ACCESSIBILITY, TRAVEL BEHAVIOR, AND URBAN FORM CHANGE

Louis Ari Merlin

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Approved by:

Yan Song

David Godschalk

Daniel Rodriguez

Noreen McDonald

William T. Lester

ABSTRACT

Louis Ari Merlin: Accessibility, Travel Behavior, and Urban Form Change
(Under the direction of Dr. Yan Song)

Accessibility is a central concept for urban planning both from theoretical and practical perspectives. Theoretically, accessibility is a major driver of patterns of land value and residential density in metropolitan urban regions. Practically, planning for accessibility offers the opportunity to shift away from transportation planning's historic focus on mobility (speed) and towards a focus on greater land use-transportation integration. This dissertation takes as its premise that transportation planners ought to be planning for higher accessibility and traces some of its implications. Does higher regional accessibility lead to the travel patterns that planners and travel behavior researchers expect? How are US metropolitan regions performing with regard to an accessibility-based performance benchmark over time?

There is broad consensus among transportation researchers that accessibility measures indicate the ease of access to opportunities across space. Theoretically, we expect households in such high accessibility areas to travel less in distance on a per trip basis, but with greater trip frequency and with a greater range of choices than similar households in lower accessibility areas. This dissertation explores the connection between high accessibility locations and such types of travel patterns. In specific, two of the three dissertation papers explore the accessibility-travel behavior relationship: *Measuring Complete Communities* and *Does Accessibility Influence Activity*

Participation? These two papers ask what types of built environments are associated with more localized travel and more frequent travel. Interestingly, both of these papers find that local accessibility may be more important for supporting these desired travel patterns than regional accessibility.

Furthermore, if planners should be planning for higher regional accessibility for households, how are metropolitan planning agencies performing based upon this metric? This is the question asked by the third dissertation paper, *Changing Accessibility in US Metropolitan Areas*. This paper examines the accessibility performance of four contrasting metropolitan areas over time. Changing travel times are found to have a greater influence over accessibility change than changing urban forms. Tracking accessibility change over time provides planners with an alternative view of urban sprawl; metros with lowering accessibility are presumably providing decreased access to opportunity for their residents over time.

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1.1 Accessibility in Contemporary Planning Practice

1.1.a Accessibility vs. Mobility Debate

A group of transportation researchers and analysts have been promoting the use of accessibility measures to evaluate urban transportation systems going back at least 20 years. Among the researchers who have taken this tack are Cervero (1996), Handy (1997), Bertolini (2005), Levine (2010), and Guers (2010). These researchers have all highlighted the contrast between measure of accessibility and measures of mobility, arguing that although mobility measures dominate the current practice of metropolitan transportation planning, accessibility measures are superior for assessing the true purpose of transportation systems: Enabling people to reach their destinations of interest. In short, these proponents have argued that accessibility measures should be preferred over mobility measures for evaluating the performance of metropolitan (and larger scale) transportation systems.

The need for focusing on accessibility measures rather than mobility measures is more acute than ever in 2014. First, urban transportation systems in the US seriously contribute to carbon emissions, which are exacerbating global climate change. Recent estimates of carbon emissions suggest that 28% of total US carbon emissions are from the transportation sector, while US transportation contributes as much as 5% of total global greenhouse gas emissions (Sieferlein & et.al., 2009). Improving mobility in a metropolitan environment can contribute to more far-flung development patterns, thereby exacerbating both auto dependence and increased reliance on long-distance vehicular travel and petroleum use. Improving accessibility, on the other hand, often results in more compact development patterns and reduced vehicle miles traveled, therefore reducing the greenhouse gas emissions from transportation (Ewing, Bartholomew, Winkelman, Walters, & Chen, 2008; Ewing & Cervero, 2010). Second, the United States economy is just emerging out of a major recession, spanning approximately the years 2008-2011. There is currently a renewed emphasis on the importance of investing in transportation infrastructure to spur employment opportunity and economic activity. Accessibility measures explicitly account for access to employment opportunities, whereas mobility measures do not. Therefore it is arguable that accessibility is a more credible driver of economic activity and opportunity than simple mobility or travel speeds. Third, transportation finance is becoming increasingly strained in the US as the Highway Trust Fund is not growing in line with increased transportation infrastructure needs (National Surface Transportation Infrastructure Financing Commission, 2009). The former goal of free flow on all highways has become infeasible and policy makers need more precise ways to optimize the expenditure of transportation dollars. Focusing on accessibility as a performance measure is promising in this regard as well because such measures more precisely capture the contribution of our transportation system to economic opportunity. Accessibility measures also highlight the opportunity for maximizing the use of *existing* transportation infrastructure through better land use planning. In each of these cases, the challenges of the contemporary policy era highlight the need for a shift away from mobility measures and towards accessibility measures in their stead.

Despite two decades of promotion from the academics listed above, most metropolitan planning organizations do not focus on accessibility measures in their regional transportation planning efforts. At the beginning of my dissertation research I examined the long range transportation plans and spoke to the staff of six leading metropolitan planning organizations: Atlanta Regional Commission, Chicago Metropolitan Area for Planning, the Puget Sound Regional Council, the San Diego Association of Governments, the Southwestern Pennsylvania Commission (Pittsburgh), and the Wasatch Regional Council (Salt Lake City). What I found was that the dominant performance measurements for long range transportation planning are still primarily congestion and mobility-based measures. Other measures considered to be important by these MPOs included transit mode share and future land consumed by development. Accessibility measures were generally a distant third or in some cases were not present as performance measures. This was true even though many of these same plans explicitly call for using existing transportation infrastructure more efficiently. Therefore it appears that the staff of many MPOs do not understand the connection between accessibility measures and making the best use of existing transportation infrastructure. Furthermore, many MPOs do not distinguish clearly between the concept of accessibility and the concept of mobility as distinct planning goals. So despite the repeated strong arguments made by transportation academics on planning for accessibility, there remains in 2014 a gap between the state of the theory and the state of the practice. Contemporary metropolitan planning practice in the United States does not adequately incorporate accessibility-based performance measures into its long range transportation planning efforts.

Counter to the overall trend, a few metropolitan planning organizations do stand out over others with regard to incorporating accessibility-based performance measures. For example, the Puget Sound Regional Council (PSRC) applies a wide range of accessibility measures in its evaluation of its long range transportation plan and in its regional scenario planning. The PSRC's accessibility metrics include measures of accessibility by multiple modes, including auto, transit, bicycling, and walking. In addition, the PSRC has made broad conceptual use of accessibility measures, applying them for such distinct concepts as transportation performance, economic development opportunity, and equity. As such, the PSRC's *Vision 2040* Plan represents the state of the art for incorporating accessibility performance measures into regional scenario planning.

1.1.b Accessibility and New Planning Goals

Accessibility and its links to theories of urban form and agglomeration economies are some of the oldest ideas in urban planning. However some new dialogues within contemporary planning have also focused on the importance of accessibility as a critical concept. In particular, accessibility has emerged as an important factor in promoting active living and in providing healthful access to nature, two relatively new areas of focus within urban planning. This is because accessibility as a concept is central to the purpose of cities in their most general sense – offering residents more *convenient* access to a variety of socially important *opportunities*. Recent research, events, and trends have highlighted some new needs, i.e. the need for physical activity and the need for access to nature within cities. While the needs that have been identified may be new, the importance of convenient access and a range of choices for meeting these needs is a universal requirement, and something that all cities can work to improve.

