bay Area, Kawabata and Shen (2007) demonstrated considerable inequality and temporal changes in job accessibility and commute times between those who use Cars and those who use public Transit, including locations within the metropolitan area. Results from their regression models indicate that greater job accessibility was significantly associated with shorter commute times for any mode of transportation used, but the degree of this association was considerably greater for public transit than for car use. Throughout different studies, these results have been consistent in US auto-oriented cities. This is the reason why Kawabata and Shen assert that, in order to be able to make a systematic international comparison of the relationship between employment accessibility and commute times, we must first understand the nature of the commute inequality between Car and public Transit use in metropolitan areas with different transport systems and urban spatial structures.

3.2.3 Transport inequities in Latin America

A wide body of literature describes Latin America's uncontrolled and unplanned urbanization, a process which has produced cities with strong social inequalities discernible in social segregation. The general depiction of this process can be found in the emerging peripheries produced by

informal settlements, where the urban poor concentrate far from the urban centralities with a lack of suitable facilities and services (i.e. ONU HABITAT, 2008).

Latin American cities' urban periphery transportation problems are well known. People face long expensive trips on multiple modes of public transportation to reach centrally located jobs (Alcantara, 2018; Guerra, 2017). In some cases, the formal transit system doesn't fill the demand. Therefore, different informality schemes lead to a complex interplay of formal and informal transport alternatives in travel choices (Cervero and Golub, 2007). In large cities, sometimes wealthy suburbs develop into gated communities whose inhabitants become dependent on cars as a means of transportation (i.e. Alcantara's case of Brazil (2018)). In Mexico City's case, quality of public transit and road infrastructure decreases in a trend center-periphery with a significant variation in transportation fees due to discontinuity in metropolitan transit services (Flores-Espinosa, 2018). Such dynamic affects under-privileged groups disproportionately, restricting their accessibility from peripheral, often informal, settlements.

To tackle this problem several cities have implemented massive transport initiatives such as Bus Rapid Transit and cable-way systems, this latter for hilly neighborhoods. Nevertheless, there still exist disparities both in access and mobility. Hernandez (2018) argues that because Latin America mobility is unevenly distributed it constitutes a field of contestation and dispute among social classes. Blanco, et al. (2018) refer to this as "contested mobilities" by associating and thus stressing the fact that in recent years Latin America has emerged as a transport innovator and a place of important new urban contestations. According to these authors, the dynamic role of mobility interventions in shaping and reshaping Latin American cities' urban form has had uneven, unequal and often unfair social and economic outcomes for different population groups living and working within cities and their urban peripheries. Thus, the demand for world-class, central-city

lifestyles incrementally pushes the poor to the urban periphery, where public transport services are increasingly in short supply. Actually, this process presents a problem not only for the rapidly developing Latin American cities, but also for developed and developing cities worldwide.

In the region, previous studies have mostly focused on evaluating area-level accessibility to jobs or other shopping, health and education opportunities (Moreno-Monroya, 2018; Hernandez, 2018; Figueroa, et. al., 2018; Guzman, et. al., 2017). Accessibility analyses have also been used to evaluate the role of transport public policy in alleviating inequalities (Guzman & Oviedo, 2018; Guzman, et. al., 2018; Delmelle, & Casas, 2012; Bocarejo, et. al., 2014). Still another approach has been to estimate transport disadvantage indexes aimed at identifying district needs/supply shortfalls or spatial gaps to bring about transport system improvements (Pucci, et. al., 2019; Jaramillo, et. al., 2012). The main findings of this body of literature can be summed up in three main ideas: 1) An unequal transport supply and accessibility tends to favor the most affluent social groups by placing the urban poor in transport disadvantage (Figueroa, et. al 2018; Delmelle, & Casas, 2012; Guzman, et. al., 2017); 2) Income is highly related to different mobility variables such as mobility assets possession, trip generation rates and differentiated use of modes of transportation (Blanco & Apaolaza, 2018); and 3) Location (or territorial context) plays a key role in urban poor's disadvantage at making accessibility values to activities largely bound to the spatial distribution pattern of activities (Blanco & Apaolaza, 2018; Guzman, et. al. 2018; Guzman, et. al., 2017; Delmelle, & Casas 2012). In spatial terms, most studies remark that the urban poor tend to locate in the peripheries, so they experiences difficulties such as unsafety and transportation discomfort, especially since they face lengthy travel times because the highest concentration of opportunities (mainly jobs), infrastructure and public transport services locate in city central areas along the mass Transit lines (for Brazilian cities see Alcantara, 2018; for Santiago, Chile see Lukas

& López-Morales, 2018 and Figueroa, et. al. 2018; for Medellín, Colombia see Bocarejo, et. al., 2014 and for Bogotá see Guzman, et. al., 2017). In regards of observed traveled times there has not been an exploration of its determinants in the context of Latin American cities, specifically evaluating aspects of urban structure.

3.2.4 *Commuting in the MCMA*

The MCMA does not have a consolidated polycentric urban structure yet (Montejano et al., 2016; Suárez & Delgado, 2009), since it is dominated by a dispersed central area with a contiguous elongation through adjacent highways. Thus, the early stage of a polycentric urban structure entails a still highly influential central area.

In the first decade of this century Graizbord and Santillán (2005) and Duhau (2003) analyzed commuting flows at municipal level. Their conclusion was that the periphery has developed its own attraction coefficient, given that commutes to the central city are not overly intense or have become less so. However, most recent studies have pointed out that longer commutes from the periphery to the inner city is the overriding pattern. All studies that remark the huge influence of MCMA's CBD agree that, in this very imbalanced urban structure, most people living in the periphery must commute long distances (Montejano et al., 2016; Casado, 2012; Guerra, 2014). Thus, workers living in the CBD or in the subcenters make shorter trips in terms of distance and time than the average metropolitan commuter, and those living in the periphery and going to the CBD travel the longest distances. Suárez and Delgado (2009) found that the number

of work trips to the central city has steadily increased in both absolute and proportional terms relative to the working population growth.

As described for many Latin American cities, Guerra (2017) argues that in MCMA, wealthier households price poorer households out of the most job-accessible central neighborhoods, forcing them to live in suburbs where the commute time gap between using a car and public transit is greater in favor of the former. Contemporary car ownership rates match income spatially, with car ownership being the highest in the slow-growing and wealthy western half of the city (Guerra, 2015). In relation to urban structure and commute times, Suárez et al. (2016) measured commute times at municipal level and different income groups sensitivity in urban structure using two linear programming transportation models to evaluate the spatial mismatch between residential locations and places of work. Their results indicate that there is a strong relationship between residential location and place of work in MCMA, with the urban structure comprising on average an 83% of commute times. Their results also prove that lower income groups are more sensitive to urban structure (a higher percentage of commute times is explained in the model) than other income groups. Thus, these groups must dedicate more effort to optimizing their work trips. Low-income workers have shorter commutes than other income groups living within the same area. This can be explained by the location of informal work activities, which seems to be a function of residential location of workers in the informal sector in response to the disadvantages of the housing and formal employment urban structure.

3.3 RESEARCH OBJECTIVE AND HYPOTHESIS

Objectives.

- To determine the relations between One-way Average commute time and the urban structure separately for Car drivers and Transit users
- To identify if there are groups of population with a locational disadvantage in relation with their commute time experience

Hypothesis

- It is expected a stronger relationship between commute time and urban structure for Transit users than for Car drivers.
- It will be possible to relate a location disadvantage condition for certain groups of people that face a prominent travel cost in the access to jobs.

3.4 METHODOLOGY AND DATA

3.4.1 *Average one-way travel to work*

The spatial unit of analysis is the Traffic Analysis Zone (TAZ) from the 2017 Household Origin destination survey (HODS17), which subdivide the MCMA in 194 TAZs. Travel times comes from two data sources. One is the own HODS17 (INEGI, 2017), here the one-way Average Commute Time (ACT) was calculated for each TAZ at origin. For each individual trip to work the starting and ending times are recorded, in base of these the total time spent in the trip is calculated,

therefore ACT includes any intermediate waiting time. In order to get the aggregated one-way ACT at TAZ-level, the information of each individual commute trip in the database is weighted by its corresponding expansion factor. Trips can have more than one mode of transportation, but in order to simplify, those made by car were labeled as car users while the rest were considered transit users. Non-motorized travel (trips exclusively made by walking, biking or any combination of both) was dropped from the dataset. Trips considered started exclusively at peak hours (between 07:00 and 10:00 hours) and stayed within the metropolitan area. Thus, Transit users could include various combinations of transportation modes: collective, subway, Bus Rapid Transit (BRT), trolleybus, motorcycle, taxi, commuter train, light rail, cableway, bus, school bus and staff shuttlebus. Additionally to the ACT by TAZs, ACT estimates for each state were also calculated for comparison purposes.

The other source of travel time information used in this study was the region's travel demand model, TRANUS (model 2013, modeling date 25-02-2014), provided by ITDP (2014). The calibrated trip matrixes include travel times at peak morning hours between the region's 978 TAZ. However, these times were correlated into HODS17-TAZ by associating each HODS17-TAZ with the TRANUS-TAZ that contains the HODS17-TAZ's centroid in order to maintain congruency with the geographical unit of analysis selected for the present study. In the case of peripheral HODS17-TAZ for which the geographic centroid did not lie in an urban area, a correction was made to place the reference point in its corresponding central urban area. I used two travel time matrixes for this study: Transit service and private Car. Additionally, I extracted from the HODS17 the work trips matrixes for Car drivers and Transit users that capture commuter flow between each pair of TAZ (INEGI, 2017) using the factor expansion of each trip. The ACT was calculated using TRANUS data, taking into account these inter-TAZ work trips. ACT values were displayed in a

map and graphed according to distance to urban center in order to compare the resulting pattern among car and transit.

3.4.2 *Regression Models*

The dependent variable is one-way ACT because it most affects quality of life and decisions about residential location for urban dwellers. Therefore, it is probably the best variable to identify any undue commute burden faced by certain groups of the population (Khattak et al., 2000). Thus, the dependent variable for a corresponding TAZ consists of the sum of commute flows between this and each one of the other TAZs weighted by the corresponding travel time divided by the total number of commuters in that TAZ. This yields a localized and standardized metric of travel costs. In the case of the HODS17 data, this approach produced the same output that the average commute time of individual trips in each TAZ weighted by its corresponding factor expansion. Four dependent variables of ACT are analyzed separately: 1) TRANUS Car time, 2) TRANUS Transit time, 3) HODS17 Car time, and 4) HODS17 Transit time. For each of these, I estimate three regression models: OLS and two spatial regressions, spatial lag model (Lag-ML) and spatial error model (Err-ML). All three models have the same set of covariates to allow direct comparison between them.

The initial step in a spatial analysis is to make a diagnosis of the univariate spatial autocorrelation in absence of covariates. This involves using global measurements of spatial dependence such as Moran's I statistics for continuous variables. For this analysis, neighboring HODS17-TAZ were set using first-order queen-based contiguity spatial weights and then, row-standardized in the contiguity matrix. When spatial dependence was diagnosed, the next step was

to attempt to model this dependence with substantive covariates. There are two main sources of spatial dependence: 1) spatial diffusion, which occurs when spatially proximate units are influenced by the behavior of their neighbors and vice versa, and 2) geographic clustering of sources of the dependent variable, also called attributional dependence.

The first source is modeled via a spatial lag model while the second one is modeled via a spatial error model. A spatial lag model is estimated by maximum likelihood (ML), while spatial error dependence is estimated either by ML or by generalized method of moments (GMM). Thus, in the case of the remaining spatial dependence with covariates, a spatial diagnostic was applied to ensure that appropriate spatial model specifications were adopted according to the proposed approach (Anselin 2005; Darmofal, 2015). The first step was to run the non-robust LMlag and Lmerror diagnostic tests, the results of which can lead to three different paths: 1) if none of these diagnostic tests determine the presence of spatial dependence, OLS estimates are suitable; 2) if only one of the diagnostic tests determined the presence of spatial dependence, the corresponding model should be estimated; 3) if both diagnostic tests determined the presence of spatial dependence, both the robust LMlag and the robust Lmerror diagnostic tests should be used, and the model used should be that with the higher value in these statistic tests.

Covariates in these models include the urban structure operationalized with an indicator of job accessibility. The approach of assessing accessibility was based on the formula developed by Shen (1998), according to the results presented in Chapter 2 of this dissertation. For each dependent variable, the corresponding job accessibility indicator was used according to the transportation mode and travel time source. One criticism to this approach might be the fact that travel time is involved in both sides of the equation, i.e. in the average commute time and in calculating the job accessibility measure. However, this does not necessarily cause a relationship

in the regression outcome, as seen in the results. The dependent variable reflects commute times taking into account actual commuter destinations, and the independent variable (job accessibility) reflects the potential reachable places to work. This approach has been employed by Shen (2000) and Kawabata and Shen (2007).

In the case of employment, trips to work attracted to each HODS17-TAZ were considered to be a proxy of total employment (formal + informal), an approach previously used by Suárez and Delgado (2009). The remaining socioeconomic variables were extracted from the 2010 socioeconomic census (INEGI, 2010). The MCMA contains 5,648 census tracts, so values of the 2010 census tracts that lay within each of the HODS17-TAZ were added. Aggregating spatial data may introduce errors in the spatial analysis (known as the modifiable areal unit problem), but the HODS17-TAZ were the smallest area units for which all the necessary data were available. EAP density considers only urban areas (in hectares), given that peripheral HODS17-TAZ includes non-urban land use such as forests and agriculture. I draw on a mixed land use (MLU) index, estimated at block level by Montejano et al. (2016). This indicator ranges from 0 (concentration of one class of land use) to 1 (equilibrium between four land use classes: residential, leisure, services and commercial). This indicator takes the centroid of each block and within, in a buffer of 500 m, all economic units recorded in the census are counted (Montejano et al., 2016). I considered percentage of the block area within each HODS17-TAZ with an index value higher than 0.225 (percentile 75).

The other covariates are the presence of different percentages of socially disadvantaged groups: indigenous population, people with physical disabilities in terms of mobility and migrants (who arrived in the past five years). Thus, the specification of the regression models is complete according to Shen's (2000) recommendation, who stated that including socioeconomic variables

and land use/urban structure variables together avoids possibly biased estimations and increases the explanatory power of the models as well.

Table 3.1. Variable descriptive statistics.

Variable	Mean	Standard deviation
<i>Dependent Variables</i>		
ACT Car – TRANUS (min)	42.32	17.41
ACT Transit – TRANUS (min)	88.64	30.77
ACT Car – HODS17 (min)	49.06	8.98
ACT Transit – HODS17 (min)	68.21	13.0
<i>Explanatory variables</i>		
Employment Accessibility		
TRANUS – Car	0.98	0.11
TRANUS-Transit	0.68	0.14
HODS17-Car	0.86	0.13
HODS17-Transit	0.71	0.14
EAP Density (pop/ha)	52.93	27.49
Job Density (Jobs/ha)	24.02	36.95
Mixed land use (%)	30.34	20.7
Percentage of Female Headed Households (%)	27	5.26
Percentage of Illiterate pop. (%)	2.53	1.17
Percentage of migrants (%)	4.43	4.2
Percentage of the physically disabled (%)	2.18	0.51
Percentage of indigenous population (%)	1.59	0.91

3.5 RESULTS AND DISCUSSION

3.5.1 Average Commute Times

The general ACT in the metropolitan area is 63.03 minutes, being lower for Mexico City (59.01 min) than in the State of Mexico (67.21 min). The portion of MCMA located in the state of Hidalgo is a very small peripheral area omitted in this comparison exactly for this reason. This well-known pattern among states is similar if it is disaggregated by transportation mode. Commute times by private Car are always lower than commute times by Transit (Table 3.2).

Table 3.2. ACT (in minutes) by gross geographical units (states) and transportation mode in 2017.

	MCMA	Mexico City	SoM
General	63.03	59.01	67.21
Car	48.8	47.97	50.1
Transit	68.47	63.65	73.08

Source: Personal calculation based on HODS17 data (INEGI, 2017).

When looking at commuting times by transportation modes we can see that lower commute times in Mexico City than in SoM are in part due to higher Car usage in the former. Thus, SoM is where people have the longest commutes (Table 3.3).

Table 3.3. Transportation mode choice for commuting in 2017 (Percentages).

	Collective	Car	Subway	Walking	BRT	Taxi	Bicycle
MCMA	45.2	24.7	21.1	12.7	4.8	4.3	2.7
Mexico City	38.7	27.5	24.1	12.1	5.7	5.3	1.9
SoM	51.1	22.2	18.3	13.1	3.9	3.5	3.5

Source: HODS17 report (INEGI, 2017). Note: the sum of percentages is higher than 100% due to some trips were made using more than one transportation mode.

However, the ACTs among TAZs within each state are heterogeneous. In order to create a description of the geography of ACTs in MCMA, first it is necessary to identify the periphery that is weakly linked to the metropolis. This primarily corresponds to what is called ‘the fringe’ in Figure 3.1. Figure 3.1a illustrates this fringe as dark areas in the periphery. Here are the largest percentages of intra-TAZ trips to work, that is, people that remain within the TAZ for work purposes. This means that its functional relation with the rest of the metropolis is less intense. The fringe is mostly a semi-urban area that reflects the leap-frog development in the urban sprawl process over the last decades. This periphery has fewer connections (the lighter shaded areas in the periphery in Figure 3.1b) because of the number of TAZ where people work.

Omitting the fringe, the remaining area can be considered to be the metropolitan region with more robust functional commute relationships. Here a central/east–west dichotomy can be detected. Those TAZ with more journey-to-work connections with other TAZs are located in the east (Figure 3.1b), while the areas with highest access to jobs are located in the inner city, mostly inside CDMX (Figure 3.1c). The overall picture shows a pattern where people living further away from the urban center spend more time commuting. This fact was expected according to the neoclassical models of urban economics developed by Alonso (1964).