A raft of recent research has explored the relationship between built environments and physically active travel (Panter, Jones, & van Sluijs, 2008; Pont, Ziviani, Wadley, Bennett, & Abbott, 2009; Sugiyama, Neuhaus, Cole, Giles-Corti, & Owen, 2012). While there are many individual characteristics and aspects of the social environment which influence active travel, the built environment appears to play a significant role as well. The advantage of the built environment as a public health intervention tool, in particular, is that it can influence the health or activity behaviors of a large population at the same time. And one of the most important aspects of the built environment which can serve to promote physically active travel is the accessibility of destinations of interest (Pont et al., 2009; Saelens & Handy, 2008; Sugiyama et al., 2012). That is, the availability of a variety of destinations of interest nearby one's home is a critical feature for promoting active travel (however, other neighborhood features are associated with walking or biking in one's neighborhood for recreational purposes). So accessibility at the local scale turns out to be important in advancing more physically active health behaviors. Interestingly, from the public health perspective, accessibility is not simply about the availability of opportunities in space but also about minimizing the barriers that are in the way of active travel and about maximizing the convenience of active travel opportunities. The "accessibility" that is relevant to active travel is a very broad concept, going beyond simple spatial measurements into the detailed physical experience of one's local built environment.

Likewise there is an increasing body of research which suggests that physical access to nature is key to human psychological and spiritual health (Beatley, 2011). This is particularly true for children, for whom access to natural areas can create opportunity for physical activity and reduce mental stress (Louv, 2008). Innovative urban thinkers such as Beatley and Louv draw upon a growing body of psychological and behavioral research to suggest that access to nature is a fundamental human right. Their arguments imply the need for a new kind of accessibility in cities, one that focuses not just on access to employment and services but that is equally focused on providing access to nature. Importantly, many of these benefits are most crucial for those with the least mobility and/or the least opportunity – the young, the old, and the infirm. Therefore the goal of cities should be to provide as ubiquitous access to nature as possible – it is not enough to have one or two large centrally located parks. The importance of physical proximity, a variety of choices, and freedom of movement are crucial to a range of human needs – including access to nature. This new understanding is both deepening and complicating planners understanding of accessibility as a function of livable, sustainable cities.

1.2 Three Views on Accessibility: Bid Rent, Travel Behavior, and Performance Measures

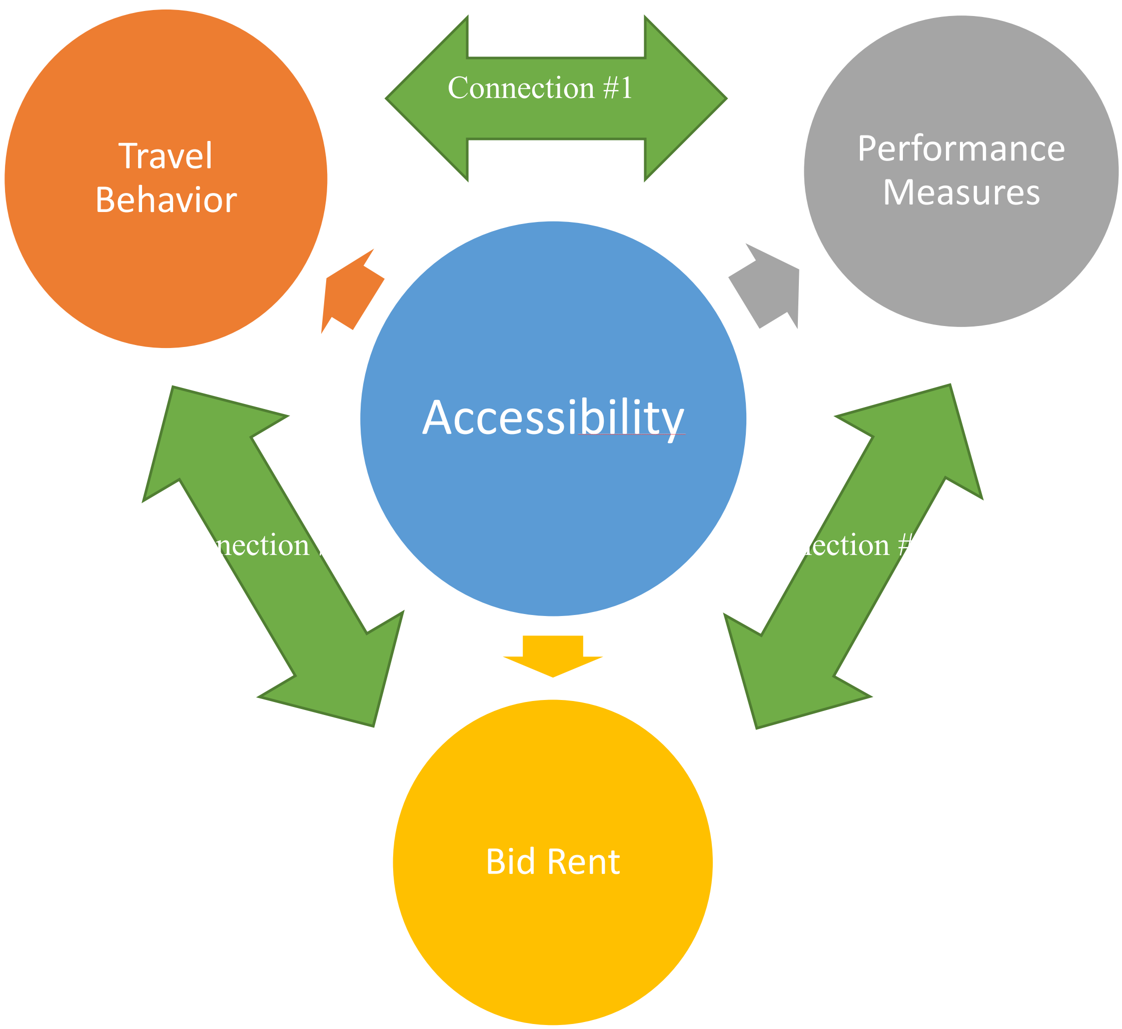
Accessibility measures feature prominently in three bodies of planning literature which for the most part have had little overlap. One body of literature connects accessibility with bid rent theories of urban form. In this literature accessibility measures have been employed to generalize bid rent theory from monocentric to polycentric urban forms (discussed in detail in *Section 1.5*). A second body of literature examines how living in a high accessibility environment influences travel behavior (discussed in detail in *Section 1.6*). High accessibility built environments have been associated with shorter travel distances, more localized travel patterns, and higher amounts of some kinds of travel or activity. The third body of literature focuses on accessibility measures as performance measures of transportation systems, and relies heavily on theoretical arguments that travel is a derived demand. Although these three bodies of literature are certainly conceptually related, explicit connections between these literatures have not frequently been made (See *Figure 1-1*). One of the goals of this dissertation is to see how connections between these various perspectives on accessibility measures can be improved.