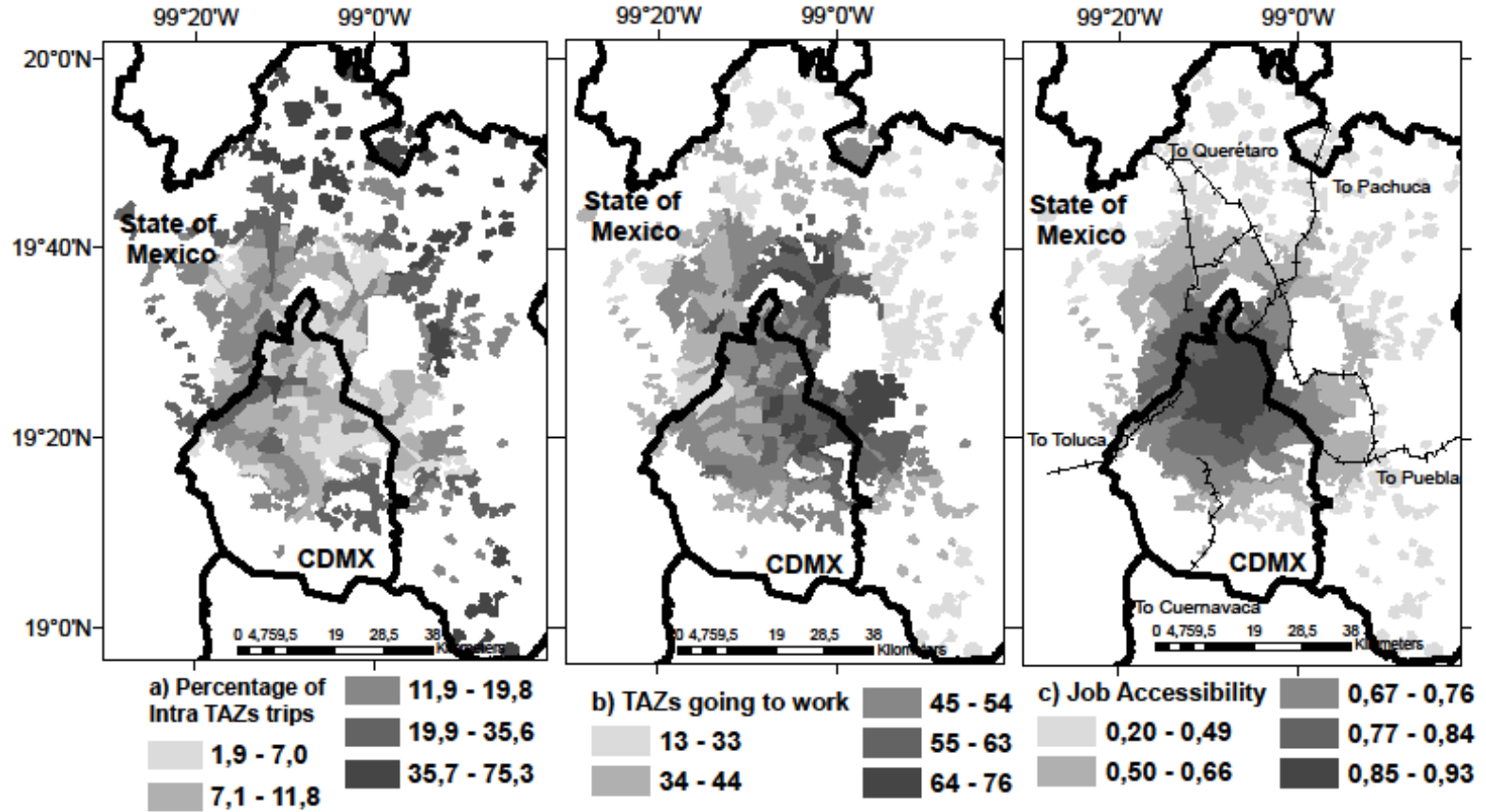


Figure 3.1. a) Percentage of intra-TAZ trips to work, b) Number of TAZ where commuters travel to work, and c) Shen's-type job accessibility considering total employment.

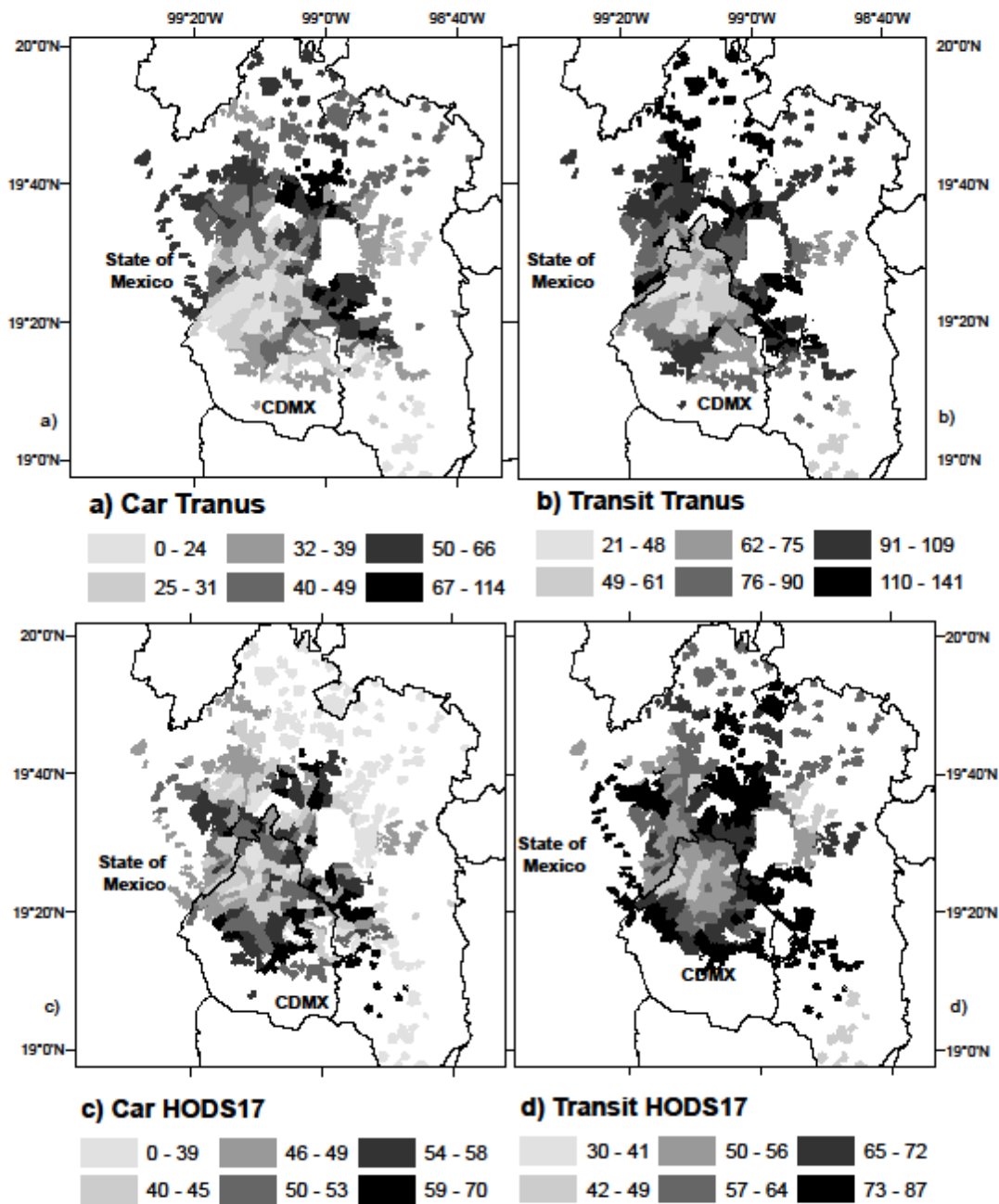


Figure 3.2. Average commute time by Car (a) and Transit (b) according to the TRANUS model; and by Car (c) and Transit (d) according to HODS 2017. *Source:* Authors' calculations using data from HODS17 (INEGI, 2017) and ITDP (2014).

Figure 3.2 shows ACT maps for Car drivers and public Transit users with TRANUS (a and b, respectively) and HODS17 data (c and d, respectively). Natural breaks for each map are displayed in order for the geographical pattern to be easily identifiable maximizing differences among categories. There are obvious differences between the two datasets. Overall, the value range is larger in TRANUS than in HODS17 data. In both datasets, ACT in the fringe is heterogeneous. The dark areas in the fringe are TAZ where ACTs are high, probably due to long trips going to other TAZ, although as mentioned above, the proportion of those trips is small in comparison to those within the same TAZ. On the other hand, there are some clear areas in the fringe with low ACTs. As shown below, ACTs by car display a more random geography given the low spatial correlation. Also, there is a noticeable difference in the pattern of ACT by car in the periphery between both datasets.

There is a clear correspondence between the two datasets in the fringe area where ACT by Transit is high, namely those darker areas in the north, west and east, and those with low ACT by transit in the northeast, southeast and northwest. ACT by private Car is again highly random, especially in the HODS17 data, with some slight identifiable TAZ clusters of high ACTs in the southeast, southwest and in the north. However, some central TAZ also suffer from high ACTs. This means that ACT by Car varies among central city neighborhoods as well, and the causes of these differences between contiguous TAZ could be for various reasons such as congestion effect, urban form, infrastructure, among others. In the TRANUS map, there is a noticeable area of low ACTs by Car going from the center along to the southwest, probably due to fact that the best road infrastructure is located there. In the case of ACTs by Transit, the lowest values are in the central area given that the best transit infrastructure is here where subway and BRT systems are

predominant. However, in the periphery, transit systems largely rely on inefficient semi-formal bus systems. Thus, the gap between ACT by car and ACT by transit is narrow in the central area.

There is a general noticeable inverted U-shaped pattern in the relationship between ACT by transit and distance to the urban center. ACT increases as the distance to the urban center increases, reaching a point where commute times decrease in the outer TAZs, probably due to unbearably high travel costs of traveling to the center. Since the best transit infrastructure is located in the inner city, low commute times in the center are explained. Additionally, there is less variation of commute times among central-city neighborhoods (Figure 3.3b and 3.3d). These aspects are consistent for both travel times datasets.

The pattern is different when commuting by Car. TRANUS data still shows that ACT times and their variation increase as the distance to the center increases, while in the outer TAZs, commuting times decrease. However, there is no any noticeable curve, though there is one outlier around 12 km away from the urban center. These ACTs by Car with HODS17 show a flat pattern with a slight decrease in the outer TAZs. No noticeable curve in commuting time exists even within 30 km from the urban center, which indicates the inner-city does not necessarily offer an advantage. On the contrary, a congested environment limit Car mobility.

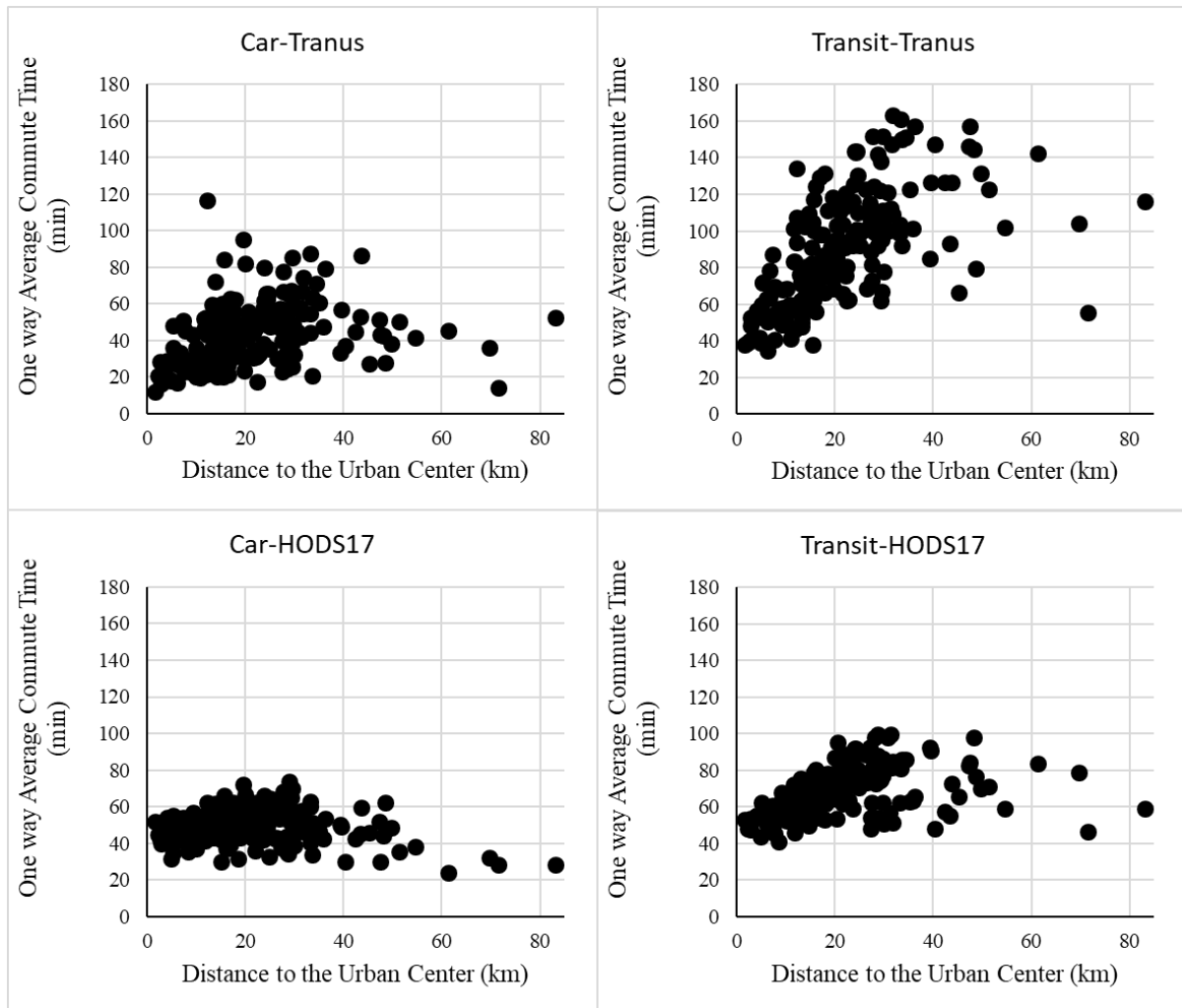


Figure 3.3. Average commute time by Car (a) and Transit (b) according to the TRANUS model; and by Car (c) and Transit (d) according to HODS 2017. *Source:* Authors' calculations using data from HODS17 (INEGI, 2017) and ITDP (2014).

Moran's statistic confirms the existence of a positive spatial autocorrelation for the four variables under examination. Using TRANUS data, this indicator is 0.55 and 0.65 for ACT by Car and public Transit respectively. In the case of HODS17 data, Moran's I is 0.67 for Transit users, but for Car users such spatial correlation is of less magnitude with a statistic of 0.18 (Table 3.4).

Table 3.4. Univariate (dependent) spatial autocorrelation detection.

Variable	Moran's I	Moran's I test	Permutation test
		p-value	p-value
ACT by Car (TRANUS)	0.5544	< 2.2e-16	0.01
ACT by Transit (TRANUS)	0.6516	< 2.2e-16	0.01
ACT by Car (HODS17)	0.1828	6.419e-05	0.01
ACT by Transit (HODS17)	0.67	< 2.2e-16	0.01

Note. ACT (Average Commute Time). Airport tract was dropped from this analysis.

Table 3.5 presents the results of the spatial diagnostic test, which can be used to identify the nature of spatial autocorrelation. With TRANUS data for commuting by Car and Transit models, both non-robust tests indicated a spatial dependence with the presence of covariates. However, for the commuting by Car, the results of the robust versions of the diagnostic tests are not significant at 5% level. Only the LM_{lag} test is significant at 10% level. In this case, LM_{lag} is the correct specification. In the Transit model case, the error model is the correct specification, since only LM_{err} test in the robust version is statistically significant at 0.05. With HODS17 data, the non-robust LM_{lag} test for Car users and both non-robust versions for Transit users are statistically significant at 0.05. In the robust versions only LM_{lag} test is significant at 0.05, which demonstrates that the lag model is the correct specification for Car drivers and Transit users using the HODS17.

Table 3.5. Autocorrelation tests for OLS residuals

Test	TRANUS				HODS17			
	ACT-Car	p-value	ACT-Transit	p-value	ACT-Car	p-value	ACT-Transit	p-value
LM (lag)	11.13	0.0008	6.20	0.012	3.96	0.046	87.66	2.2e-16
Lm (error)	8.78	0.003	10.85	0.0009	2.20	0.137	77.28	2.2e-16
Robust LM (lag)	2.95	0.0854	0.287	0.591	4.58	0.032	11.33	0.0007
Robust Lm (error)	0.607	0.4359	4.937	0.026	2.82	0.092	0.95	0.327

3.5.2 *Regression Analysis*

I did an exploratory analysis with the OLS model using all covariates initially considered in order to identify multicollinearity and to select the best possible specification. Some variables were removed from the analysis given the high correlation between socioeconomic covariates. For example, the inclusion of an index of marginalization, which is a composite index calculated by the governmental Agency of Population Affairs based on census variables, results in high collinearity. The census does not record income. The job accessibility index using the Shen (1998) methodology is highly correlated with distance to the center. High correlation between covariates is problematic since this collinearity result in estimation bias. Therefore, in order to avoid this, the distance to the center variable was removed from the model. The percentage of female workforce and the percentage of population with post-basic education also resulted problematic when included in the models, according to the variance inflation factor test which quantifies the severity of multicollinearity (values higher than 10). Thus, I deleted these as well. However, the final specification still considers enough variables to study the urban structure and socioeconomic aspects of commuting in the MCMA.

1

Table 3.6. OLS, Lag-ML and Err-ML regression results for Car and Transit using TRANUS and HODS17 data

Variable	TRANUS						HODS17					
	ACT Car			ACT Transit			ACT Car			ACT Transit		
	OLS	Lag-ML	Err-ML	OLS	Lag-ML	Err-ML	OLS	Lag-ML	Err-ML	OLS	Lag-ML	Err-ML
Constant	180.16 ***	154.75 ***	180.33 ***	214.94 ***	186.59 ***	224.58 ***	59.93 ***	50.28 ***	60.57 ***	81.34 ***	24.0 **	85.80 ***
Accessibility*	-126.94 ***	-115.85 ***	-129.05 ***	-185.9 ***	-173.2 **	-183.07 ***	7.14	5.61	7.99	-20.96 +	-1.80	-17.25
EAP Density*	0.23 ***	0.198 ***	0.192 ***	0.21 ***	0.211 ***	0.20 **	0.063 *	0.057 +	0.06 +	0.097 **	0.072 **	0.06 *
Jobs Density	-0.09 ***	-0.083 **	-0.077 *	-0.07 +	-0.062 +	-0.02 -	-0.046 +	-0.036	-0.03	-0.103 ***	-0.024	-0.002
Mixed land use	0.143 ***	0.101 *	0.107 *	0.165 **	0.131 *	0.096 +	0.048	0.039	0.043	0.083 *	-0.015	-0.003
% Female Headed Households	-0.56	-0.369	-0.513	-0.43	-0.227	-0.702	-0.378	-0.37	-0.47	-0.455	-0.43	-0.63 +
% Illiterate pop.	-5.81 ***	-5.267 ***	-5.011 ***	-2.77 +	-2.745 +	-1.89	-2.954 *	-2.792 *	-2.946 *	0.133	-0.045	0.572
% Migrants	0.004	0.011	-0.05	0.82 **	0.796 **	0.613 *	-0.231	-0.188	-0.22	0.561 **	0.540 ***	0.648 ***
% Physical disabilities	0.13	1.015	1.15	-0.55	0.409	-0.84	-2.432	-1.97	-1.905	-0.343	0.898	0.41
% Indigenous pop.	2.004 +	1.82 +	1.43	1.23	1.193	-0.865	2.298 *	2.08 *	2.06 +	4.283 ***	2.21 *	1.67 +
ρ		0.2068 **			0.1477 *			0.1909 *			0.6859 ***	
λ			0.3307 **			0.3867 ***			0.1683			0.7516 ***
R2	0.6954			0.829			0.1416			0.4796		
Adjusted R2	0.6804			0.821			0.0993			0.454		
Log likelihood	-710.06	-705.39	-705.09	-764.06	-761.21	-757.61	-682.35	-680.43	-681.1355	-705.44	-660.56	-662.96
AIC	1442.131	1434.78	1434.18	1550.12	1546.42	1539.23	1386.708	1384.86	1386.27	1432.89	1345.13	1349.93
BIC	1478.02	1473.93	1473.34	1586.01	1585.57	1578.38	1422.59	1424.01	1425.42	1468.78	1384.29	1389.09

Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '+' 0.1 ' ' 1

2

Table 3.6 presents regression results from the ACT models by driving alone and public Transit with TRANUS and HODS017 data. The table also reports the goodness of fit indicators: R and R² values for OLS, as well as the log-likelihood, Akaike Information Criterion (AIC) and Bayesian Information Criterion (BIC) values for the three regressions models, OLS, Lag-ML and Err-ML. A higher log-likelihood value and lower AIC or BIC values suggest a better fit.

The Lag-ML and Err-ML regressions provide similar fit for Car model with TRANUS data. The respective rho (ρ) and lambda (λ) coefficients are significant at 0.01 level. Although the first appears to be the correct specification and description of results will focus in this model. In the case of public Transit with TRANUS, Err-ML regression provides the better fit in congruence with the correct specification explained above. The lambda (λ) parameter is highly significant ($p < 0.001$). In the analysis with the HODS17 data for Car users, the Lag-ML model seems to have better fit according to Log likelihood and AIC, although with OLS BIC performs better. The rho coefficient from the Lag-ML model shows significance at 5%, being not statistically significant the lambda parameter of the Err-ML model. In the case of commuting by Transit, the Lag-ML regression has better fit with any of the indicators (log-likelihood, AIC and BIC) with a significant ρ coefficient ($p < 0.001$). Thus, the following analysis is focused on highlighting the main findings from the Lag-ML regression, making comparison with the other two models (OLS and Err-ML) when necessary for a better interpretation.

In the model using the TRANUS data, after controlling for other variables related to the urban spatial structure (EAP density and jobs density) and socioeconomic aspects, job accessibility has a significant inverse association ($p < 0.001$) with ACT for Car drivers as well as for Transit users. The degree (represented by coefficients) was higher for public Transit commuters than for Car commuters with the TRANUS data. For example, a unit increase in access entails a decrease of 115.8 and 183 minutes in commute times using Car and public Transit, respectively. In terms

of direction (sign) and significance, these findings are consistent with the literature for US cities. In his study of Boston, Shen (2000) found that general access and general one-way commute times are inversely associated: a decrease of 4.5 minutes for every one unit increase in general access. In their study of San Francisco, Kawabata and Shen (2007) also found an inverse and significant association of job access and commute time, which is considerably greater for public Transit use than for driving a Car, with the coefficient being -9.1 and -3.2 respectively for the year 2000. The relative high magnitude of the coefficient for the MCMA could be due to a wide range of modeled times in TRANUS. On the other hand, this coefficient makes sense if we consider that a unit increase (or decrease) of access entails almost the entire range of observed access values (see Table 3.1).

When using HODS17, job access is not statistically significant with any spatial regression models, not even with OLS in the case of commute times for Car drivers. Likewise, spatial regression models fail to detect a significant inverse association between job accessibility and ACT for Transit commuters. Only in the case of OLS there is a weak significance at 10%, where one unit increase in job accessibility leads to a decrease of 20 minutes in ACT. This disconnection between observed ACT and job accessibility raises two not mutually exclusive interpretations. First, there is an effect of the metropolitan fringe where there are TAZs with low access and low ACT. The fringe is a semi-urban area where rural life styles are prominent, and an important share of people is employed in agriculture. Urban jobs would be difficult to reach given high cost of traveling to the inner city. I hypothesize that the expected inverse relationship between ACT and job access would be identifiable if dropping the fringe from the analysis, likewise there could exist different associations between job access and ACT according to different geographical subregions in the metropolitan area. Second, it seems that there is a congestion effect in those areas with high access and high ACT. This means that there are jobs-rich areas that are not connected by efficient

and rapid mass Transit systems such as the subway. Instead people still rely in inefficient semi-formal minibus service. This is the case for employment subcenters in the west and in the south of the MCMA. From a public policy perspective, this disconnection would not mean to discard job access as a way to reduce ACT. Rather, this is why transport public policy must intensify this relationship through physical planning policies that bring opportunities closer to areas where workers that have to take long trips reside.

Using TRANUS data, the EAP has a significant and positive association with commute time for driving alone and for public Transit commuters. The magnitude of this association is similar for both transportation modes. One unit increase in EAD density increases ACT by 0.2min. Using HODS17 data, EAP still holds a significantly positive relation with ACT in both transportation modes, with weak significance for Car (at 10%) and higher significance for Transit commuters (at 1%). The magnitude of this relationship is lower with HODS17 than with TRANUS, where one unit increase in EAD density increases 0.072 min. ACT by Transit. Kawabata and Shen (2007) found that in San Francisco there was a positive relation of population density and commute times by Car, whereas the relation was inverse for commutes by Transit. This is explained as the effect of traffic congestion that slows travel speeds by Car. The inverse relation of Transit happens because the Transit system service is usually better in locations with higher population densities. Nevertheless, in the case of MCMA, there might be a congestion effect for both modes of transportation.

Jobs density is associated with shorter commutes for Car drivers using TRANUS data. In other words, commute time by Car decreases 0.083 min as jobs density increases one unit. However, there is not significant association for Transit users in the Err-ML regression, as in the case of HODS17 data with both transportation modes and both spatial regression models. In these cases, only OLS regressions seem to detect that negative association between jobs density and

ACT. This apparent disconnection of ACT by Transit with jobs density would suggest a mismatch between nearby available jobs and potential skilled workers to fill this labor force demand.

Mixed land use shows a positive association with ACT by Car and Transit with TRANUS data, being significant at 0.05 and 0.1 levels, respectively. One percent increase means an increase of 0.1 min and 0.09 min of commute time for Car and Transit respectively. This association is difficult to explain, but it could be associated with an effect of congestion, as in the case of EAD density. The effect of other mixed land use indicators remains to be tested as a future research line. This positive association between ACT and mixed land use is not consistent with HODS17, where none of the spatial regression model detect any association.

The proportion of female headed households is not associated with ACT with any of the transportation modes. None of the regression models with any travel time data was able to detect any significant association. These results do not show this group as having any spatial relation with the patterns of metropolitan commute time. However, a further analysis of a group formed by the combination of female headed households and low-income populations could be of interest since it could offer a different picture.

An increase in the proportion of illiterate populations is significantly associated with a decrease in commuting time by Car. TRANUS data indicates that 1% increase in the share of illiterate population is associated with 5.2 minutes of decrease in this Car commuting, while this reduction is of 2.7 minutes using HODS17 data. The proportion of illiterate population has weak significance (at 10%) for commuting by Transit with TRANUS data. However, there is no any significant association with HODS17 data.

An increase in the proportion of migrants is significantly associated with an increase of ACT by public Transit. This increment is of 0.61 and 0.54 minutes, according to TRANUS and HODS17 data respectively, for every one percentage increase in the share of residents living in a

different state in 2005 (five years prior to the census year). The situation of migrant workers can be considered to be a fairly consistent effect that reflects the problem of affordable housing close to job centers. This causes recent migrants to reside far from employment locations. This an indication that more public Transit is needed in outlying areas where there are high percentages per TAZ of this population group. The percentage of people with physical disabilities is not statistically significant (at the 5% level) with any model, dataset and transportation mode. Thus, the metropolitan geography where this group reside did not appear to be associated with the pattern of metropolitan ACT.

An increase in the proportion of indigenous populations is positively associated with ACT by driving alone. This association has weak significance (10%) with TRANUS but with HODS17 it turns out to be significant at 5%. According to TRANUS, 1% increase of indigenous populations is associated with an increase of 1.82 min, while for HODS17 the ACT increase is of 2.08 min. In the case of ACT by public Transit, the positive association is significant with HODS17 (5%). The ACT increase is about 2.21 minutes every 1% increase in the share of indigenous residents. I interpret this as a sign of disadvantage in transport for this group due to urban structure. Therefore, the design of transportation programs directed to help this group is a public policy worth exploring. Public investment in TAZs with a high percentage of this group should be made a priority under principles of equity.

3.6 CONCLUSIONS

The intra-metropolitan geography of ACT clearly shows a highly unequal city in the experiences of journeys-to-work. ACT is lower for Car drivers than for Transit users for each TAZ, although the gap is wider in TRANUS than the disparity in HODS17 data. After identifying the periphery that is weakly linked to the rest of the metropolis, what can be detected is a central/west – east dichotomy. Those TAZ with more journey-to-work connections with other TAZ are located in the east, while the job-rich areas are located on a north-south axis slightly positioned towards the west side with clear elongations along highways flowing towards the cities of Querétaro and Toluca. Overall, the relationship between ACT by Transit and distance to the urban center form an inverted U-shaped curve. Commuting times increase as the distance to the urban center increase, reaching a point where commute times decrease in the outer TAZs. Conversely, the relationship between ACT by Car and distance to the center shows a semi flat pattern with a slightly decrease in the outer TAZs.

A strong spatial correlation was detected for ACTs for both Car drivers and public Transit users. However, for the former the magnitude was lower in the HODS17 data according to Moran's statistic. The Lag-ML regression is the correct specification for ACT by Car with TRANUS and HODS17, as well as for ACT by Transit with the HODS17. On the other hand, the Err-ML regression is the correct specification for ACT by Transit with TRANUS.

After controlling for other variables related to urban spatial structure and socioeconomic aspects, job accessibility plays a significantly inverse role in determining ACT for Transit users and for Car users using travel times from TRANUS. Overall, the degree (represented by coefficients) and significance of job access is higher in ACT by Transit users than for Car drivers

in the three regressions. However, this response is not consistent using observed travel times from HODS17, where the significance for Transit users is weak ($p < 0.1$) in the OLS regression and not significant in the Lag-ML regression. The main policy implications are to use job access as a way to reduce ACT, thus intensifying this relationship through physical planning policies that bring opportunities closer to areas where workers have to take long trips. Additionally, it is of great importance to keep building subway lines for those routes for which BRT systems cannot be substitutes, as it has not been the case over the past two decades.

Other covariates were also significant using TRANUS. EAP density is positively associated with ACT by driving alone and for Transit commuters. Jobs density center is negatively associated with ACT by Car, while the significance is weak in the case of Transit users. Mixed land use is positively associated with ACT by both Car drivers and public Transit users.

Using the HODS17 data, the association between ACT and urban form variables was not robust. There is only one result of importance: the positive association between EAP density with ACT by Car (at 10 %) and public Transit (at 1%). Job access does not have a consistent response for ACT with any of the two transportation modes. Longer commute times do not appear to be associated with proportions of population groups such as female headed households, illiterate population, and people with physical disabilities. On the other hand, a consistent result using TRANUS and HODS17 is that an increase in the proportion of migrants is significantly associated with an increase of ACT by public Transit. Moreover, according to the HODS17, an increase in the proportion of indigenous populations is positively associated with ACT for both Car drivers and public Transit commuters.

It is important to point out the limitations of this study. The precision of travel time data sources is of special importance. Travel times in TRANUS and HODS17 data are substantially different. Modeled times should include data not only from travel surveys but also from periodic

measurements on the levels of service in transportation infrastructure in order to offers a more realistic panorama of average travel time between TAZs. Thus, it is strongly recommended that the metropolitan transportation agency in MCMA, COMETRAVI, collects and maintains reliable longitudinal information for a more thorough analysis in the evolution of commuting in the MCMA.

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Chapter 4. URBAN STRUCTURE AND ITS INFLUENCE ON TRIP CHAINING COMPLEXITY IN THE MCMA

Abstract

This project studies the relationship between the urban structure of the Mexico City Metropolitan Area (MCMA) and two aspects of commuter travel patterns: 1) number of stops in a tour and 2) complexity of trip chaining. Two regression models were explored, one for each dependent variable of interest. The analysis was applied for Car drivers, Transit users and travelers with mixed transportation separately. Covariates include individual, household, travel and urban form variables, which showed differential effects according to the transportation mode. According to the number of significant covariates, it can be said that there is less impact of urban form on trip generation and complexity of travel for Car drivers (only mixed land use at destination being significant for complexity of travel) and mixed transportation (being only significant mixed land use at origin and destination for extra trip, and jobs and population densities for complexity of travel) than for Transit users (being significant job access and population density for complexity of travel, mixed land use at origin and jobs density for extra trip, trip rates and complexity of travel). The directions of these effects vary according to the transportation mode and are discussed in terms of reported literature.

4.1 INTRODUCTION

By the end of the first decade of the 21st century, more than half of the world population lives in urban settlements. With an increasing worldwide urbanization trend, developing countries are absorbing most of this urban expansion. In MCMA, like in any city in the developing world, suburbs are dominated by poor and densely populated neighborhoods whose residents face long and expensive trips on multiple modes of public transportation to reach centrally located jobs (Guerra, 2017). The quality of public Transit and road infrastructure decreases in a trend center - periphery, having a significant variation in transportation fees as a cause of a discontinuity of metropolitan Transit services (Flores-Espinosa, 2018). Even households located in low-diversity and inaccessible peripheral neighborhoods, when using a Car, must drive a ‘a lot’ (Guerra, 2014).

A broad body of literature consistently confirms that the use of private motor vehicles is positively associated with an increase of complex trip chains (more intermediate stops) in the journey to work given the flexibility of transportation (Currie & Delbosc, 2011; Silva, 2018; Wallace et al., 2000; Wang, 2015). Concas & DeSalvo (2014) argue that in the US long commutes are positively associated with the use of private Cars and that an increase of complex trip chaining is considered a strategy of households to deal with expensive work trip costs, allocating non-work-related activities on the way to work. In this context, impacts on travel chaining patterns of long commutes in the developing world remain less understood. How do commuters (both Transit users and Car drivers) respond to long travel distances in their travel chaining behavior? Is the urban structure playing a role for this to happen? There is limited evidence to answer these questions even today.

In this paper, the previous questions are addressed by having trip generation and complexity of travel as aspects of travel demand to analyze, while urban structure remains as the key explanatory variable of interest. This is further operationalized with indicators such as job accessibility and distance to the metropolitan center. The effect of the built environment is additionally tested with a mixed land use indicator at Traffic Analysis Zone (TAZ)-level. In literature analyzing the travel behavior-built environment relationship, the main methodological challenge has been to isolate the direct effect of the built environment controlling different covariates and indirect effects, if people make rational decisions about location (Boarnet, 2011). Indeed, different travel behavior aspects can have interrelated effects. This is part of the academic debate to determine and quantify the direction of these interrelations. In this direction, several studies report that a traveler decided a trip chain pattern before making mode choice, not the other way around (Ye et al., 2007; Yang et al., 2016). Xianyua (2013) agrees with this, although his study recognizes that a considerable variation in decision order exists given that nearly 30% of the cases showed a mode choice first decision order.

Thus, any analysis having transportation mode as an explanatory variable of trip chaining is prone to fall in an endogeneity bias. However, Wang (2015) argues that commuting can be reasonably regarded as less endogenous to other schedule and travel decisions given that, for most commuters, travel comprises of mostly fixed daily destinations at the same hours, thus the engagement, duration and location of work are generally determined by long-term and/or outside factors evaluated through a planned behavior based on aspects of individual and household needs and costs. Therefore, this author argues, analyzing commute tours independently from other tours may not produce a significant bias relative to a full-fledged activity-based travel demand analysis.