In addition to building upon these bodies of literature, the dissertation also serves as a critique of these same bodies of literature. The dissertation explores the practical and conceptual insights which flow from thinking about these different connections. Connection #1 (Figure 1-1) highlights the relationship between accessibility-based performance measures and travel behavior. If higher accessibility environments are beneficial, this should be reflected in different travel patterns for those living in such environments. Connection #2 focuses on the relationship between bid rent theory and performance measures. Bid rent theories often claim that real-world urban forms are close to efficient, but accessibility-based performance measures provide a concrete way for testing this hypothesis. In particular, tracking accessibility-based performance measures over time helps to answer the question of whether urban forms are evolving in a manner consistent with bid rent theory. Connection #3 examines how bid rent perspectives on urban form are directly reflected in travel behaviors. This third connection is not explored closely in the dissertation, but is discussed briefly within this introductory chapter in *Section 1.2.d* on excess commuting. In sum, the goal of the dissertation is to make a number of arguments and analyses to integrate these three disparate literatures on accessibility.

1.2.a Bid Rent Theory: Accessibility as a Descriptor of Urban Form

There is a lengthy literature over several decades linking accessibility measures with bid rent descriptions of urban form. In recent years, the literature on accessibility as a descriptor of urban form has successfully taken on the challenge of extrapolating bid rent theory from simpler monocentric forms to polycentric forms (for a full discussion of this in *Section 1.5* below). However this literature has satisfied itself with a descriptive stance relative to metropolitan urban form, and has therefore neglected to make the

Figure 1-1: Three Views on Accessibility



connection between the accessibility measures embedded within it and their alternative interpretation as measures of urban system performance.

The origins of linking gravity accessibility measures to patterns of urban form can be traced back to Hansen (1959) among others. More recently, Helling (1992) compared gravity accessibility measures with distance to the central business district in describing land use patterns, finding the gravity measure to be the superior descriptor. Song (1996) compared gravity measures, cumulative opportunity measures, and distance to the central business district, and found that gravity measures were best at describing regional patterns of population density. Ahlfeldt (2011) conducted a similar exercise, concluding that gravity measures of accessibility to employment opportunities describe patterns of land rents better than simple distances to major transportation infrastructure. In summary gravity measures have consistently been confirmed as superior for describing regional patterns of urban form relative to other, simpler models for understanding urban form, such as straight line distance to the CBD.

A smaller bid-rent literature has claimed that the success of bid rent theory in explaining patterns of urban form suggests that such urban form patterns are in fact efficient (Brueckner, 2000b; McGrath, 2005). However bid rent theories only loosely describe patterns of land use density or intensity, and it is well understood that they do not apply particularly well to real cities for several reasons. One of the most important reasons that bid rent theories cannot describe real-world urban forms well is because the urban built environment is durable and infrequently redeveloped (Brueckner, 2000a). The claim that urban forms are evolving in a relatively efficient way is evaluated in part by the third paper from the dissertation, *Changing Accessibility in US Metropolitan*

Areas, which examines how accessibility changes over time for four major metropolitan areas in the US. This paper finds that metropolitan urban forms are evolving in way that is consistent with bid rent theory, but the results are not conclusive.

Accessibility measures integrate information about both changes to travel times and changes to spatial patterns, and therefore allow the analyst to evaluate the performance of a particular urban system over time. Because accessibility measures incorporate within them the benefits of increased speeds, they allow for an even-handed comparison of urban system performance over time; that is a "sprawling" urban system could outperform a compact one if increases in speeds compensate adequately for decreases in proximity. In contrast, changing patterns of residential density alone are not readily interpreted as a transportation performance measure and therefore cannot tell us whether the urban system is performing better or worse over time. In addition because accessibility measures can be developed at fairly disaggregate scales, the researcher can use them to examine how accessibility is changing for particular populations, or differentially across space or for different modes. Therefore one way to evaluate the claim that urban systems are evolving efficiently is to apply accessibility measures to them and track the trends of accessibility change in aggregate, by mode, and by location. As mentioned before, this is the subject of the third dissertation paper, *Changing Accessibility of US Metropolitan Areas*.

1.2.b Accessibility and Travel Behavior

Accessibility is the one measure of the built environment that has displayed the most consistent significant influence on travel behavior across empirical studies. Ewing and Cervero found that accessibility is the most influential aspect of the built environment in reducing VMT across their two literature reviews of the built environment and travel behavior (Ewing & Cervero, 2001, 2010). In particular, living in a higher accessibility environment has been associated with shorter commutes (Levinson, 1998; Manaugh, Miranda-Moreno, & El-Geneidy, 2010). Also, residential locations in higher accessibility environments have been associated with higher property values, although these effects on property values are often relatively marginal (Giuliano, Gordon, Pan, & Park, 2010; Srour, Kockelman, & Dunn, 2002).

An alternative way to examine the influence of accessibility on travel behavior patterns is to examine its influence on the size of a household's activity space. Here again the results are fairly consistent, with most research finding that those who live in higher accessibility environments have smaller activity spaces (Buliung & Kanaroglou, 2006; Cerda, 2009). However despite this smattering of activity pattern research which extends beyond the commute, the influence of accessibility on VMT for trips other than commuting is not well understood. One of the ways this dissertation contributes to this body of research on travel behavior is to examine the influence of accessibility on non-work travel in two of the three dissertation chapters (*0* and *0*). Interestingly, it appears that the recent increased emphasis by researchers on exploring accessibility as a performance measure has led to reduced attention to the accessibility-travel behavior relationship.

1.2.c Accessibility as a Performance Measure

Some of the key papers arguing for the increased use of accessibility as a performance measure for transportation systems are as follows. Cervero (1996b) was one of the first to make an extended argument that transportation system performance ought to focus on accessibility rather than auto-based mobility. Handy and Neimeier (1997) reviewed various kinds of accessibility measures and contrasted the concepts of local and regional accessibility. Bertolini (2005) highlighted how accessibility measures could be used in applied projects to integrate transportation and land use planning considerations. Grengs and Levine (2010) applied gravity accessibility measures to compare and contrast Washington DC and San Francisco, emphasizing accessibility as a comparative measure as well as one one that could be used to track transportation system performance over time. Guers et al. (2010) discuss how logsum measures can be used to perform a monetized cost-benefit analysis of future transportation-land use scenarios. Each of these papers provides insight into how transportation planners can use accessibility measures as performance measures and how these measures can be interpreted in a practical setting.

This body of work has enhanced our understanding of various measures of accessibility and has offered valuable guidance on how to implement these measures in practice. However at the same time this literature has at times relied too strongly on arguments regarding the theoretical appropriateness of accessibility measures. How do we know that the specific accessibility measures which are being operationalized measured corresponds with travelers' experience or perception of how opportunity is distributed across space? Largely the accessibility measures which exist are based upon data availability and convenience, and there is little connection with the cognitive processes by which travelers make decisions. Because of the theoretical focus of the accessibility as performance measurement literature, it has generally neglected tying specific proposed accessibility performance measures to particular travel behavior outcomes of interest.

Therefore one of the purposes of this dissertation is to explore the connection between various proposed measures of accessibility and their influence on specific travel behaviors. The dissertation investigates whether the influence of high accessibility environments on travel behaviors is in accordance with theoretical expectations and policy preferences.