In MCMA, mode choice of transportation is primarily driven by socioeconomic aspects, where affluent households tend to predominantly use private Cars (Guerra, 2014). Even Car ownership geography is highly related to income (Guerra, 2015). In a preliminary descriptive analysis in our case study, trip chaining is more prevalent for Car drivers than for Transit users in concordance with existing literature. Therefore, this paper aims to determine the effect of urban structure on trip generation besides the role of transportation mode. Thus, at individual level analysis, this research addresses the following questions: 1) whether there is a relationship between urban structure and trip generation of commuters, and 2) whether there is a relationship between urban structure and travel complexity of commuters. Are these relationships different for Car drivers than for Transit users? These questions are addressed using two different regression models. In the first, the number of extra trips (beyond the basic tour home-work-home) will be used as the dependent variable, a count model being appropriate. Then, in order to elucidate the characteristics of trip complexity, an ordered multinomial model is applied. Here the dependent variable is categorical with three ordered levels: Simple Trip Chain (STC), Complex with Intermediate Stops (CIS) and Complex with Home-based Stopovers (CHS). The analysis is done for Car drivers, Transit users and commuters with mixed transportation separately.

4.2 LITERATURE REVIEW/BACKGROUND

4.2.1 *Urban structure and trips complexity*

There is a broad body of research having trip generation, trip chaining and trip complexity as objects of study. These terms are often used interchangeably unless a difference is noted. A trip chain pattern refers to a sequence of trips that starts and ends at home within a day. Thus, this home-based tour connects multiple out-of-home activities (Primerano et al., 2008). In the case of commuting, that tour entails a sequence of trips linked together between two anchor destinations, such as home and work (Concas & DeSalvo, 2014). This commuting-based trip chain might contain one or more commuting trip purposes regardless the existence of other purposes (Yang et al., 2016). A travel tour involves the chaining of trips. Thus, both concepts also tend to be used interchangeably in the literature. An individual trip within a trip chain or tour is not consistently defined in the literature. Often individual segments of travel in a trip chain can be referred to as “legs” or “stops”, where these trip legs might involve an intervening activity (e.g., work or shopping) but can also involve changing modes (e.g., a bus to rail interchange) (Currie & Delbosc, 2011). Whether we consider stops (like minor activities) or trips by themselves (might be major activities) or both, it is important to define them first. For example, Wang (2015) worked specifically with those commuters having only the Home-Work-Home travel and analyzed the intervening stops, which according to the US National Household Travel Survey (NHTS), are activities lasting 30 min or less.

There are two main approaches to measuring trip complexity (or trip chaining) at individual or household level: 1) number of stops made during a tour (or the chains within the tour being defined as the trips or trip chains or links) and 2) using categories of the shape of the travel. In the

first approach, trip chaining is a numerical variable, a tour being more or less complex depending on the number of legs per chain (examples are Noland & Thomas, 2007; Wang, 2014; Currie & Delbosc, 2011). In the second approach, tour categories are referred according to the sequence of trips. Each author might define their own categories. However, it is possible to identify some basic groups. For example, a tour in the form home-work-home (HWH) is a simple work chain with no intermediate stops. A tour in the form home-work-other activity-home (HWOH) is a complex work chain, with “O” being any other non-commuting activity, and trip generation can be counted as those intermediate stops between home and work (HW) traveling. Researchers could focus on intermediate stops before or after work or both, counting the total stops. In a tour of the form home-work-home-work-home (HWHWH), the chain contains commuting trips with a mid-trip that returns home. In this tour there can also be non-commuting activity stops (examples are Kuppam & Pendyala, 2001; Yang et al., 2016). Both approaches of measuring complex trip chaining can be coupled if the number of intermediate stops is counted for specific categories of trip chaining.

Trip chaining is a facet of travel behavior of interest in different aspects of transportation studies. For example, patterns of trip chaining inform travel demand models in order to improve their forecasting power (Kuppam & Pendyala, 2001), thus having an important implication in respect to Transportation Demand Management (TDM) (Wallace et al., 2000) which is essential for the planning and management of transportation systems. Trip chaining is also an important variable mediating in the relationship between built environment and other aspects of travel behavior such as travel mode choice (See Concas & DeSalvo, 2014; Van & Witlox, 2011; Xianyua, 2013) or distance traveled (Chen & Akar, 2017; Silva, 2018). Additionally, an emerging field in the intersection of transportation and social policy aims to unveil the link between trip complexity and transport related social exclusion (Delbosc & Currie, 2011).

As part of this diversity in study approaches, trip generation and chaining methodologies used vary in great extent. Some studies have focused on the relationship between activity participation and travel complexity to understand how individuals make travel decisions given their use of time under the time-budget approach (see for example Golob, 2000). However, these studies often lack an explicit component for the built environment. On the other hand, other models focus on transportation mode decisions as main variable of interest, incorporating urban form variables and trip complexity as a mediating variable, although in this case often omitting activity participation variables (for example in Concas & DeSalvo, 2014). Models can become very complex when they add an increasingly number of variables, making it difficult to identify particular relations of interest, thus determining the scope of the study is an important aspect to consider. Overall, in the literature there has been interest to know how such trip complexity is affected by socioeconomic aspects, travel variables, the built environment and travel mode.

4.2.2 *Determinants of trip complexity*

Without being extensive, the following literature review will sum up the main findings that underlay initial expectations for the present case study. A consistent report in the literature is that gender (females) and age have a positive relationship toward increased trip chaining (Noland & Thomas, 2007; Susilo & Kitamura, 2008; Yang *et al.*, 2010; Kuppam & Pendyala, 2001; Chen & Akar, 2017; Wang, 2015). In the case of age, Bhat (2001) points out that the relationship is not linear given that until a certain point, the direction turns negative. In this study, the threshold was 96 years old. Other authors also report that elderly people tend to make simple tours (Chen &

Akar, 2017; Kuppam & Pendyala, 2001). Thus, the direction of the effect would depend on age range under testing. In the case of educational attainment, it has been reported that having a college or a higher degree increases the number of stops in a tour (Wang, 2015; Silva, 2018).

In the case of household income and the presence of children in the household, most evidence suggests that they increase trip chaining (Kuppam & Pendyala, 2001; Bhat, 2001; Goulias & Kitamura, 1989; Strathman *et al.*, 1994; Krizek, 2003; Susilo & Kitamura, 2008; Wang, 2015; Noland *et al.*, 2007). However, some reports contradict this. Chen & Akar (2017) and Wallace *et al.* (2000) found that household income has negative impacts on trip chaining. Wang (2015) also found that household income level has little, if not a negative, relationship with commute trip chaining. This author argues that the difference between reports may come from the fact that they do not distinguish commute tours from other trip chains. Bhat (2001) found that households with small children are likely to return directly home after work rather than making an evening commute stop.

Household size decreases the tendency of trip chaining, i.e., they are negatively associated (Chen & Akar, 2017; Susilo & Kitamura, 2008; Van Acker & Witlox, 2011; Wallace *et al.*, 2000). Wallace *et al.* (2000) indicates that this is because larger households may have a greater number and variety of destinations, which decrease the tendency of making complex tours. Kuppam & Pendyala (2001) argue that commuters belonging to large households are more likely to have children and greater household obligations. This contributes to fewer out-of-home activities (and possibly a greater in-home activity engagement) and complex chains. However, Wang (2015) found that having young children significantly increases the number of stops. On the other hand, an increase of adults in a household has a negative impact on the number of stops, because stops made for household needs can be split amongst adult household members. Noland *et al.* (2007) found that households with a single adult, regardless of the number of children, make more

complex trips than those with two adults. This would suggest that household size should be related to adults and the number of children should be taken as a separate variable.

The previous socioeconomic variables, which can capture the effects of workers' needs and preferences, are considered to be stronger determinants of tour complexity than land-use characteristics. In this sense, the effect of land use patterns, which affect the cost of travel, on trip chaining are still inconclusive and subject of analysis given that inconsistent and even conflicting findings remain (Wang, 2015).

The role of population density is not consistent. Noland & Thomas (2007) found that people in low population density neighborhoods tend to rely much more upon trip chaining and tours that involve more stops along the way, indicating that this would compensate for location deficiencies. Ma *et al.* (2014) also found that density reduces tour complexity. Wang (2015) found little relationship between number of stops and land use densities at local level (i.e., census tract level population density at the home and job ends and city level employment density at the job end). On the other hand, some studies suggest that higher densities are associated with more complex tours (Chen & Akar, 2017; Antipova & Wang, 2010). The hypothesis of a positive relation between density and trip chaining is stated by Crane (1996) who argues that more dense and diverse urban areas might encourage trip-chaining as a way to decrease travel distances, but since they could reduce the marginal costs of additional trips that could be included in the chain. The final effect might be an increase in the total number of trips.

The effects of accessibility are also mixed. The effect of population density is related to that of access, which can sometimes be considered interrelated, such as the case of Noland & Thomas (2007), who used population density as proxy of accessibility. Some studies point out that accessibility is negatively associated with tour complexity (e.g., Krizek, 2003; Limanond &

Niemeier, 2004; Williams, 1988). On the other hand, Golob (2000) found that network and especially zone-level accessibility indexes are positively related to participation in out-of-home non-work activities and homebased non-work trip chains. Ma *et al.* (2014) also argue that greater public transport accessibility increases trip chaining. Accessibility as a multidimensional concept is measured in different ways, so this can be the source of disagreement.

The effects of mixed-land use patterns on tour frequency are also diverse. Higher presence of shops and services where travelers live and work is associated with reduction of activity stops within commute tour (Frank *et al.*, 2008). Similar findings are reported by Chen & Akar (2017), who argue retail density influences trip chaining negatively, however non-retail density affects it positively. Ma *et al.* (2014) found that mixed land use at workplaces having higher density and accessibility is associated with more stops within one work tour or a more complex tour pattern. Overall, this supports the hypothesis stated by Crane (1996) in which mixing urban activities could increase trip chaining.

Location of residence and travel in relation to the urban center have also been objects of study. In Melbourne, Australia, Delbosc & Currie (2011b) found that the volume of travel generally increases with distance from the center. The fringe sample has the highest trip rates and longest distances travelled. Wallace *et al.* (2000), using data from Seattle, Washington, found that accounting for household characteristics, tours based in urban centers include fewer trip links, while those living outside urban centers are more likely to plan complex tours. Bhat (2001) found that an individual whose home is located in an urban area is more likely to return home directly after work (i.e., is less likely to make a stop during the evening commute). It can be said that the context of a specific city regarding its urban structure would determine the effect of this variable on trip chaining.

Sometimes travel characteristics are included in the study of trip chaining as important covariates to control. Another approach is used when trip chaining is considered as a variable mediating other travel behavior variable of interest. Wallace *et al.* (2000) found that, as the distance between home and work increases, so does the number of stops along the way. Thus, people living further away from work tend to chain more trips together, which reduces the average distance and travel time of each individual trip as more trips are linked. Wang (2015) also found that distance to work has a rather small effect on the number of stops during commute. In Table 4.1 there is a summary of these initial expectations.

Table 4.1. Expected determinants of travel complexity

Variable	Aspect	Expected influence on trip chaining
Gender (female)	Socioeconomic	Positive
Age	Socioeconomic	Non-linear; increasing with age until inflection point then decreasing with age
Educational attainment	Socioeconomic	Positive
Household income	Socioeconomic	Not consistent
Number of children in the household	Socioeconomic	Not consistent
Household size	Socioeconomic	Negative
Population density	Socioeconomic	Not consistent
Accessibility	Urban form	Not consistent
Mixed-land use	Urban form	Not consistent
Location of residence in relation to the urban center	Urban form	Peripheral area residents chain more than those living in the urban center

4.2.3 *Travel mode choice, urban form and socioeconomic aspects of commuting in MCMA*

To my understanding, there has not been a previous study about trip chaining and travel complexity in MCMA. Only basic descriptions comparing trip rates among states have been reported where travelers from Mexico City (where the inner city is located) make more trips than people from the State of Mexico (where most of the suburbs are located). In Mexico City, the average number of trips per traveler is 2.26, while in the State of Mexico is 2.16. This same trend is found either per dwelling or household (INEGI, 2017). In terms of commute time, the average commute is longer in State of Mexico than in Mexico City (INEGI, 2017).

As explained above, a consistent report in different contexts is that using a Car is an important factor to increase trip rates. The obvious explanation is that a Car offers flexibility to make multiple stops in the work trip, unlike Transit systems that rely on rigid routes. In MCMA, Car ownership is highly associated with income and residential location. Guerra (2015) asserts that central locations are where wealthier households tend to live owning and driving Cars, while poorer households rely more on Transit and tend to live further from the urban center. Furthermore, when driving, these households must travel longer distances to work (Guerra, 2014). This allow us to hypothesize the role of location for travel complexity, where those suburban residents driving a Car could make a less complex trip than those drivers in the inner city. This could be even more significant for Transit users.

As to socioeconomic aspects and commuting in MCMA, Suárez *et al.* (2016), using two linear programming transportation models, found that low-income workers make shorter commutes. This is probably explained by the location of informal work activities as a response to the disadvantages of the urban structure of formal employment and housing. As explained above,

in MCMA income is highly related to travel mode, Transit being predominant for the poor. Thus, the effect of income on travel complexity beyond its effect on travel mode could be hypothesized to be positive in consistency with most of existing literature. Educational attainment and age are expected to have a positive relationship, as well with travel complexity as they are correlated with the use of a Car. In the case of gender (female), a positive relation can be expected in congruence with the literature, even though they tend to use a Car less (Guerra, 2014).

In the case of urban form and commuting in MCMA, Guerra (2017) found that Transit expenditures are significantly and substantially associated with factors such as Transit supply and urban form, this relation being positive for distance to the subway and negative for job and population density. Thus, based on these findings, I could hypothesize that those factors decreasing Transit expenditures would be tending to increase travel complexity. In other words, lower job and population densities are associated with more complex trips and trip rates.

4.3 RESEARCH OBJECTIVES AND HYPOTHESIS

Objectives

- To determine whether there is a relation between urban structure and trip generation of commuters. Are these relationships different for Car drivers than for Transit users?
- To determine whether there is a relation between urban structure and travel complexity of commuters. Are these relationships different for Car drivers than for Transit users?

Hypothesis

- It is expected that urban structure will have an association with trip rates and travel complexity of commuters. It is expected that this association will be stronger for Transit users than for those Car drivers.

4.4 METHODOLOGY AND DATA

4.4.1 *Data*

The main source of data is the 2017 Household Origin-Destination Survey (here referred as HODS17) (INEGI, 2017) which collected individual trip data together with household, dwelling and socioeconomic characteristics of the traveler. Travelers with at least one trip to work were considered as commuters, and all their trips in a weekday within the MCMA were subset from the original dataset. For each commuter, individual trips were aggregated into tours. Each commuter has their own single tour, which works as the analysis unit. Each tour can consist of one trip or of two or more trips chained together. The focus is on the tour as a whole and not only in the journey to and from work, as it is sometimes considered.

The way in which travel information was recorded follows a trip-purpose approach rather than an activity-based approach. This means that every movement from one place to another was recorded as a trip with a corresponding purpose in its destination. Thus, the number of trips is highly related to the number of out-of-home activities pursued by each traveler. This can be considered as a participation-based access measure, i.e. those places reached by the traveler. Ten different purposes are recorded: 01 to home; 02 to work; 03 to study; 04 to shop; 05 leisure and

recreation (with family or friends); 06 to take or pick up someone; 07 to do paper work; 08 medical assistance; 09 a religious activity; 10 other. Purposes 01 and 02 (to home and to work) account for 95% of trips done by commuters.

In the HODS17, each trip is split by segments for each mode of transportation used. Individual legs within a trip are referred to as changing transportation modes, not stops. Thus, one trip can have more than one mode of transportation. In the survey, twenty options were considered, such as private Car, *colectivo* (minibus), cab, subway, BRT, cableway, walking, etc. Unlike other studies that consider the transportation mode for the tour as that used in the trip to work or those that apply an ordering scheme to assign a specific transportation mode to the tour, I considered three tour categories, tours with Car-only trips (20.7%); tours with no Car-only trips, i.e. multimodal excepting Car trips (76.7%) and tours joining Car-only trips and no Car-only trips (2.6%). However, for simplicity, I renamed these categories as Car drivers, Transit users, and commuters with mixed transportation, respectively. The Transit user category includes modal non-Car transportation including walking-only tours (12%) and biking-only tours (2.57%), but the majority corresponds to multimodal Transit tours (80%).

For each trip, the HODS17 recorded number of stops (stops of less than 10 min with no additional transport fee payment). They represent participation in minor activities, which include leaving or picking someone up, going to a gas station; going to an ATM, making a quick purchase, attending a brief meeting, resting, doing some quick paper work or other. As a first approach studying commuting-based trip chain in MCMA, this paper considered such intermediate stops (minor activities) and trips (major activities) together and named these generically as “trips” (“stops” are also called interchangeably). The basic tour home (H)-work(W)-home(H) was considered as the base line from which extra trips by commuter were counted. Thus, the first

dependent variable of interest is a composite variable called “number of extra trips” (beyond the loop HWH). They can also be considered as stops by themselves as in most of the literature. The measurement is a count of the number of stops, thus this variable results in a generic indicator of trip generation. Although tours made by commuters comprise trips that are linked, the term *trip chaining* is not used because in the literature this term often refers to trips (or stops) between to anchor destinations (HWH) and not to extra trips done after getting home, which can be trips to other jobs or any other activity. Thus, commuters having only the pair of trips (home-work-home) will be assigned 0 extra trips. Some assumptions are that commuters with record of only 1 trip to work were assigned 0 extra trips (these trips might correspond to people working at night shifts), while those having two work trips were assigned 1 extra trip. The intermediate “gas station” stop was removed because this activity is associated specifically with the use of a Car and this might artificially increase Car trip generation.

The second variable of interest is related to categorizing the travel pattern of commuters, where I include all trips done in a weekday. To do this, I drew on definitions used by Jang (1996), who considers a trip as travel originating at home and returning eventually to home. His categories include the trip Home-Work-Home as a Simple Trip Chain (STC). If in this trip there are intermediate stops before returning home, the tour is categorized as Complex with one trip. When there is one return trip to home before going to any other destination, then the tour is considered as Complex with two trips (Figure 4.1).

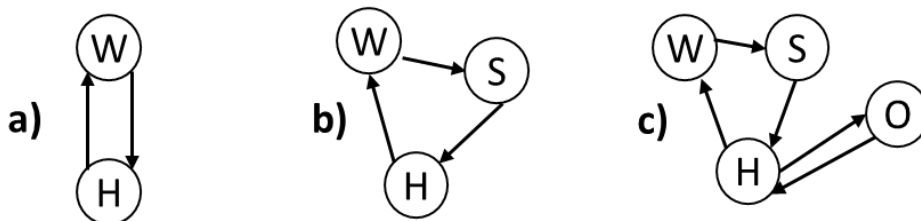


Figure 4.1. a) Simple trip chain, b) Complex with one trip, c) Complex with two trips (Jang, 1996).

In the present paper the categorization of travel patterns of commuters will be based on these categories but with some important nuances. Simple Trip Chain (STC) will still correspond with that Home-Work-Home tour, which in the HODS17 is recorded as two trips: one trip going to work and one going home. Complex with intermediate stops (CIS) will correspond to tours with intermediate trips before or after going to work, thus having at least three trips according to the HODS17. The third category will be Complex with home-based stopovers (CHS). This includes tours where there are intermediate stops at home. In the HODS17 the number of trips will vary according to the intermediate stops at home and other activities pursued, but a basic CHS tour would have at least four trips recorded. Hereafter, tour is used to refer to these three categories. Thus, the measurement of this variable is this categorical specification with the corresponding three ordered levels.

Covariates include the socioeconomic status of the dwelling recorded in four classes (see Table 4.2). As characteristics of commuters three variables were considered: gender, age and educational attainment. According to the departure trip time and arrival trip time, travel time of each trip was calculated. Then, for each tour, travel time from household to work was selected. In case of more than one trip to work, the first was selected. For those travelers for which travel to work was not their first trip, travel time from the Traffic Analysis Zone (TAZ) of household to the TAZ of work was used. This variable reflects the cost of travel to work. Total travel time of tour was not considered given that it can be endogenous because the number of trips is positively associated with the total duration of the tour (Wallace, et al 2000).

Travel distance was initially considered from the network street from the TAZ where the household is located to the TAZ of work location in their first work trip. However, with this latter variable, I had problems in the model estimation given a lack of convergence, probably due to its partial correlation with travel time and the fact that the same distance is shared between several trips with the same TAZs in origin and destination. Thus, network distance from home to work was dismissed.

In terms of urban form variables, I draw on an index of mixed land use (MLU) estimated at the block level by Montejano et. al. (2016). This indicator ranges from 0, which indicates a concentration of one class of land use, to 1, which indicates a perfect balance between four land use classes: residential, leisure, services and commercial). This indicator takes the centroid of each block and within in a buffer of 500 mts where all economic units recorded in the census are counted, I considered the percentage of the area of blocks within each HODS17-TAZ with an index value higher than 0.225 (percentile 75). Another variable is distance to the center, which is measured from the commuter TAZ of residence to the central TAZ, where the historic center (also called Zócalo) is located, in both cases using the centroid as a point of reference. Unfortunately, there is no more specific geographical information of house location in HODS17. To describe job accessibility, I used a Shen's type indicator at area level, this indicator is calculated separately for different modes of transportation. In the regression models, the corresponding job access index was included according to the transportation mode of commuters. For commuters with mixed transportation, the general job accessibility indicator was used. The formula developed by Shen (1998) is a variation of the Hansen Accessibility Index that captures the 'demand side' of accessibility, that is, the spatial distribution of workers. This indicator was calculated for the MCMA at TAZ-level of the HODS17 in Chapter 2 of this dissertation. The general accessibility

considers the average accessibility calculated for Transit users and Car drivers. This indicator is a dimensionless variable; however, its magnitude is related to the relationship between workers and available jobs. For example, the average accessibility in the region (MCMA) is the ratio between the number of jobs (total trips to work 6,811,580) and the number of potential workers (Economically Active People, EPA 8,966,847), which is 0.76. The average of accessibility among TAZs weighted by EPA result in that same regional average as in the relationship demonstrated by Shen (1998). Shen's indicator suggests important nuances of locational accessibility, as the most opportunity-rich neighborhood scores ten times higher (7.6) than this metropolitan average. The complete list of covariates and the way they were coded can be seen in Table 4.2 and 4.3.

Descriptive analysis indicates that a low degree of correlation exists between covariates. The Variance Inflation Factor (VIF) indicator shows values lower than 3 for any variable in the whole covariates vector. This indicates a low risk of presence of multicollinearity that results in a loss of precision in parameter estimates. Another aspect to consider is self-selection, which is difficult to control given the availability data. Guerra (2014) points out three reasons that make this process less relevant on biasing estimates than what is expected in US cities. The first is that self-selection is more likely to be an issue when rates of ridership are low in comparison with Car use, which is totally opposite to the case of MCMA. The second is that only the wealthiest households have substantial control over where they live, and they do that in the inner city where Transit access is high and there is great diversity of land use. The third is that Transit service is ubiquitous, even in suburbs in the form of minivans or minibuses.

Table 4.2. Description of categorical dependent and independent variables

Variable	Transit	Car	Mixed
<i>Dependent Variable</i>			
Travel complexity ¹	STC: 43763 (91.8%) CIS: 2154 (4.5%) CHS: 1754 (3.7%)	STC: 11256 (87.5%) CIS: 1009 (7.8%) CHS: 601 (4.7%)	STC: 731 (46.4%) CIS: 444 (28.2%) CHS: 401 (25.4%)
<i>Explanatory variables</i>			
Dwelling socioeconomic category ²	L: 441(0.9%) ML: 28613 (60%) MU: 15138 (31.8%) U: 3479 (7.3%)	L: 40 (0.3%) ML: 4854 (37.7%) MU: 4340 (33.7%) U: 3632 (28.2 %)	L: 7 (0.4%) ML: 650 (41.2%) MU: 602 (38.2%) U: 317 (20.1%)
Gender ³	M: 28447 (59.7%) F: 19224 (40.3%)	M: 8946 (69.5%) F: 3920 (30.5%)	M: 761 (48.3%) F: 815 (51.7%)
Kin ⁴	HH: 20831 (43.7%) S: 6972 (14.6%) DS: 14570 (30.6%) GCh: 854 (1.8%) O: 4143 (8.7%) NK: 301 (0.6%)	HH: 7310 (56.8%) S: 2101 (16.3%) DS: 2648 (20.6%) GCh: 86 (0.7%) O: 658 (5.1%) NK: 63 (0.5%)	HH: 613 (38.9%) S: 422 (26.8%) DS: 414 (26.3%) GCh: 22 (1.4%) O: 94 (6%) NK: 11 (0.7%)
Educational attainment ⁵	Ns: 723 (1.5%) Be: 22703 (47.6%) Dk: 54 (0.1%) Me: 14219 (29.8%) Hi: 9972 (20.9%)	Ns: 57(0.4%) Be: 3053 (23.7%) Dk: 16 (0.1%) Me: 2871 (22.3%) Hi: 6869 (53.4%)	Ns: 6(0.4%) Be: 447 (28.4%) Dk: 4 (0.3%) Me: 402 (25.5%) Hi: 717 (45.5%)

Note: ¹ Simple Trip Chain - STC, Complex with intermediate stops - CIS, and Complex with home-based stopovers - CHS; ² Lower class - L, Middle Lower class - ML, middle upper class - MU, upper class - U; ³ Male - M, Female -F; ⁴ Head Household - HH, Spouse - S, Daughter/Son - DS, Grandchild - GCh, Other - O, No Kin - NK; ⁵ No school instruction - Ns; Basic education - Be (Pre-elementary school; Elementary school; Junior High School); Medium - Me (Vocational schools-JHS; High school; Normal school; Vocational schools-HS); and High - Hi (Bachelor; Master and PhD); Don't know - Dk;

Table 4.3. Description of numerical dependent and independent variables

Variable	Transit				Car				Mixed			
	\bar{x} :	σ :	min:	max:	\bar{x} :	σ :	min:	max:	\bar{x} :	σ :	min:	max:
<i>Dependent Variables</i>												
Number of extra trips ¹	0.27	0.73	0	13	0.46	0.95	0	10	1.37	1.57	0	12
<i>Explanatory variables</i>												
Age (years)	39	13.5	6	95	42.7	12.2	6	90	39	13.1	6	81
Household Size ²	4.1	1.85	1	22	3.8	1.68	1	16	3.9	1.63	1	15
Number of available vehicles in the household ³	0.34	0.58	0	6	1.35	0.82	0	8	1.01	0.78	0	6
Time traveled to workplace (min)	57.8	40.3	1	360	49.3	32.1	1	390	45.7	34.4	1	240
Job Accessibility ⁴	0.71	0.14	0.19	0.93	0.88	0.12	0.32	1.07	0.77	0.14	0.22	0.96
Pop Density (pop/ha)	124.4	60.7	15.2	286.6	112.7	58	15.2	286.6	118	55	15.2	286.6
Jobs Density (Jobs/ha)	40.68	60.9	2.52	555.3	44.94	49.62	2.52	555.3	47.3	54.5	2.52	555.3
Mixed land use at Origin (%)	30.1	21	0	96.2	28	19.0	0	96.2	29	19.6	0	96.2
Mixed land use at Destination (%)	38.2	24	0	96.2	36.3	22.3	0	96.2	37.2	23.2	0	96.2

Note: ¹Counts; ² Average Household size is the ratio between number of people in the dwelling and the number of households in the dwelling; ³ Counts; ⁴ Dimensionless variable.

4.4.2 Regression Models

As mentioned above, the unit of analysis is the weekday commuter tour. Models were separately applied for Car drivers, Transit users and commuters with mixed transportation.

The first model analyzes the relationship between the number of extra trips (stops) each commuter made and the urban structure controlling for socioeconomic characteristics. The outcome y_i (extra trips) is modeled using the Zero-Inflated Negative Binomial (ZINB), given the presence of lots of zeros which is probably structural, indicating an additional process by which the individual is very unlikely to have any extra trip events. The percentage of zeros in Car tours is 73.45%, in Transit tours is 83.41% and in mixed transportation tours is 39.59%. I considered some zeros could occur by chance even between individuals with some non-trivial chance of extra trips. ZINB is a two-component mixture model combining a Negative Binomial event count with an additional point mass at zero:

$$\gamma_i \sim ZINB(\Psi_i; \lambda_i; \alpha) \quad (4.8)$$

$$\text{logit}(\Psi_i) = \mathbf{z}_i \boldsymbol{\gamma} \quad (4.9)$$

$$\text{log}(\lambda_i) = \mathbf{x}_i \boldsymbol{\beta} + \text{log}(t_i) \quad (4.10)$$

y_i is a structural zero with probability ψ_i . Otherwise, it is a (potentially zero) count with expected value λ_i and overdispersion α . The covariate vectors \mathbf{x}_i and \mathbf{z}_i are potentially overlapping. Thus, the model for counts (betas) was estimated for the vector (\mathbf{x}_i) of covariates. On the other hand, in the model for Zero-inflation (gammas) the vector (\mathbf{z}_i) was the same that for the count model. Estimation of ZINB was done using *zeroinfl* in the *pscl* library in R.

For the trip complexity variable an ordered probit model was applied. The compact equation is:

$$\Pr(y_i = j | x_i) = \int_{\tau_{j-1}}^{\tau_j} \text{Normal}(x_i \boldsymbol{\beta}, 1) dx_i \boldsymbol{\beta} \quad (4.11)$$

where y is an ordered response variable, i indexes cases, j indexes categories of the response, τ is a $j + 1$ vector of cut points with $t_0 = -\infty$, $t_1 = 0$, and $t_j = \infty$ for identification, x is a vector of covariates, and $\boldsymbol{\beta}$ is a vector of coefficients.

Counterfactual simulations were run and graphed using R packages *tile* and *simcf*.

4.5 RESULTS AND DISCUSSION

There were 132,420 single trips by commuters within MCMA recorded in the HODS17 for an average weekday. Those were done by 62,113 commuters. Some commuters made more than 1 trip to work, thus 64,321 single trips to work were completed on an average weekday. The frequencies of number of extra trips have a right skewed distribution, the magnitude of the zero-inflation by transportation mode is an indicator that this plays an important role in determining the number of extra trips. Thus the differences in the quantity of zeros according to transportation mode (Transit users > Car drivers > Mixed transportation) are statistically significant (one tail two-sample z-test for proportions, p-value < 2.2e-16) (Figure 4.2). This means Transit users tend to generate fewer extra trips than Car users, and users with mixed transportation tend to generate more trips than these two categories. In other words, commuting by Car is associated with higher trip generation than using Transit, which is an aspect highly reported in the literature. The explanation could be that a Car provides more flexibility in comparison to Transit to better accommodate the needs of trips with multiple purposes and stops (Yang et al., 2016). A model having transportation mode as covariate confirmed this (results not showed). In regards to trip

complexity, transportation mode plays also an important role. For example, for Transit users the share of STC (91.8%) is considerably higher than the share it has for Car (87.4%) drivers and mixed transportation (46.3%) (Figure 4.3). In order to have a more detailed analysis of the effect of urban structure on trip chaining, I decided to apply a regression analysis for each transportation mode separately

Each covariate is analyzed joining together the results of the three models, logit and count sub-models in the ZINB model (Table 4.4) and the probit model (Table 4.5), in this order given the interrelation among them. This way there is a better integration and conveying of the main findings. The logit sub-model refers to the probability of a structural extra zero. Thus, a positive coefficient means an increment in the probability of making zero trips, and a negative coefficient means an increment in the probability of making an extra trip. In the count model, a significant positive coefficient increases the probability of larger counts of events, in this case extra trips, while a significant negative coefficient increases the probability of reducing the counts. Finally, in the ordered probit model a positive significant coefficient favors the result in the highest category, in this case the more complex trip pattern (CHS), while negative coefficients favor outcomes toward the lowest category, the less complex pattern (SCT). In the probit model, coefficients are difficult to read (Table 4.5). To show more effectively the impact of covariates in the outcome, counterfactual simulations were done. These are displayed in Figure 4.8 for Car drivers, in Figure 4.7 for Transit users, and in Figure 4.9 for mixed transportation. It is to be noted that probabilities for the first two groups, Transit users and Car drivers, are very close to 1 for STC trips. This happens because, in the data, this tour category is highly representative, especially for Transit representing 91.8% of commuters. Covariates influence in different ways the probabilities

of the three categories. Probabilities for mixed transportation show mode balance probabilities among trip chaining categories.

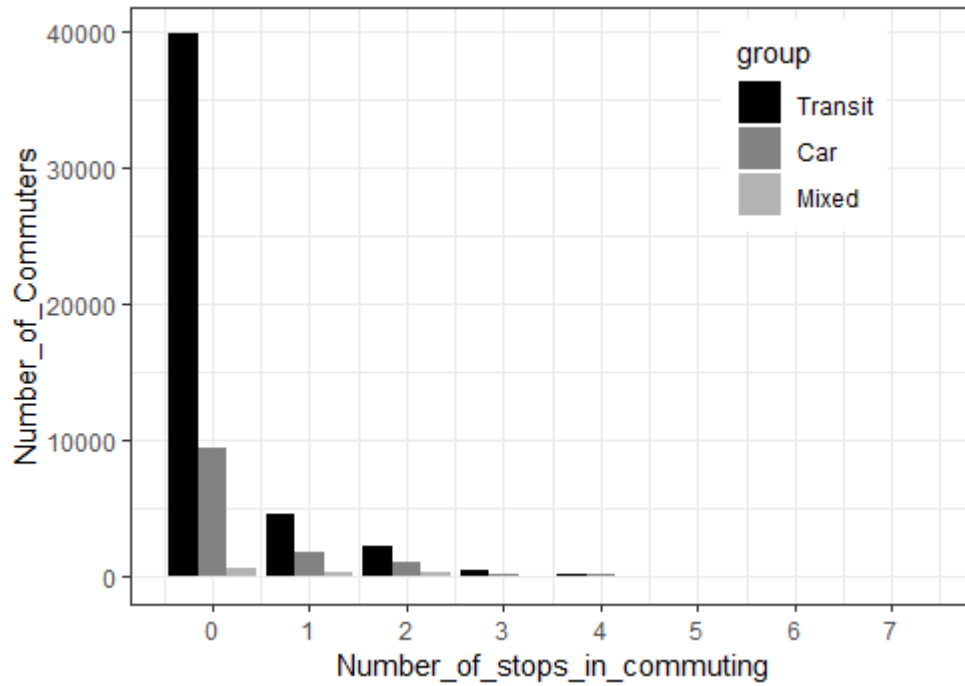


Figure 4.2. Number of extra stops for commuters traveling by Car, Transit and mixed transportation.