Furthermore, the view of accessibility as a performance measure for the urban form-transportation system has some conceptual limitations. Thusfar, the implicit view in this literature is that the accessibility around a person's home location should be as high as possible in order to provide transportation system benefits. However, by definition, accessibility cannot be high everywhere. What kind of regional urban form is suitable for taking best advantage of accessibility patterns? Here the bid rent literature provides a complementary perspective. A regional urban form where patterns of residential density roughly correlate with patterns of accessibility allows the most people to take advantage of regional accessibility patterns while also incorporating the trade-offs between access and space which are integrated into the bid rent model. The bid rent perspective allows us to conceive of accessibility as not a single criteria to be optimized but rather as a regional spatial pattern of opportunity.

1.2.d Excess Commuting: The Urban Form-Travel Behavior Connection

Finally it should be pointed out that there is another connection which has been made in previous research, indicated in this diagram as Connection #3 (*Figure 1-1: Three Views on Accessibility*), i.e. the connection between bid rent theories of urban form and travel behavior. The excess commuting literature endeavors to explain the length and direction of urban commutes based upon bid rent theory. This theory suggest that workers will travel to the closest appropriate job available to minimize commuting costs, or alternatively, that workers will seek residential locations as close as possible to their work location, while taking into account the land cost gradient (Hamilton, 1982; Small & Song, 1992). Over time the excess commuting literature has arrived at the conclusion that commute cost minimization alone does not well explain residential location choice (Giuliano & Small, 1993; Small & Song, 1992). However the theoretical minimum commute has remained an important research measure for understanding local jobs housing balance (Horner, 2008). Some have claimed that the weakness of the theoretical minimum commute in explaining actual commutes means that urban form is unimportant in explaining commutes. However, Yang has established that generalized regional access to employment is an important factor in explaining average commute lengths (Yang, 2008; Yang & Ferreira, 2008). As a result of these findings, i.e. the importance of regional job access and the relative unimportance of the theoretical minimum commute, the literature has gradually shifted its focus from matching workers with *individual* job locations towards matching workers with a broad set of *choices* of possible jobs (Yang & Ferreira, 2008). This movement is underscored by the practical reality that workers often change jobs (and households often have more than one worker) and therefore households should not rationally decide their residential location based upon their current job location alone. In essence, the excess commute literature has been increasingly influenced by the choice-based thinking embedded within the accessibility concept. Therefore for this third connection between urban form and travel behavior, accessibility concepts and measures have become increasingly relevant as well.

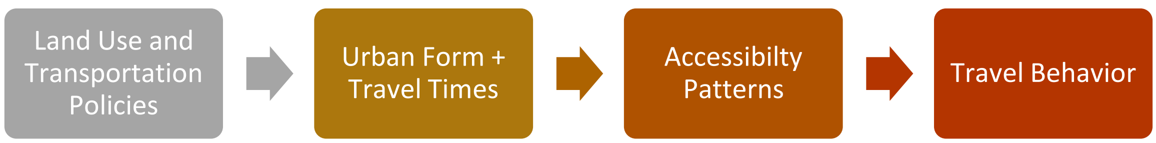
1.3 Research Questions

As stated above, accessibility measures can be viewed as a window into the performance of the combined urban form and transportation system, or the "urban system" for short. Accessibility measures are objective measures which integrate a variety of information about the urban system into one or more succinct measures. Because of their ability to summarize a wide range of information succinctly, they provide some insight into the transportation and land use policies applied and their influence on desired travel behavior, social, and economic outcomes. For example, it is difficult to evaluate the costs and benefits of a new piece of transportation infrastructure in isolation because it is inherently connected with the whole transportation infrastructure network. Accessibility measures provide us with one approach for assessing before and after benefits.

A simplified causal chain of influence can be traced in this way (See *Figure 1-2: Accessibility as Part of a Causal Chain Between Policies and Travel Behavior*): Land use policies influence urban form change. Transportation policies influence investments in infrastructure and the management of transportation infrastructure and therefore travel times. Urban form combined with the mobility provided by transportation infrastructure together result in spatial patterns of accessibility across a metropolitan region. Then these accessibility patterns in turn influence travel behavior in interesting and significant ways. Therefore part of the value of accessibility measures is that they provide insight into how complex patterns of urban form and transportation infrastructure are likely to influence activity patterns and travel behavior. Of course there are several feedbacks within this causal chain – travel behaviors influence travel times and the policy environment as well. However this step-by-step causal chain helps isolate some of the key relationships we wish to understand about how policies influence travel behavior outcomes. This sequence of causal events is summarized in Figure 1-2.

The dissertation examines the last two pieces of this causal chain. The first two papers from the dissertation explore the relationship between accessibility patterns and travel behavior, or the third and fourth boxes in the Figure 1-2 diagram. The first paper,

Figure 1-2: Accessibility as Part of a Causal Chain Between Policies and Travel Behavior



Measuring Complete Communities, examines whether different aspects of accessibility as well as other urban form features can make travel patterns more localized. This is similar to research which has been done linking high accessibility environments to smaller activity spaces (El-Geneidy, 2010). The second paper, *Does Accessibility Influence Activity Participation*, examines whether a more accessible built environment can promote greater participation in nonwork activities. Both of these papers focus on connecting specific accessibility measures to travel behaviors that are theoretically expected but which have not necessarily been well documented empirically.

The third paper of the dissertation, *Changing Accessibility in US Metropolitan Areas*, examines accessibility patterns over time and how they are influenced by both urban form change and transportation system change. Therefore here the focus is on the connection between the second and third boxes of Figure 1-2. The innovation in this paper is to examine urban system change over time from the perspective of accessibility. This yields a prescriptive rather than a descriptive analysis of urban system change, i.e., it answers the question of whether or not the urban system is performing better or worse over time. The various urban form and travel time components which influence accessibility change are also identified and described in this paper. This helps to identify how much of accessibility change is due to changes in urban form, and how much is due to changes in mobility provided by the transportation system.

1.4 Defining and Measuring Accessibility

The definition I propose for accessibility is the ease and scope of opportunities for interaction across space within the urban environment. This definition is based upon previous similar definitions, but I add an emphasis on the role of increased scope or choice (Geurs & Van Wee, 2004; Handy & Niemeier, 1997). In this dissertation, accessibility measures are place-focused: they reflect how much a particular *location* is connected with opportunities which may be distributed throughout the metropolitan area.

One reason accessibility measures are particularly informative is that they form a connection between the local and the regional. As opposed to more conventional measures of urban form such as density or mixed use, accessibility measures provide information about how much the entire regional built environment influences a particular location.

A great deal of recent research on how the built environment can influence travel behavior has focused on relatively small-scale urban form features. Much of this research has been motivated by the idea that if planners can build better neighborhoods, then we can reduce travel demand. But the preponderance of evidence suggests that regional context has a greater influence on travel behavior than local context (Cervero & Gorham, 1995). Of the four “D’s” which influence travel behavior – destination accessibility, density, diversity, and design – destination accessibility has the largest influence on reducing vehicle miles traveled (Ewing & Cervero, 2010). To some extent, planning researchers have been focusing on the incorrect scale for understanding how urban form influences the amount of vehicular travel. One of the reasons a focus on accessibility measures is warranted is that thinking about accessibility sharpens our focus on how regional-scale urban form features influence travel behavior.

Two of the three dissertation papers examine one particular type of accessibility measure – gravity measures of accessibility to employment opportunities from residential locations. There are many strengths and weaknesses of this particular measure, a thorough discussion of which goes beyond the scope of this introduction. Some of the strengths of this measure are that it accounts for regional patterns of opportunity; that the data are often available to compute such measures; that as measures of spatial opportunity they reflect patterns of land use; and that these measures aggregate a great deal of spatial information into a succinct summary. Some of the weaknesses of these measures are that they do not reflect variations in individual capabilities or time constraints; that they do not reflect different attitudes about the inconvenience of travel time; and that they do not incorporate the patterning of activity spaces based on habitual travel behaviors. In summary, it could be said that these types of gravity accessibility measures are both powerful but also have their drawbacks.

1.5 The Monocentric Model in a Polycentric Era

In truth, the monocentric model, as traditionally framed, holds little relevance to the contemporary era of polycentric and dispersed urban areas. To take just one example, Giuliano found that less than 10% of regional employment was located within the traditional regional center of downtown LA in 2000 (Giuliano, Redfearn, Agarwal, & He, 2012). However considering the general principals of urban bid rent theory, i.e. that urban land values and density patterns are derived primarily from access to urban opportunities, then the "monocentric" model remains relevant to this day. The key to adapting traditional bid rent theories to contemporary urban environments is to move away from the traditional measurement of urban access, i.e. distance to the central business district, and to adopt in its place accessibility measures which are generalizable to polycentric or dispersed urban forms.

Bid rent theories suggest that households tradeoff between the desire for greater housing and space consumption and their preference for lower commuting costs in time or money (Anas, Arnott, & Small, 1998; Brueckner, 1987). The implications of bid rent theory within the traditional monocentric framework are that land rents and residential densities rise with proximity to the CBD, or alternatively stated, that rents and residential and population densities vary inversely with distance. The relationship between distance to the CBD and population density has generally been assumed to take on a negative exponential form, and density gradients have often been used to compare the relative concentration of population between various urban areas and for particular urban areas over time (Anas et al., 1998; Mieszkowski & Mills, 1993). Density gradients describe metropolitan-scale urban forms through the use of a single parameter from the negative exponential function, and therefore allow a succinct description of the relative concentration of the population. It has been widely observed that urban areas worldwide have seen a trend of almost unabated decentralization, as marked by declining density gradients, for at least the last 100 years (Mieszkowski & Mills, 1993). The primary explanation for this continued decentralization trend has been declining travel costs and increased travel speeds, linked with the spread of the auto in particular but also linked with faster transit travel as well (Ahlfeldt & Wendland, 2011; Mieszkowski & Mills, 1993).

There are several weaknesses in the assumptions behind the traditional monocentric model, but in particular the assumption that most employment is contained within the CBD is increasingly out of date (Garreau, 1991; Glaeser & Kahn, 2001; Weitz & Crawford, 2012). The trend of employment decentralization is particularly pronounced in the United States, where development patterns are often guided primarily by development interests and with only a weak influence from public policy. In the US, lower land prices and high levels of auto access provided by an expanded interstate system have resulted in the development of numerous major employment centers outside the central city in most major metropolitan areas (Garreau, 1991). The study of metropolitan employment subcenters, their locations, sizes, functions, and commuting patterns, has become an academic subject of interest in its own right, with a corresponding growth in the literature (Giuliano & Small, 1991; McDonald & Prather, 1994; McMillen & Lester, 2003; Redfearn, 2007).

However a number of carefully constructed studies have confirmed the continued relevance of urban bid rent theories to a dispersed or polycentric era. Helling compared integral, gravity, and cumulative opportunity accessibility measures with distance to the CBD for explaining residential location patterns, and found that gravity-based accessibility measures best explain variations in net residential density (1992b). Song compared monocentric, polycentric, and dispersed models of the location of worker households, and found that a dispersed model, based upon gravity accessibility measures, fitted worker residence distribution best (S. F. Song, 1994). Ahfeldt studied the residential land rent gradient in Berlin, Germany, and, making use of gravity-based accessibility measures to employment, found that these variables explain the residential land rent gradient better than simple distances to transportation infrastructure (Ahlfeldt, 2011). Taken together, these studies strongly suggest that monocentric descriptions of urban form no longer work well across much of the western world. In addition these studies suggest that accessibility measures can still be used to describe regional urban form because these measures capture the geographic dispersion of destinations across space. Table 1-1 illustrates the various accessibility measures used in these studies and how they have been operationalized.

Table 1-1: Papers Applying Bid Rent Theory to Polycentric/Dispersed Urban Areas

Author, Year	Accessibility Measure	Impedance Measures
Ahlfeldt, 2011	Gravity	Travel Times, Multiple Modes Straight Line Distance, Multiple Modes
Helling, 1998	Gravity, Integral, Cumulative	Travel Times, Auto
Song, 1994	Gravity	Travel Times, Auto Distance, Auto

The primary difference between these updated versions of the bid rent model and the traditional monocentric model is that these approaches take into account that destinations of interest, in particular workplaces, can located anywhere throughout the metropolitan area. Each individual job location is considered a potential attraction, and usually by assumption all jobs are considered as equally attractive. In some cases travel distances are used to take into account the difficulty of reaching these destinations, and sometimes travel time is used. In each case, these applications of the bid rent model make use of accessibility measures instead of the distance to the CBD to improve the explanatory power of the model. However, there is an important mathematical distinction between the use of distance to the CBD and the use of accessibility measures. Accessibility *increases* with decreasing distance, so land rents and population densities increase with higher levels of accessibility.

The functional form of the relationship between residential density and accessibility is not necessarily determined by theory. Ahfeldt assumes a log-log relationship between land price and work accessibility (See Equation 1 below). Song and Helling both assume that accessibility is linearly related to the log of residential density (See Equation 2).

1) $log(land\ price) = log(accessibility\ to\ jobs)$

2) $log(residential\ density) = \beta_0 + \beta_1(accessibility\ to\ jobs)$

So what are the implications of these results? Firstly, that urban bid rent theory continues to be relevant in the contemporary era of polycentric or dispersed urban forms. This means that both land values and residential density patterns are expected to correlate with measures of urban accessibility for polycentric urban areas. In fact, theoretically accessibility should be the *primary* variable explaining patterns of urban land values, though amenities and public goods could also be significant influences depending upon the context. Secondly, that distance to the center of the urban area is second best as a predictor of urban form. Once urban accessibility is adequately accounted for, distance to the CBD may not contribute significantly as an explanatory factor (Ahlfeldt, 2011). Thirdly, gravity measures of accessibility have proven to be widely effective in describing urban form patterns. Furthermore, travel time based measures appear to be more effective than distance-based measures. To summarize, urban bid rent theory, though sometimes apocryphally referred to as the "monocentric" model, remains relevant in a polycentric urban era.

Furthemore, it is noteworthy that urban bid rent theory has been used not just to *describe* urban forms, but also to argue whether observed urban forms are efficient (Brueckner, 2000b; McGrath, 2005; Mieszkowski & Mills, 1993). Specifically, some urban economists have argued that if bid rent theory explains urban forms well, then this suggests that urban forms are responding in an efficient manner to transportation costs. This dissertation deepens this line of analysis by connecting it to travel behavior theories which advocate for accessibility as an outcome measure. It is this way of thinking about accessibility that is explored in the next section.