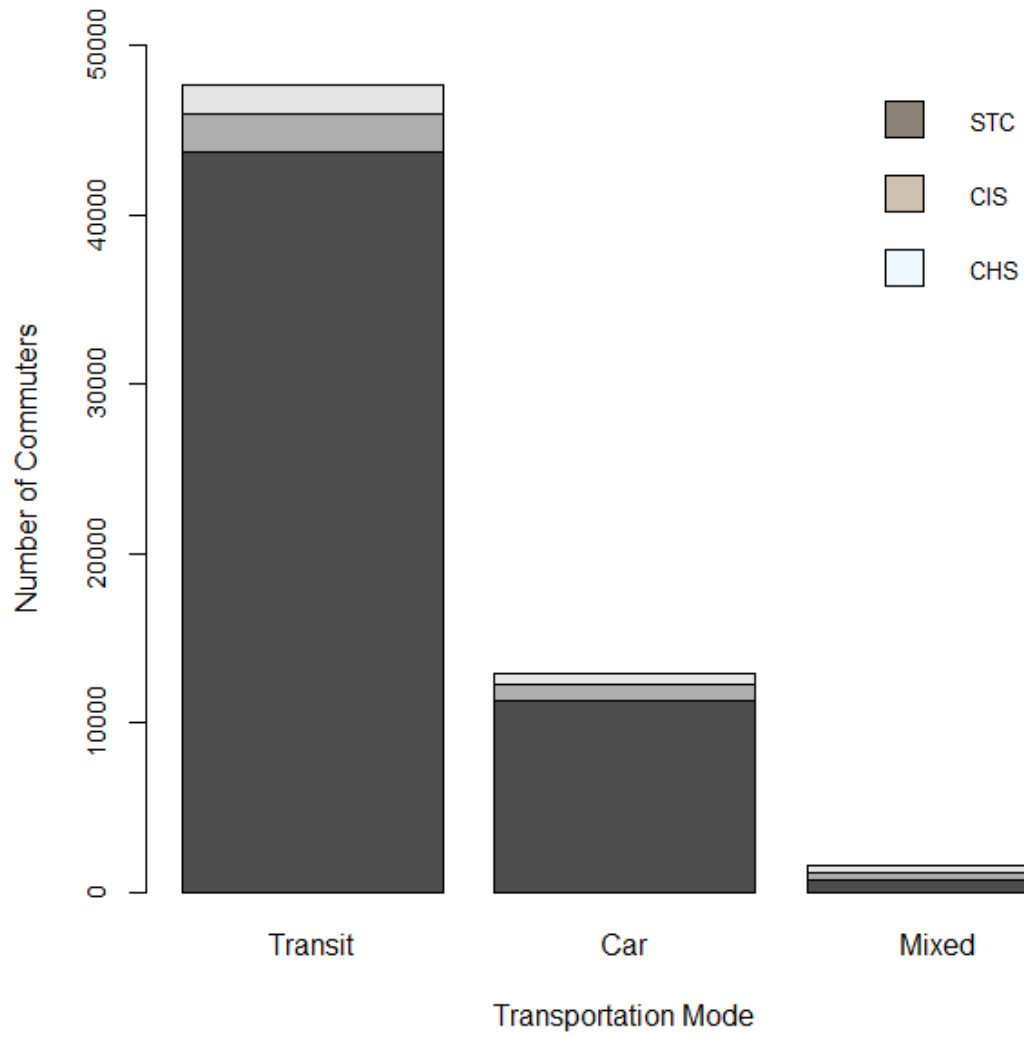


Figure 4.3. Number of commuters by transportation mode and its corresponding share of tour complexity categories.

Table 4.4. Regression results for Zero Inflated Negative Binomial model

	Transit n=47671		Car n=12866		Mixed n=1576	
	Estimate	P value	Estimate	P value	Estimate	P value
Logit model						
(Intercept)	0.511	0.003**	0.395	0.311	-1.86	0.02*
GenderFemale	-0.375	2.1e-13***	-0.091	0.361	0.575	0.025*
Age	0.003	0.055+	0.01	0.008**	0.028	0.001**
Kin_Spouse	-0.004	0.950	-0.063	0.625	0.677	0.026*
Kin_Daughter/Son	0.089	0.178	0.38	0.002**	1.03	0.002**
Kin_Grandchild	0.004	0.98	0.738	0.123	1.88	0.048*
Kin_Other	0.050	0.6	0.264	0.154	0.266	0.710
Kin_NoKin	-1.002	0.098+	0.733	0.153	-13.7	0.993
Educ_None	-0.067	0.721	-0.065	0.913	-0.42	0.783
Educ_Medium	-0.087	0.112	-0.287	0.006**	-0.21	0.387
Educ_High	-0.311	3e-06***	-0.559	4e-08***	-0.68	0.0089**
Educ_Dontknow	0.330	0.660	0.239	0.876	-13	0.989
Socioeco_lower	0.148	0.612	1.103	0.058+	1.09	0.305
Socioeco_upper middle	-0.075	0.17	-0.133	0.169	-0.28	0.262
Socioeco_upper	0.208	0.025*	0.116	0.296	0.217	0.469
Household Size	0.077	1.6e-09***	0.035	0.158	0.005	0.934
Available vehicles	0.002	0.96	-0.036	0.506	-0.481	0.005**
Time One-way	0.001	0.032*	-0.004	0.0001***	0.0003	0.898
Job Accessibility	-0.359	0.113	-0.558	0.210	-0.236	0.824
Jobs Density	-0.001	0.002**	-0.0004	0.644	-0.013	0.015*
Population Density	-0.0003	0.519	0.0006	0.389	0.003	0.138
Mixed land use at Origin	0.006	3.7e-06***	0.003	0.140	0.011	0.05*
Mixed land use at Dest	-0.0009	0.401	0.003	0.076+	-0.013	0.007**
Count model						
(Intercept)	-0.0092	0.941	-0.326	0.183	0.651	0.004**
GenderFemale	0.206	1.7e-08***	0.182	0.002**	0.021	0.768
Age	-0.004	0.001**	-0.003	0.112	0.003	0.167
Kin_Spouse	0.018	0.698	-0.241	0.001**	-0.037	0.676
Kin_Daughter/Son	-0.287	3e-09***	-0.521	5e-11***	-0.162	0.085+
Kin_Grandchild	-0.304	0.025*	-0.519	0.154	-0.273	0.349
Kin_Other	-0.327	7e-06***	-0.405	0.0009**	-0.567	0.0006***
Kin_NoKin	-0.9	0.0003***	-0.233	0.528	-0.82	0.014*
Educ_None	-0.056	0.690	-0.27	0.559	-0.62	0.412
Educ_Medium	-0.017	0.672	0.067	0.342	0.059	0.493
Educ_High	0.0108	0.816	0.0048	0.940	0.120	0.142
Educ_Dontknow	-0.185	0.763	-0.490	0.676	0.207	0.656

Socioeco_lower	-0.271	0.257	0.458	0.384	0.063	0.902
Socioeco_upper middle	-0.057	0.145	-0.045	0.439	-0.095	0.224
Socioeco_upper	0.020	0.758	0.028	0.677	0.039	0.66
Household Size	0.028	0.003**	0.087	1e-07***	0.002	0.886
Available vehicles	0.034	0.254	-0.0003	0.991	0.079	0.04*
Time One-way	-0.004	<2e-16***	-0.001	0.05*	-0.002	0.019*
Job Accessibility	0.107	0.510	0.353	0.207	-0.117	0.695
Jobs density	-0.0009	0.003**	-0.0001	0.863	0.0002	0.658
Population Density	-0.0005	0.085	0.00005	0.903	-0.0003	0.589
Mixed land use at Origin	0.005	6e-08***	0.0005	0.692	-0.001	0.321
Mixed land use at Dest	-0.001	0.05*	-0.0008	0.461	0.0001	0.913
Log(theta)	0.702	5.2e-09	1.04	2e-09	2.16	1e-12

Note: Signif. codes: '***' 0.001 '**' 0.01 '*' 0.05 '

For Transit users, the variable gender/female is negative and statistically significant in the logit model. This means female commuters are more susceptible to make at least one more trip than their male counterpart. In the count model, female Transit users have a significant positive coefficient, which means their trip rates are also higher than their male counterparts. The probit model also confirmed that they tend to make more complex tours than males (Table 4.5). For Car drivers, gender is not relevant in the decision to make an extra trip. In other words, it is not significant to have or not a structural zero trip that can happen by chance, given its not significant coefficient in the logit model, but in the count model, female commuters have a significant positive coefficient. This means that, for these commuters, the decision to make an extra trip is not related to their gender. Yet, once they do an extra trip, the subsequent number of trips are higher for females than for males. The probit model confirms that females tend to do more complex trips than males when traveling by Car. In the case of mixed transportation, we see the opposite effect, where males are more susceptible of making an extra trip. It seems than females are less willing to change transportation mode in their travel tours. The count model shows that for these commuters, trip generation is not related to gender, although the probit model shows that males

make tours more related to the form CHS, i.e. more complex tours, than females. The difference in probability in the change from male to female is around 2% in favor of more complex trip chaining for Transit users (Figure 4.7b), while it is -4% for mixed transportation (Figure 4.9b). Overall results for gender tend to go in favor of the reports in the literature especially for Transit users, while for Car drivers a nuanced result is shown in the case of a structural zero. However, for mixed transportation, there is an opposite result according to the initial expectation.

This gender difference is usually explained by female commuters' household role due to they are more inclined to perform maintenance activities (Kuppam & Pendyala, 2001). Culturally, in MCMA female commuters have more household maintenance and child care responsibilities than male commuters. Additionally, women are more likely to have multiple, unstable jobs and thus need to travel to multiple job locations than male commuters. If we take transportation mode as a proxy of socioeconomic status (Guerra, 2015), we see that the coefficient of female commuters is larger for Transit users than for Car drivers (0.206 vs 0.182 and 0.235 vs 0.127 for the count and probit models, respectively). Thus, low income female commuters (Transit users) chain more trips than females from higher income levels (Car users). In other words, although overall Car is the major driver to make more complex tours than using Transit, in a separate analysis by transportation mode, the increase of travel complexity by female commuters is larger for Transit users than Car drivers. I interpret this to mean that female Transit commuters are using trip changing as a way to face such disadvantages. Regarding mixed transportation, there is an opposite effect in gender, a possible interpretation is that female commuters tend to avoid multimodal transfers by security concerns.

1

Table 4.5. Probit results

	Transit n=47671			Car n=12866			Mixed n=1576		
	Estimate	T value	P value	Estimate	T value	P value	Estimate	T value	P value
Gender/Female	0.235	12.42	4.8e-33***	0.127	3.31	0.0009***	-0.327	-4.44	9e-6 ***
Age	-0.004	-6.3	4.4e-10***	-0.001	-1.08	0.28	-0.004	-1.48	0.139
Kin/Spouse	0.011	0.43	0.66	-0.133	-2.73	0.0064 **	-0.276	-2.94	0.003 **
Kin/Daughter/Son	-0.173	-6.98	5.3e-12 ***	-0.325	-7.03	3e-12***	-0.43	-4.43	1e-5 ***
Kin/Grandchild	-0.128	-1.97	0.049*	-0.349	-1.85	0.064	-0.647	-2.37	0.017 *
Kin/Other	-0.205	-5.81	8.3e-09***	-0.337	-4.57	5.4e-6***	-0.625	-4.38	1e-5 ***
Kin/NoKin	-0.044	-0.44	0.66	-0.54	-2.27	0.023 *	-0.95	-2.53	0.011 *
Educ/None	0.039	0.55	0.582	0.1	0.47	0.638	-0.13	-0.24	0.810
Educ/Medium	0.036	1.73	0.083	0.143	3.23	0.001**	0.078	0.931	0.352
Educ/High	0.224	9.36	5.1e-20***	0.187	4.42	1e-05***	0.149	1.83	0.067
Educ/Dontknow	-0.01	-0.053	0.957	-3.491	-2e+07	0***	0.409	0.73	0.465
Soc/lower	-0.189	-1.746	0.081	-0.087	-0.29	0.771	-0.658	-1.29	0.197
Soc/upper middle	0.049	2.45	0.01**	0.064	1.69	0.091	0.074	0.978	0.328
Soc/upper	0.006	0.194	0.846	0.063	1.42	0.155	0.107	1.12	0.262
Household Size	-0.013	-2.61	0.009 **	0.0288	3.05	0.0023 **	0.007	0.371	0.710
Number of vehicles	0.023	1.55	0.121	0.075	4.02	6.2e-05 **	0.213	5.11	3e-7 ***
Time One-way	-0.006	-24.40	6e-104***	-0.004	-9.82	8e-22 **	-0.003	-4.07	5e-5 ***
Job Accessibility	0.248	2.77	0.005**	0.285	1.65	0.099	0.125	0.388	0.698
Jobs density	-0.0006	-3.90	0.0001***	-0.0003	-0.821	0.411	0.001	2.33	0.02*
Population Density	-0.0004	-2.31	0.021*	-0.00008	-0.252	0.801	-0.001	-1.95	0.05*
Mixed land use at Origin	0.001	3.53	0.0004***	0.0007	0.896	0.37	0.00008	0.045	0.964
Mixed land use at Dest	-0.0006	-1.74	0.082	-0.001	-2.78	0.0055 **	0.002	1.72	0.085
STC COT	1.08	16.62		1.37	9.64		-0.342	-1.39	
COT CMOT	1.502	22.85		1.91	13.3		0.469	1.9	

Note: Signif. codes: 0 '***' 0.001 '**' 0.01 '*' 0.05 '.' 0.1 ' ' 1

2

Variable age for Transit users has a weak positive association (significance level at 10%) in the logit model, whereas in the count model it has a negative effect and in the probit model it significantly favors simple tours. The coefficient value is very small. In the simulations, with an increase of age from the mean up to 1sd, the difference in probability toward the more complex tour is around -0.5%. This means that these commuters tend to make less and simpler tours if age increases. Notwithstanding, age is slightly associated in the initial decision to make or not an extra trip. For Car drivers and commuters with mixed transportation, age has a positive and significant coefficient in the logit model, which means that older people tend not to make an extra trip, with a higher probability of a zero happening by chance. However, in the count and probit models for these same commuters, age had no effect, showing that there is no effect in the amount and complexity of travel. Overall, these findings match the expectations of the reports in the literature for commuter by Transit. Given the non-linearity of the relationship stated by Bhat (2001), it seems that age distribution in our study tends to show a negative relation with trip chaining.

The categorical variable kin has head-household as the level of reference. For Transit users, this variable is not significant to make an additional trip. However, in the count model the head of the household generally increases the number of extra trips in relation to other family members, except for spouse. The probit model confirms that the head of the household is generally the member that makes more complex tours than other members, such as daughter/son and other. Regarding Car drivers, the kin variable was significant and positive for daughter/son, meaning they have less propensity to make an extra trip than the head of the household. In the count regression, head-households are related to a higher number of extra trips than the rest of the categories, except for grandchild and no kin. The probit model also confirms more travel complexity for the head of the household, except for grandchild. In the case of mixed transportation, in the logit model significance with kin variable was positive for spouse,

daughter/son and grandchild, which means an increment in the probability of making zero trips in these categories in comparison with the head of the household. In the count model, a smaller number of trips is associated with other kin and no kin categories. The head of the household is generally the member that makes more complex trips than the other members, and this is significant for all other members. Overall, these results indicate that the head of the household is the family member with the highest probabilities of making extra trips. Education tends to increase the probability of an extra trip, given the negative coefficients with higher education for the three transportation modes and with medium education for Car drivers. Basic education is the level of reference. Interestingly, education was not relevant for the extra trips count in any transportation mode. Education increases the complex shape of tours, the highest category being positive and significant for Transit users and Car drivers, while for Car drivers, medium category was also significant.

For Transit users, household socioeconomic status has a positive and significant coefficient for the upper class. Lower middle class is the level of reference. This means affluent people tend not to make an extra trip when using Transit. Upper-middle class has a positive significant effect on travel complexity for Transit users. None of the other socioeconomic classes had a significant relationship with making an extra trip (logit model) in any transportation mode. Additionally, the household socioeconomic category was not relevant for the extra trip count for any transportation mode and for complex shape of travel. This result does not match the majority of the literature about income. Thus, it situates this study alongside other studies that find a small, if not a negative, role of this variable.

Household size refers to all family members, including children. In the logit model, household size is positive and significant for Transit users but not for the other modes of

transportation analyzed. This means an increment in the probability of making zero trips for Transit users. Here, the count model shows that, once a stop during the work trip is done (or an additional trip), household size is positively related with the total number of stops that follow (or additional trips). However, the probit model shows that household size decreases travel complexity. This means an overall negative relationship. In the case of Car drivers, the count model shows that there is an increase in the number of extra trips, while the probit model shows an increase in travel complexity. Thus, this suggests a prevalent CHS pattern. For mixed transportation there was no identifiable effect in the three models under study. Results for Transit users are similar to the reported literature. However, for Car drivers we saw the opposite effect, which contradicts much of the literature that reports a negative relationship between household size and travel complexity. The number of available vehicles does not have any effect in Transit users in any of three models analyzed. For Car drivers, this variable has no effect in the ZINB models. Nevertheless, the probit model shows a significant effect toward increasing travel complexity. The more consistent effect is on mixed transportation, where it increases the probability of making an extra trip. It also increases the counting of extra trips as well as the complexity of travel. Having an available Car enables a tour where you can return home before attending other activities.

One-way travel to work time was positive and significant for Transit users. This means that, for these commuters, there is an increment in the probability of making zero trips. However, for Car users, the effect was the opposite, i.e. a negative coefficient that entails an increase in the probability of making an extra trip as long as the one-way travel time increases. This means that only Car drivers can adapt to long commutes to undertake additional activities. For mixed transportation, there was no significant effect. In the count model, one-way travel time consistently has a negative significant coefficient for the three transportation modes analyzed. This means that, as it was expected, this travel cost variable decreases the count of extra trips, no matter what

transportation mode was used. Consistent results are found in the probit model, given that this variable favors simple trips for all transportation modes. The simulation shows that a change in work trip time (in one direction) from the mean time minus 1sd indicates that the difference in probability is around 2% for Transit users (Figure 7) and Car drivers (Figure 8), and 1% for mixed transportation (Figure 9).

Regarding urban form variables, job access has no effect in the ZINB models with any analyzed transportation mode. In the probit model, only for Transit users, job access is positively associated with increased complexity of travel. This means that people living in areas with high job access tend to make an intermediate stop at home if they travel by Transit. Job access captures a location effect given that this indicator has a negative linear relation with respect to the distance from the metropolitan center at Traffic Analysis Zones (TAZs) level (Chapter 2 of this dissertation). Thus, the inner city has the greatest access to jobs, while the city periphery generally has poor access to jobs. However, some zones in the city periphery have moderate job access as they have highway access to other nearby cities.