1.6 Accessibility and Travel Behavior Research

Accessibility can also be considered for its travel impacts, i.e. in increasing the level of travel opportunity available to a particular individual or household. According to Handy and Niemeier, accessibility is defined as "the potential for interaction, both social and economic, the possibility of getting from home to a multitude of destinations offering a spectrum of opportunities for work and play (Handy & Niemeier, 1997)."

Accessibility measures have been empirically associated with shorter vehicular travel distances, higher residential property values, and preferred residential location choices. Several comparative studies of urban form measures have suggested that accessibility to jobs is the built environment variable most associated with reduced vehicle miles traveled (Cervero & Duncan, 2006; Ewing & Cervero, 2001, 2010; Kockelman, 1997). Several other studies have associated higher residential accessibility with reduced travel demand, especially reduced VMT (Cerda, 2009; Levinson, 1998).

Research has also connected higher accessibility with higher residential land values (Ahlfeldt, 2011; Cerda, 2009; El-Geneidy & Levinson, 2006; Giuliano et al., 2010; Iacono & Levinson, 2010; Srour et al., 2002). Some of these studies conclude that other factors are more important than accessibility in determining residential land values, but in each of these studies, accessibility to jobs has a statistically significant and positive influence on land values. Finally, accessibility has also been strongly linked residential location choice (Cervero & Wu, 1997; Cho, Rodriguez, & Song, 2008; Levine, Inam, & Torng, 2005; Srour et al., 2002; Waddell et al., 2003). Taken together, this research suggests that accessibility is linked to higher land values, reduced dependence upon vehicular travel, and preferred residential locations.

1.7 Summary of Research Questions for the Three Papers

The following sections detail the research questions and methods for the three dissertation papers. A summary of results and implications for each paper is contained in the conclusion.

1.7.a Measuring Complete Communities

Research Question. Jobs-housing balance measures have a long history in planning and have been associated with more self-contained communities and shorter commutes. However, jobs-housing balance measures suffer from an arbitrariness of scale and a neglect of regional spatial context. This paper investigates a wide variety of urban form measures to see which best explain community completeness with respect to nonwork travel.

Methods. Starting with the 19-county Chicago metropolitan region, I examine community completeness for two geographic scales: Centered Communities and Census

Places. Therefore the same metropolitan region is examined twice through different geographic decompositions. Centered Communities consist of a cluster of one or more employment centers and residential areas within a 15-minute drive time radius of these centers. The other geography is Places, which are generally incorporated towns and cities. Examining two distinct geographic scales adds to the robustness of the analysis.

A community's level of completeness is measured as its internal tour capture rate for nonwork tours. The internal tour capture rate is defined as the percentage of the time a nonwork tour was successfully completed within a particular geography. Internal trip capture is used as a secondary dependent variable and for a robustness check.

Community urban form is measured with three types of variables: size and density variables, mixed use variables (including jobs-housing balance), and accessibility variables. Mixed use variables include raw jobs-housing ratio, jobs-housing balance index, Entropy, Dissimilarity, and Exposure indices. This paper also introduces a variety of accessibility variables which have not previously been examined in the context of internal trip capture or community completeness.

1.7.b Does Accessibility Influence Nonwork Activity Participation

Research Question. Most of the research on the benefits of accessibility has focused on reducing the externalities of travel, but one of the primary benefits of accessibility for households is the ability to engage in a greater range of activities at lower cost. This study examines a national travel data set to see if urban form patterns which offer greater accessibility can facilitate household participation in out-of-the-home activities. Although several studies have examined the relationship between accessibility and nonwork trip generation in the past, few have looked at data sets that include such a wide range of built environments. Using such built environment diversity helps to answer the key question motivating this study: Do households benefit from higher accessibility environments through increased participation in out-of-the-home activities?

Methods. The approach of this study is to model levels of nonwork travel activity as a function of supply and demand for household activity participation. Demand for travel activity is assumed to be determined by household structure and resources – the number, gender, and ages of household members, household member relationships, and household income. The supply of opportunities for travel activity is determined by time constraints, the availability of private vehicles, and the level of accessibility provided by the built environment. Using these variables, I estimate the influence of the built environment (and therefore accessibility) on a variety of measures of travel activity.

For nonwork travel activity, I examine three dependent variables: Individual activity episodes, household activity episodes, and individual tours. Each of these variables is aggregated to the household level.

Because I expect that the built environment to have a different influence depending upon a households' level of vehicle ownership, the analysis segments households into three groups: households without vehicles (Zero Vehicle Households), households with only one vehicle but more than one driver (Limited Vehicle Households), and households with two or more vehicles, or exactly one vehicle and exactly one driver (Full Vehicle Households).

Travel data for this paper is from the National Household Transportation Survey (2009), a nationally representative survey of US household travel behavior. It includes a 24-hour detailed travel survey of modes, times, trip purposes, and a variety of individual and household sociodemographic data. As a national survey, it contains a much wider range of land use variation than most metropolitan area travel surveys, including households from metropolitan areas of all sizes as well as nonmetropolitan areas. The rich data provided by the NHTS supports the development of robust models for predicting household-level travel activity.

1.7.c Changing Accessibility in US Metropolitan Areas

Research Questions. Accessibility is influenced by both the proximity of locations and by travel speeds. However, in US metropolitan areas the overall trend has been negative on both fronts: US metropolitan areas are spreading out, resulting in decreased employment proximity, and roads are increasingly congested, resulting in slower travel speeds. If this is indeed the case, then most US metropolitan areas are actually delivering less accessibility to their residents over time. Metropolitan-scale smart growth efforts, however, could potentially channel development into existing built-up areas, and therefore lead to higher accessibility relative to more sprawling metro areas.

The primary research questions concern how accessibility changes over time in US metropolitan areas, and to what extent accessibility change is influenced by changes to urban form and to travel times. More specifically, is accessibility increasing or decreasing over time in US metropolitan areas, and what are the primary underlying causes of these changes? In terms of policy, are there different trends for metropolitan areas where more compact urban form patterns prevail, versus metropolitan areas where more sprawling urban form patterns prevail?

Methods. Based on longitudinal information on travel times, population location, and employment location from Metropolitan Planning Organizations, I calculate the accessibility to work for four metropolitan areas' populations for the years 2000 and 2010. I aggregate these population-based accessibility scores to the metropolitan level in order to evaluate changes to metropolitan urban form over time, i.e. are metropolitan areas becoming more or less accessible over time. Then the paper breaks down these total changes in metropolitan accessibility into shifts due to changing residential patterns, shifts due to changing employment patterns, and shifts due to changing travel times.

The four metropolitan areas are selected for variation along two dimensions: change in average population proximity, and change in average traffic congestion. Theoretically, proximity and travel times are the drivers of metropolitan accessibility change, so these four metropolitan areas should highlight contrasts trends with regard to accessibility change.

1.8 Conclusion

This dissertation explores the connections between accessibility measures, travel behaviors, and urban form change. The first two papers examine the relationship between accessibility and travel behavior. The first of these, *Measuring Complete Communities*, connects higher local accessibility and lower regional accessibility with more localized travel patterns. The second, *Does Accessibility Influence Nonwork Activity Participation*, finds that local built environment accessibility can facilitate greater household participation in nonwork activities. The third paper, *Changing Accessibility in US Metropolitan Areas*, examines accessibility change over time via gravity measures and seeks to decompose the various influences on such accessibility change. This paper finds that changes to travel times are the dominant influence on accessibility change for the 2000-2010 period for four major metro areas and for both auto and transit travel modes.

The dissertation in its entirety concludes that the relevance of accessibility measures depends upon the policy question of interest. Particular accessibility measures are associated with more localized travel patterns and with greater activity participation. However maximizing regional accessibility to employment may not help achieve the diverse range of current transportation planning goals. Specifically, two of the three papers find that local accessibility may be more important than regional accessibility for promoting the particular goals of more localized and more convenient travel.

Furthermore, the results from the third paper suggest that when seeking to promote higher regional accessibility for households, it is difficult to coordinate land use change and transportation system change at the regional scale. The four metropolitan areas examined include several which experienced improvements in transportation system mobility (both auto and transit based) while at the same time seeing a decline in the proximity provided by urban form. It appears difficult to channel regional development patterns towards higher accessibility areas, even in ‘smart growth’ metropolitan areas such as metro Seattle. The coordination of land use patterns with existing and planned transportation infrastructure is a challenging regional and local planning task. However it is a task that is no doubt aided by a better integration of accessibility measures into regional and local planning processes.

Chapter 2 Measuring Community Completeness: Jobs-Housing Balance, Accessibility, and Convenient Local Access to Nonwork Destinations

2.1 Abstract

Using 2007 travel diary data from metropolitan Chicago, I investigate what aspects of urban form contribute most to community completeness, as defined by internal tour capture for nonwork tours. The paper examines two distinct geographic scales – Census-defined "Places" and synthetically constructed "Centered Communities." Centered Communities are defined as nonwork travel sheds centered upon concentrations of retail and service activity. Higher accessibility share (a new urban form measure) and higher mixed use both significantly predict greater community completeness, as do higher levels of residential or employment density. Furthermore, I find that mixed use measures describe something distinct from proximity to job-based attractions; they capture whether urban forms provide an appropriate *balance* of activities necessary for a complete community. To build more complete communities, planners need to ensure that the level of local accessibility to a variety of attractions of interest is high relative to the level of regional accessibility available outside their community.

2.2 Introduction

Planners have been aiming at creating complete communities since the dawn of the profession during the days of Ebenizer Howard at the turn of the 20th century. Howard's vision was one of semi-autonomous communities, Garden Cities, that physically contain all the necessary aspects of community life, including employment, but with strong connections to a greater metropolitan region (Howard & Osborn, 1965). The idea of complete communities was revived with the New Towns movement in the United States and Europe (Burby & Weiss, 1976), and reached beyond to other countries as well (Lee & Ahn, 2005). However for the most part these Garden Cities and New Towns have failed over time to be self-contained with regards to commuting trips (Cervero, 1995, 1998). Given the range of residential and employment choices available in a sizable metropolitan region, residents rarely choose to work and live in the same community if they have high levels of mobility. However not all trips are worthy of lengthy metropolitan-scale ventures, and so planners have responded by seeking to create a more modest version of completeness – one where most of a household's regular needs and at least some employment opportunities are distributed at activity centers located throughout a metropolitan region and therefore in closer proximity to where households live. This goal of being able to meet most of one's nonwork needs at a local activity center lives on in the idea of the complete community.

This interest in creating a series of relatively compact and local complete communities where residents are able to conduct the regular functions of their daily lives remains an active goal within contemporary comprehensive plans (City of Vancouver, 2003; Ontario Ministry of Infrastructure, 2006; Wood, Frank, & Giles-Corti, 2010). In part this may be a reaction against the trend of growth in nonwork travel distances; for example, shopping VMT has increased by 278% since national household transportation surveys began in 1969, whereas commuting VMT has increased just 60% (Santos, McGuckin, Nakamoto, Gray, & Liss, 2011a). As more households have had to engage in longer distance, regional-scale travel to meet regular household needs, more residents are expressing the desire for compact, self-contained, complete communities which provide the opportunity to engage in a variety of activities locally. If planners are able to facilitate the creation of such complete communities, benefits may include a greater range of easily accessible opportunities, shorter average vehicular trips, reduced burdens on regional transportation infrastructure, and a potential shift to non-motorized modes (Cervero, 1989). Moreover, creating complete communities is not only an important transportation goal, it may also foster communities with stronger identities and increased social identification from local residents (Kaiser, Godschalk, & Chapin III, 1995). For the purposes of this paper, I define a "complete community" as a sub-regional geographic boundary within which most residents are able to meet most of their daily and weekly nonwork travel demands.

Much of planners' and planning researchers' recent focus on "completeness" has been at the neighborhood scale, perhaps due to the influence of New Urbanism on contemporary planning (Duany, Plater-Zyberk, & Speck, 2000). As a result the bulk of recent urban form and travel behavior research has focused on the neighborhood scale (Cao, Mokhtarian, & Handy, 2007; Crane & Crepeau, 1998; Fan, Khattak, & Rodriguez, 2011; Handy & Cliffton, 2001; Khattak & Rodriguez, 2005; Levine et al., 2005; Manaugh, Miranda-Moreno, & El-Geneidy, 2010). Generally these neighborhoods are defined at a small scale, such as a ¼-mile or ½-mile radius (Krizek, 2003) or based upon a 150-meter grid cell and its surroundings (Manaugh et al., 2010) – i.e. typically on the order of 150-500 acres. While diverse, mixed use neighborhoods are a worthy planning goal and are likely helpful in reducing travel demand, available evidence suggests that neighborhood design explains only a small part of household activity patterns (Boarnet &

Greenwald, 1999; Handy, 1992; Krizek, 2003). For example, in Ewing et al.'s study of mixed use developments, which range in size from 100-400 acres, the average internal trip capture of these developments was just 18%. This means that approximately 82% of travel starting from these locations ventures outside these developments, even within mixed use settings (Ewing et al., 2011). Indeed, most household activity patterns span beyond the neighborhood and are strongly influenced by regional urban form (Ewing & Cervero, 2001). Therefore, there is an urgent need for greater research attention to urban form beyond the neighborhood scale, such as the community scale. One of the goals of this paper is to try to identify a meaningful scale for thinking about communities. Planners have traditionally used the term "community" to identify a scale that is larger than the neighborhood (about 150-500 acres), yet also much smaller than the region (as defined by metropolitan planning organizations, up to millions of acres); for example, Kaiser et al. define the market area of a community shopping center as 3-5 miles in radius or 10-20 minute drive time (Kaiser et al., 1995). However, the term "community" may take on different meanings, shapes, and sizes depending upon the context in which it is used. In other words, although planners and residents may use the term "community" to correspond to a wide range of scales, here I am trying to examine whether or not such "communities" can offer some reasonable version of completeness with respect to residents' nonwork activities.

Therefore, this study examines various measures of urban form across a range of community scales and tests how these measures relate to completeness with respect to nonwork trips and tours. To operationalize the idea of completeness, I examine internal trip capture and internal tour capture, or the percentage of trips or tours that begin within and are contained within a given community's boundaries. The goal of designing complete communities with respect to nonwork travel is likely to be feasible because nonwork destinations often (but not always) can serve as substitutes for each other.