People living in areas with high jobs density tend to make an additional trip if they travel by Transit. However, once they do one trip, the subsequent count of number of trips decreases with job access. The probit model confirms that job density favors simple tours for Transit users (Table 4.5). For Car drivers, jobs density was not significant in any of the three models under study. For mixed transportation in the logit model, jobs density has a negative significant effect. The coefficient was higher than for Transit users. Nevertheless, in the count model there is no relation with subsequent number of trips. The probit model shows a trend toward more complex trips. This means that there is a trend to get back home before attending other activities that does not depend on the number of total activities the traveler will have. The simulation considers a change in job density from its mean to an increase of 1 sd. The difference in probability for Transit is slightly

higher than -1% (Figure 4.7b), whereas for mixed transportation it is of around 1.5% (Figure 4.9b). Jobs density has a negative exponential relationship with the urban center.

Therefore, my initial expectation of suburban residents living in a neighborhood with poor jobs density, going to the inner city and having less complex tour and rate trips no matter which transportation mode they use, is still valid. According to Figure 4.4, we would need a change in jobs density from 200 to 400 (Jobs/ha) to increase the probability of one additional trip only around 0.1 (from 0.4 to 0.5). In Figure 4.5 the counterfactual shows we still need a significant change in jobs density, for example from 100 to 400 (Jobs/ha), in order to decrease the number of stops by 2, from 7 to 5, for each 10 travelers.

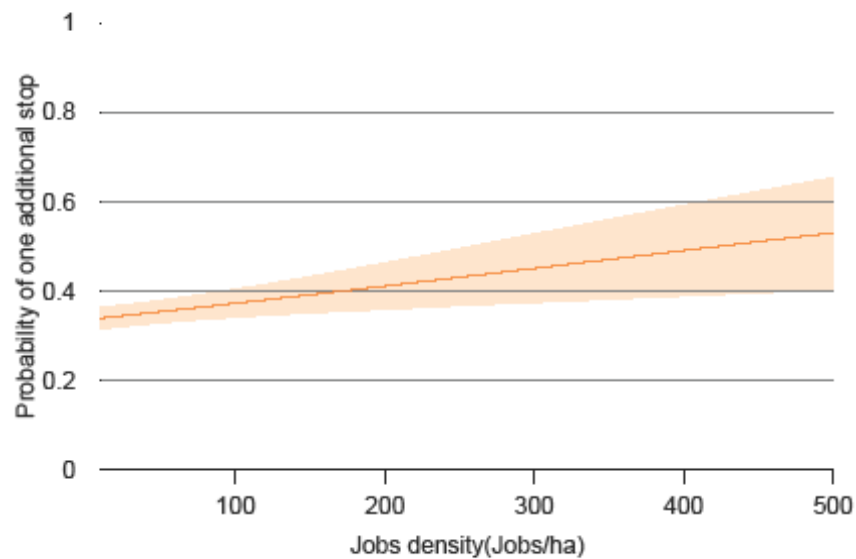


Figure 4.4. Counterfactual simulations for the logit submodel in the ZINB, probability making an extra trip for job access for Transit users. The shaded area indicates the 95% confidence interval.

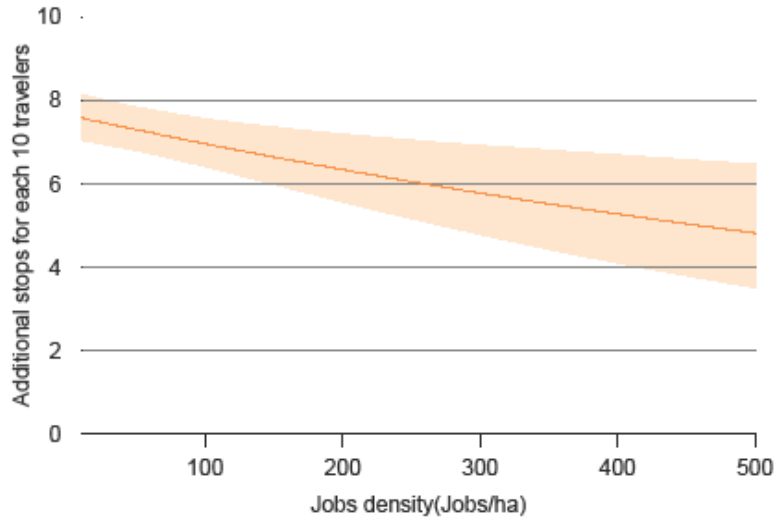


Figure 4.5. Counterfactual simulations for the count submodel in the ZINB. Job Access vs expected number of trips generated for each 10 travelers using Transit. The shaded area indicates the 95% confidence interval.

Population density has no effect in the ZINB models with any analyzed transportation mode. However, population density favors simple trips (less complex pattern) for Transit users and mixed transportation in the probit model. This latter still considering a significant association when p-value equal to 0.05, although another interpretation might consider strictly values below 0.05 for significant results. Results in the literature are not consistent (see Section 2.1; Chen & Akar, 2017; Antipova & Wang, 2010; Noland & Thomas, 2007). Mixed-land use blocks at origin have a positive effect in the logit model, which means that it increases the probability of an extra zero trip for Transit users. However, once they make one, the subsequent counting is affected positively by this variable according to the count model. The probit model confirms this variable in favor of more complex trips. This agrees with the literature only for Transit users. The simulation in Figure 4.7b considers the change from its mean up to 1sd. The difference in probability for the CHS is less than 1%. For Car drivers there was no identifiable effect in any

model of the three, while for mixed transportation there was a positive effect only in making a zero trip in the logit model. This considering p-value equal to 0.05. Mixed-land use blocks at work destination increase the probability of an extra trip only for mixed transportation, having no effect for other modes of transportation. In the count model, there is an association with less number of trips for Transit users considering still a significant results p value equal to 0.05. In the probit model, this variable favors simple trips for Car drivers, having no effect for Transit users and mixed transportation. The corresponding simulation also considers a change from its mean up to 1sd. The negative difference in probability is about less than 1% (Figure 4.8b). It seems that Mixed-land use is more significant at residence place to promote trip chaining than at work for Transit users, although it is more irrelevant for other transportation modes. Figure 4.6 shows we still need a significant change in mixed land use, from 0% to 45% in order to expect an increase in the number of stops from 6 to 8, for each 10 travelers (Figure 4.6).

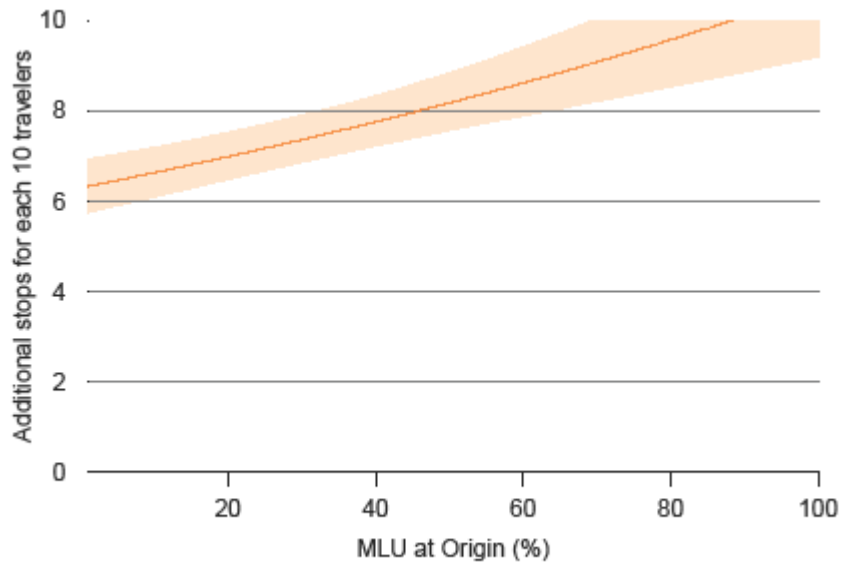
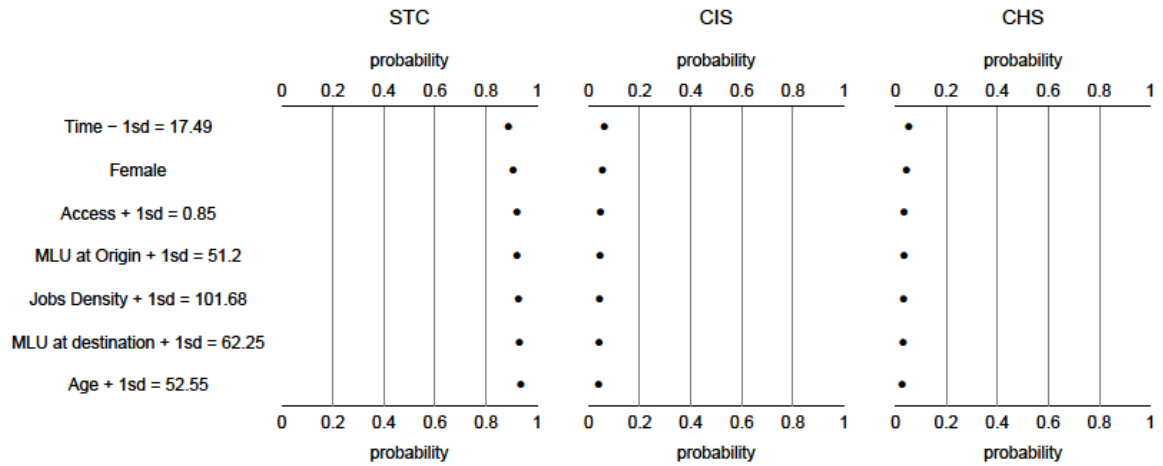
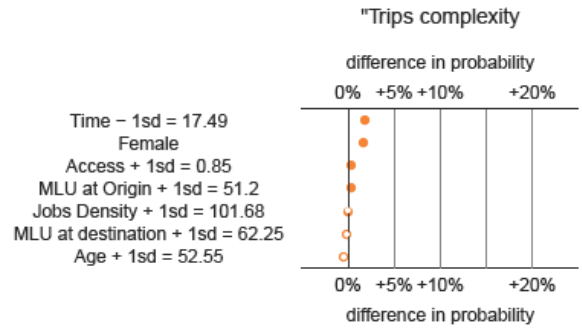


Figure 4.6. Counterfactual simulations for the count submodel in the ZINB. Percentage of mixed-land use at origin vs expected number of trips generated for each 10 travelers using Transit. The shaded area indicates the 95% confidence interval.

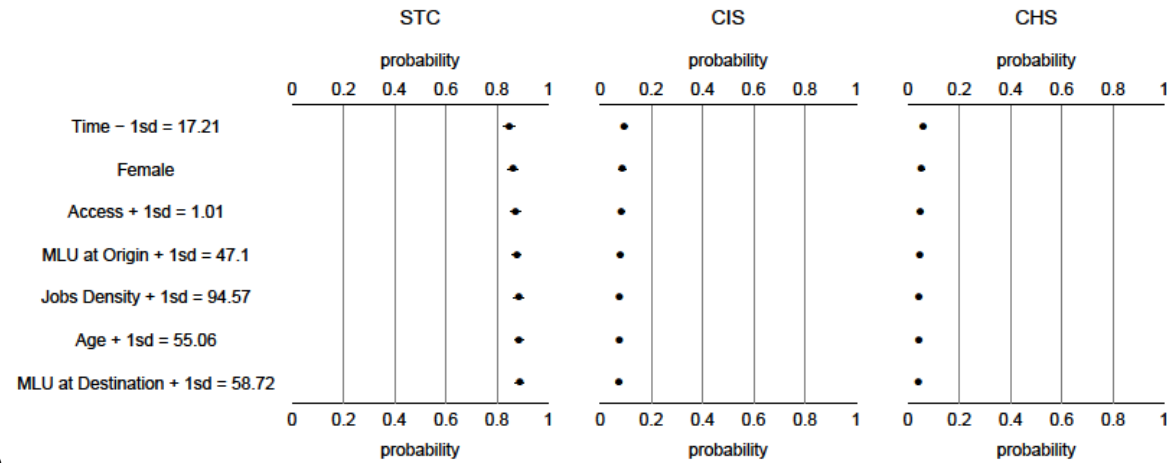


a)

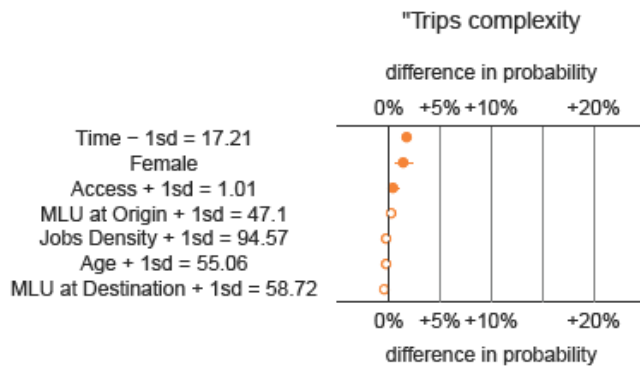


b)

Figure 4.7. Counterfactual simulations for Transit users. a) Probability of the three outcomes when the corresponding variable at the left is kept at the specified value and other variables at its mean, b) Difference in probability toward the highest ranked outcome, CHS. (Using R packages *tile* and *simcf*).

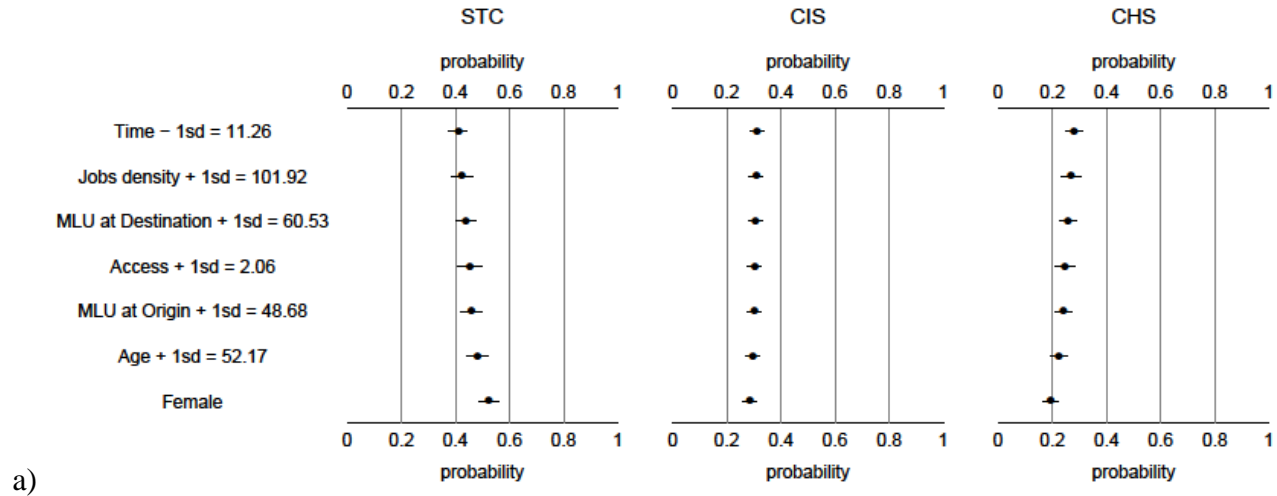


a)

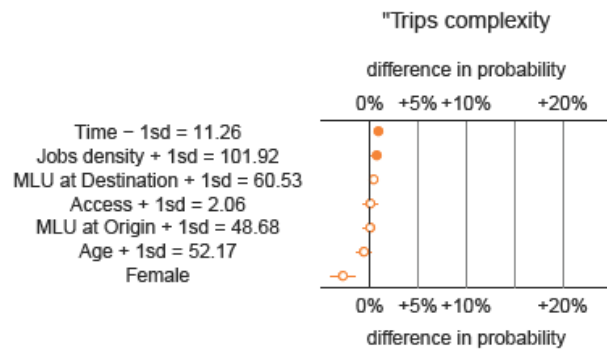


b)

Figure 4.8. Counterfactual simulations for Car drivers. a) Probability of the three outcomes when the corresponding variable at the left is kept at the specified value and other variables at its mean, b) Difference in probability toward the highest ranked outcome, CHS. (Using R packages *tile* and *simcf*).



a)



b)

Figure 4.9. Counterfactual simulations for mixed transportation. a) Probability of the three outcomes when the corresponding variable at the left is kept at the specified value and other variables at its mean, b) Difference in probability toward the highest ranked outcome, CHS. (Using R packages *tile* and *simcf*).

4.6 CONCLUSIONS

Descriptive analysis suggests trip generation and complexity of travel differ between transportation modes. In accordance with the literature, Car drivers make more trip chaining than Transit users. Therefore, this paper aimed at analyzing the effect of socioeconomic factors and urban form variables on trip generation and complexity of travel for commuters using different transportation modes. Results showed that some of these factors had a differential effect in different directions according to transportation modes.

As general findings I can say that, as expected according to the literature, gender/female increases travel rates and complexity. However, I found that in this case the effect is greater for Transit users than for Car drivers, while for mixed transportation, it is the opposite. Based on the apparent non-linear relation found in the literature between age and trip chaining, I found that it decreases travel rates and complexity only for Transit users but has no effect for Car drivers and mixed transportation. Although household income is considered to increase travel complexity, my results found that the household socioeconomic category has an overall small impact on trip generation and complexity. In the literature, household size is negatively associated with trip chaining. However, I found this is only for Transit users, while there is a positive effect for Car drivers, and it has no effect on mixed transportation. Not consistent with reports in the literature on the effect of population density, in this study I found only significant negative relationships for complexity of travel for Transit users and mixed transportation. The effect on trip chaining of mixed land use is negative according to some reports in the literature. However, I found such relationship only at work place with complexity of travel for Car drivers. Conversely, I found a positive relation between this variable at place of residence and trip generation and complex

traveling for Transit users, while for mixed transportation it increases probability of extra trip at work place and probability of zero trip at place of residence. Overall the head of the household is the member of family with higher probabilities of making more extra trips (trip generation) and more complex tours, although the significance with other members varies with transportation mode. Education tends to increase the probability of an extra trip and complexity of travel, but it is not relevant for the counts of extra trips for any of the transportation modes. The number of available Cars affects positively mixed transportation in the probability of making an extra trip, trip generation and travel complexity. For Car drivers, this variable enables a tour with the form CHS.

One-way travel time to work decreases trip generation and complexity for the three transportation modes. The propensity to make an additional trip increases only for Car drivers, suggesting a capacity to adapt to long commutes. Jobs density at residence affects mainly Transit users, given that it increases the probability of making an extra trip, but it decreases trip generation and complexity of travel. In other words, Transit users living in peripheral neighborhoods with low jobs density, in comparison with inner city neighborhoods with high jobs density, have a lower probability of making intermediate stops. However, once making a trip, generation and complexity of travel is higher. Car drivers are unaffected by jobs density. For mixed transportation, there is an increase in the probability of an extra trip, and there is a trend to make more complex tours. Overall, for urban form variables there is less impact on trip generation and complexity of travel for Car drivers (MLU at destination for complexity) and mixed transportation (MLU at origin and destination for the logit model, and jobs and population density for complexity) than for Transit users (job access and population density for complexity, MLU at origin and jobs density for extra trip, trip rates and complexity). This gives a nuance in the impact of urban form on trip complexity

which is unlike Wang (2015), who argues that regional and local built environmental and geographic characteristics have limited predictive power of stops made during commute.

The fact that only a small percentage (5%) of commuters do chain trips in their journey to work might raise concerns regarding its suitability to identify determinants of trip chaining. I found that zero inflated model successfully identified statistically significant covariates. Part of the method's robustness comes from including the whole group of commuters in the analysis. Probably the large sample size allows identifying even subtle overall effects of covariates. However, the practical significance of those relationships should be examined more closely before including the results of our analysis in public policy. Whether chaining trips is a desirable outcome or not would depend on its impact on other aspects of traveling such as total distance traveled or mode choice decision. What we saw in the counterfactuals simulations is that those people that do not chain need a great incentive to actually chain travel, for example we would need a change in jobs density from 200 to 400 to increase the probability of one additional trip only around 0.1 (from 0.4 to 0.5) (Figure 4). This change in access would entail a dramatic transformation, might be not even feasible in the long term, in the urban structure. Likewise, in regards of the change in the shape of the travel tour from simple traveling (STC) to more complex tour (CHS) the counterfactuals show that for all covariates, and specifically those related to land use, the corresponding changes in probability are no larger than 2% (Figure 4.7, 4.8 and 4.9). This impact seems negligible if we want to intervene in the overarching metropolitan travel chain patterns. Similar conclusion can be reached for the number of stops of those travelers that already chain their travel tour. As we saw in the counterfactuals, we still need a significant change in mixed land use and job access to increase and decrease, respectively, the number of stops by four for each 10 travelers (Figure 5 and 6). At the metropolitan level, however this numbers of stops can still be

relevant in magnitude given that dimensions of the entire commuting population. This can be expected, as the most promissory implications of the present work.

Transportation modelling might benefit from the results of this work, specifically in the development of tour-based models. Transport models based on single trips are becoming obsolete given the increasingly complex urban travel patterns. The forecasting power of tour-based models might benefit of including the determinants analyzed in this work according to the mode of transportation. Increases in transportation modelling is important as transportation planning uses the output of these models to plan service levels and determine future infrastructure investments (Kuppam & Pendyala 2001). From the social point of view, the importance of gender (female commuters) as a determinant of travel chaining suggests further study is needed to address the needs of this potentially disadvantaged group.

This research suggests multiple additional questions. For example, it is need to explore other possible explanatory factors of trip chaining such as activity engagement indicators, which include using activity typologies. This would not only separate the analysis between the minor (stops) or major (trips) activities, but it would also consider what kind of ‘stops’ people are making on their journeys and how this might influence the complexity of these journeys. Other factors to explore are household lifecycle (i.e., household composition and working status), time of the day, day of the week, types of jobs for workers in the household, etc. An *ad hoc* travel survey could expand the possibilities to explore these aspects. Future research efforts may aim at analyzing trip complexity of non-work trips, as well as the effect of specific public Transit modes using accessibility indicators specific to them. An important factor is the interplay between trip chaining and other aspects of travel behavior such as travel mode choice and travel distances, which remain as opportunity areas to address in the context of cities in the developing world.

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Chapter 5. SYNTHESIS: CONTRIBUTIONS, IMPLICATIONS AND FUTURE RESEARCH

5.1 SUMMARY OF FINDINGS

As stated in the introduction, the overarching objective of this research is to assess transport disadvantage conditions related to geographic location, its social dimension identifying vulnerable groups of people and its relationship with the urban structure. The journey to work is the primary object of analysis in relation with my overarching objective. The results of the three empirical chapters provide insights to accomplish the general objective.

In Chapter 2, I tested two methods to evaluate job accessibility in MCMA, Gravity Based model (GBM) and Shen's type equation. I compared its consistency between two sources of travel time data, two types of employment data (Formal and total) and two transportation modes (Car and Transit). My exploration of accessibility using the GBM shows an important variation in the metropolitan pattern. As a general description, jobs-rich areas in the inner city have the highest accessibility with a decrease in accessibility with increasing distance from the urban center, however this negative relationship is not as clear as in the Shen's type model. Total employment that considers informality increases accessibility and gives more consistent results between travel-time sources than does formal employment, probably due to the reinforcement of the role of land use in the estimation. Accessibility is always higher for Car drivers than for Transit users with TRANUS, while for HODS17 this remains true for the most part but with a few exceptions. The Shen's indicator shows a more consistent spatial pattern of accessibility (spearman correlations

close to 1) regardless of travel-time data and transportation mode with the HODS17, demonstrating the robustness of the method. In general, the spatial pattern of accessibility in relation to the urban center is a line with a clear negative slope. Again, as expected, the inclusion of informality increases accessibility. The Shen-type indicator allows us to see that accessibility by Car is slightly higher than accessibility by Transit. This means that for any TAZ its accessibility score is achieved primarily because of its geographic location. This disparity in terms of location means that accessibility in the TAZ with the highest accessibility record is 26% higher than the metropolitan accessibility average.

In Chapter 3, my analysis of the intra-metropolitan geography of one-way Average Commute Times (ACT) per Traffic Analysis Zone (TAZ) clearly shows a highly unequal city in this experience of the journeys-to-work. Overall, ACT is lower for Car drivers than for Transit users. The relationship between ACT by Transit and distance to the urban center form an inverted U-shaped curve, commuting times increase as the distance to the urban center increase reaching a point where commute times decrease in the outer TAZs. Conversely, the relationship between ACT by Car and distance to the center shows a semi flat pattern with a slightly decrease in the outer TAZs. A strong spatial correlation was detected for ACTs for both Car drivers and public Transit users, however for the former the magnitude was lower in the HODS17 data according to Moran's statistic. The Lag-ML regression is the correct specification for ACT by Car with TRANUS and the HODS17, as well for ACT by Transit with the HODS17. On the other hand, the Err-ML regression is the correct specification for ACT by Transit with TRANUS. Regression results show that job access plays a significantly inverse role in determining ACT for Transit users and for Car users using travel times from TRANUS. Overall, the degree (represented by coefficients) and significance of job access is higher in ACT by Transit users than for Car drivers. However, this response is not consistent using observed travel times from the HODS17 where the

significance for Transit users is weak ($p < 0.1$) in the OLS regression and not significant in the Lag-ML regression. Other covariates were also significant using TRANUS. For example, EAP density is positively associated with ACT by driving alone and for Transit commuters. Jobs density is negatively associated with ACT by Car, while the significance is weak in the case of Transit users. Mixed land use is positively associated with ACT by both Car drivers and public Transit users. Using the HODS17 data, the association between ACT and urban form variables was not robust. There is only one result of importance, the positive association between EAP density with ACT by Car (at 10 %) and public Transit (at 1%). Job access doesn't have a consistent response for ACT with any of the two transportation modes. Longer commute times do not appear to be associated with proportions of population groups such as female headed households, illiterate population, and people with physical disabilities. On the other hand, a consistent result using TRANUS and HODS17 is that an increase in the proportion of migrants is significantly associated with an increase of ACT by public Transit. Moreover, according to the HODS17, an increase in the proportion of indigenous populations is positively associated with ACT for both Car drivers and public Transit commuters. Thus, these results suggest percentage of migrants and indigenous population as groups in disadvantage.

In Chapter 4, in my analysis of determinants of commuter's trips chaining behavior in MCMA, covariates in the regression models covered different dimensions such as individual, household, trips and urban form characteristics. This analysis considered separately models for Transit users, Car drivers and commuters with a combination of these both modes, called mixed transportation. Covariates have different association with travel complexity among the three different transportation modes. It is not my intention to go over the findings of each covariate but I will mention only those significant results that I consider more important. Gender/female

increases travel rates and complexity. However, I found that in this case the effect is greater for Transit users than for Car drivers, while for mixed transportation, it is the opposite. I found that age decreases travel rates and complexity only for Transit users but has no effect for Car drivers and mixed transportation. Household size is negatively associated with trip chaining only for Transit users, while there is a positive effect for Car drivers, and it has no effect on mixed transportation. Population density has significant negative relationships for complexity of travel for Transit users and mixed transportation. Mixed land use is negative associated with complexity of travel for Car drivers only at work place. Conversely, I found a positive relation between this variable at place of residence and trip generation and complex traveling for Transit users. Education tends to increase the probability of an extra trip and complexity of travel, but it is not relevant for trips rates for any of the transportation modes. One-way travel time to work decreases trip generation and complexity for the three transportation modes. Jobs density at place of residence affects mainly Transit users, given that it increases the probability of making an extra trip, but it decreases trip generation and complexity of travel. Car drivers are unaffected by jobs density. For mixed transportation, there is an increase in the probability of an extra trip, and there is a trend to make more complex tours. Overall, for urban form variables there is less impact on trip generation and complexity of travel for Car drivers (mixed land use at destination for complexity) and mixed transportation (mixed land use at origin and destination for the logit model, and jobs and population density for complexity) than for Transit users (job access and population density for complexity, mixed land use at origin and jobs density for extra trip, trip rates and complexity).

5.2 CONTRIBUTIONS

This work provides an evaluation of job accessibility evaluation in the MCMA incorporating three aspects that have not previously been approached in conjunction: 1) analysis at TAZ-level; 2) considering the demand side of the labor market; and 3) disaggregating travel-time data by transportation mode. To the best of my knowledge the present work is the first attempt to apply the Shen's type equation of job accessibility to a Latin American city, which support its robustness as general methodology applicable to different cities. This equation has been previously used in US and Asian cities.

This work also provides evidence of how commuting inequity works in a megacity in a developing country, specifically in its relationships with spatial and transportation modes. Since the Global South is absorbing most of the present urban growth, the picture represented in the case study offers insights about the problems of commuting for the entire region. For example, that the entire metropolitan periphery should not be treated as a whole unified geographical category since the nature of different urban processes vary according to specific characteristics of the city under study. Moreover, in such cities with increasing economic disparities it becomes necessary to develop methods to identify population groups suffering a transport disadvantage condition that impede them to achieve a desirable integration to the city. In the case of how commuters chain trips in their journey to work, the present study has shown that land use features are still important, this suggest a stronger effect of what is commonly reported in the literature from US cities. The analysis of tour complexity by three modes of travel is innovative and a contribution to the literature.

As mentioned in the introduction section the present research approach is grounded in a research framework primarily formed by a Northern Hemisphere perspective. This invariably

entails a limitation for understanding such complexities in the Global South. Part of the limitations of the attempts to understand the Global South is due not only to fewer studies but the limited transferability of the conceptual framework. The present study constitutes an effort in this regard producing valuable insights and questions for future research.

5.3 POLICY IMPLICATIONS

Some policy implications can be drawn from this dissertation. Firstly, this work supports the general idea that accessibility is a key concept in the urban transport policy. In this sense, the findings of this job accessibility evaluation can be used to support an evidence-based transport policy in MCMA under the umbrella of equity. This includes the identification of priority areas that require public investment for either roadways or Transit systems (Figure 2.4). It also suggests that land use policies may play an important role as a way to improve accessibility attracting and fostering employment opportunities in location-disadvantaged areas (low accessibility levels) and in sub-developed corridors in high population density areas. The role of land use in achieving equitable accessibility has been largely dismissed. Another alternative that has been mentioned is to develop affordable housing programs in job-rich areas identified in this work. Maximum acceptable accessibility gaps between areas or transportation modes are issues of social choice that should be included in the public politics debate. Then, the approach followed in this work can be used to support the achievement of such goals. Overall, these results offer straightforward area-level implications to guide the metropolitan transportation policy for planning how to mitigate locational disadvantages.

5.4 FUTURE RESEARCH

An increasing availability of data has allowed to study different urban processes at a greater geographical detail in MCMA. However, there is still a large room to improve in regards to the quality of the input data. For example, the reliability of the formal employment data will be higher as long as the economic census captures the jobs of each economic unit and not a range as is done today. Additionally, informality remains as a fundamental aspect that require a more detailed accounting. The job accessibility evaluation could be analyzed for specific economic sectors, such as low-wage workers, manufacturing works, professional, etc.; unfortunately, no official data by job sector is currently available for the MCMA at TAZ level. Travel time matrices are also an important data that can have improvements in the future which could support a more robust analysis of what have been done here. Overall, with increasing data it will be possible to improve and follow the longitudinal dynamic of the main findings of this work. Recently, georeferenced land use data has been released from the government of Mexico City, these open new possibilities to explore other indicators of density and diversity of land uses as well as its effect on different aspect of travel behavior.

In the case of the study of trip chaining in MCMA, the present work is just an initial exploration several aspects remain to be analyzed. For example, other possible explanatory factors such as activity engagement indicators which includes using activity typologies, the household lifecycle, time of the day, day of the week, types of jobs for workers in the household, etc. An ad hoc travel survey could expand the possibilities for the exploration of these aspects. Future research efforts may aim at analyze the trip complexity of non-work trips, as well as the effect of specific public Transit modes using accessibility indicators specific for them. Importantly the interplay between trip chaining and other aspects of travel behavior such as travel mode choice

and travel distances are opportunity areas to address in the context of developing world cities. Applying, in this sense, structural equation modeling that have been proved to be a valuable tool to unveil interrelated aspects of travel behavior.

APPENDIX A. COMMUTERS' TRIPS

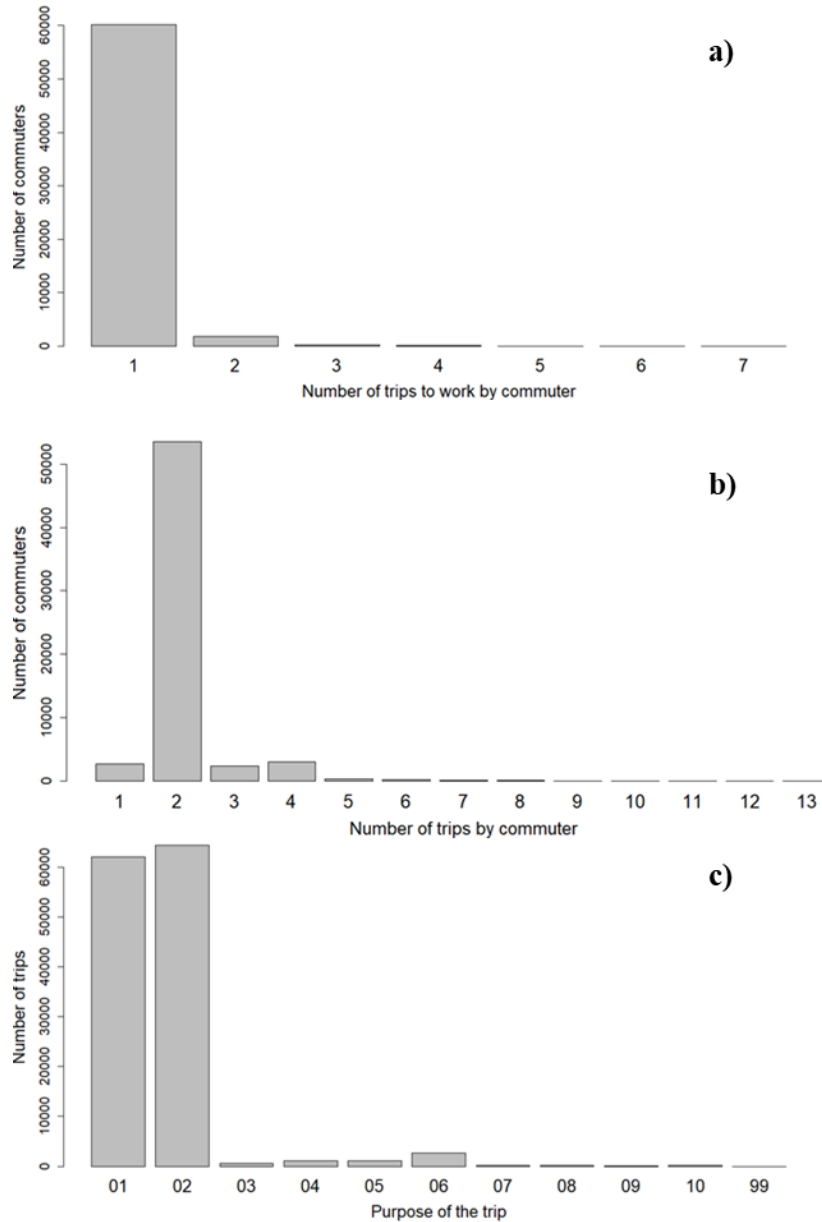


Figure 0.B.1. Number of trips to work by commuter (a) and total trips by commuter(b). Number of trips of commuters by purpose (c).

Note for c in the x axis: 01 to home; 02 to work; 03 to study; 04 Shopping; 05 leisure and recreation (with family or friends); 06 take or pick up someone; 07 do paper work; 08 Medical assistance; 09 Religious activity; 10 Other; 99 don't know.