The sections of the paper proceed as follows. The first section is a literature review of relevant works in the areas of jobs-housing balance, internal trip capture, and the identification of employment centers. The second covers research methods, including the definition of the communities at two distinct scales, definitions of various measures of urban form, a discussion of the dependent variables (internal tour/trip capture), and a review of regression equations used in the analysis. The third section covers the results. And the final section includes a discussion of principal findings, implications for policy, and potential future research directions.

2.2.a Literature Review

This section reviews three relevant literatures: the literature on jobs-housing balance, the literature on internal trip capture, and the literature on defining employment centers within a metropolitan area. The literature on jobs-housing balance is relevant because a balance between jobs and housing is what most planners currently think best characterizes a "complete" community. Also, the ratio of jobs to housing provides one suitable measure of land use mix at the community scale. The literature on internal trip capture is important because a form of this variable is used as the dependent variable in the analysis. Finally, the literature on employment centers provides a mechanism for breaking down metropolitan regions into functionally distinct, discrete communities. Therefore each of these literatures provides a piece of the puzzle regarding how to conceive of complete communities.

Jobs-housing balance. Among other scholars, Cervero in particular has conducted a number of studies on the jobs-housing balance of employment centers (or cities) and how these balances affect commuting patterns and housing choices (Cervero, 1989, 1991, 1996a; Cervero & Wu, 1998; Giuliano & Small, 1993). Cervero's 1989 study of the San Francisco Bay Area found asymmetric findings with respect to jobs-housing balance in communities: Communities with a rich supply of local housing had more of their workers living within them; however communities with a rich supply of local jobs did not necessarily have more of their residents working within them (Cervero, 1989). In a later paper revisiting jobs-housing balance in the San Francisco Bay Area, Cervero found that there was little association between jobs-housing balance and the self-containment of commuting trips, and that this correlation reduced between 1980 and 1990 (Cervero, 1996a). In a more recent study of jurisdictions in Virginia, jobs-housing balance in jurisdictions was found to be highly correlated with shorter commute times (Miller, J. S., 2011). Altogether this evidence suggests that jobs-housing balance alone is unlikely to create a self-contained community with respect to commuting travel.

Internal trip capture. In this literature, a geography is considered to be more "self contained" if it has a higher internal trip capture, either with regard to work or nonwork travel. However this literature has usually focused on the development or the neighborhood scale, not the community scale. A recent study by Ewing et al. examining 239 mixed use developments averaging about 200 acres in size across 6 metropolitan regions finds that the internal trip capture of developments increased with development size, better jobs-housing balance within the development, and higher development intensity as measured by floor area ratio (Ewing, et al., 2011). This study suggests that jobs-housing balance has the largest influence on internal trip capture rates. Average internal trip capture rates for these master planned communities were around 18%. A study of master-planned developments in Australia (ranging from 850-3500 acres in size) by Yigitcanlar generally found low levels of self-containment for commuting travel, but also found that self-containment increases with distance to the CBD, and decreases with household car use (Yigitcanlar, et al., 2007). Greenwald examined the Travel Analysis Zone (TAZ) scale and found that internal trips are more likely with higher land use Entropy (which is a measure of the diversity and balance across employment activities) and in the location of a person's home TAZ (Greenwald, 2006). In summary, internal trip capture rises with the size of the geography under study as measured by population or job counts; declines with proximity of the geography to the regional center; and rises with increased land use mix.

Metropolitan employment centers. The literature on metropolitan employment centers has generally focused on describing the location and composition of employment centers, as well as the influence of these employment centers on commuting patterns. These studies define the characteristics of polycentric urban form at the regional scale and how a polycentric structure influences changes to urban form over time (Giuliano & Small, 1991; McMillen & McDonald, 1998; Redfearn, 2009; Small & Song, 1994). Employment centers have generally been identified based upon thresholds for employment density and employment size, although more sophisticated methods have also been proposed (Redfearn, 2007). Some research has associated larger employment centers with longer commutes and higher shares of alternative modes (Cervero & Wu, 1998; Giuliano & Small, 1991), but rarely has this literature addressed internal trip capture.

Although these studies of urban form and travel behavior cross a wide range of scales and subject matters, a few clear narratives emerge on how these results are likely to apply to community completeness. Firstly, both local land use patterns and regional land use patterns should be influential in shaping the level of self-containment for communities. Traditional jobs-housing balance measures, however, only capture the influence of local land use patterns on travel. For this reason, this study also examines various accessibility measures in order to take into account the influence of both local and regional land use patterns. Secondly, communities are more likely to be self contained if they are larger and if they are have lower levels of regional accessibility (i.e. they are located further away from the center of the metropolitan area). Thirdly, communities are more likely to be self contained if they contain a wide variety of land uses or activities within them, i.e. high levels of mixed use.

Although I draw on all of the various literatures discussed above, I ask a fundamentally new question in this study: What is the relative contribution of various components of urban form to *complete communities* with respect to nonwork activity? I look at a new set of accessibility measures and compare them with more traditional measures of urban form. Also, I consider the important secondary question of how to define the appropriate geographical scale for complete communities.

2.3 Methods

2.3.a Geographies under Analysis

Starting with the 19-county Chicago metropolitan region[1], I examine community completeness for two geographies: Communities defined around employment centers (hereafter "Centered Communities") and Census Places (hereafter "Places"). The process for identifying Centered Communities was based on a division of the metropolitan region into non-overlapping nonwork travel sheds, each centered on a service-based employment core (see below). The second geography under examination is Census-based Places, which are usually incorporated cities. Boundaries for Centered Communities were built upon collections of Travel Analysis Zone (TAZ) boundaries, which were provided by CMAP, while boundaries for Places were from the US Census Bureau (CMAP, 2012; US Census Bureau, 2012a). For both geographies, I consider the set of destinations contained within them to be local, and the set of destinations outside of them to be regional.

In order to create various urban form measures and define the Centered Communities, I rely upon location-specific job and resident worker counts from LODES (LEHD Origin-Destination Employment Statistics) data from the year 2007 (Year 2007 is chosen to coordinate with the timing of the Chicago metropolitan travel survey) (US Census Bureau, 2012b). LODES data is an administratively compiled data source from Census Bureau's Longitudinal Employment Household Dynamics program[2].

[1]The CMAP TAZs overlapped with the following 19 Chicago metropolitan area counties: Boone, IL; Cook, IL; Dekalb, IL; Dupage, IL; Grundy, IL; Kane, IL; Kankake, IL; Kendall, IL; Lake, IL; Lasalle, IL; Lee, IL; Mchenry, IL; Ogle, IL; Will, IL; Winnebago, IL; Lake, IN; Porter, IN; Kenosha, WI; Walwort, WI.

[2]The Census Bureau compiles the data from multiple sources including employer-based, state-level unemployment insurance files and supplements this with IRS tax filings to identify household addresses.

The first step in identifying Centered Communities was to count the number of resident workers and jobs located in each TAZ, with jobs identified by two-digit industry NAICS code (US Census Bureau, 2012b). Resident worker and job counts for each TAZ came from summing over all Census Blocks whose centroids were located within them. Then, I calculated a retail-and-service job density for each TAZ[3] and selected 1 job/acre as the minimum cut-off for identifying retail and service "Cores." This density cut-off of 1 job/acre was selected after testing a range of potential density cut-offs, with the goal of covering as much of the region as possible while identifying distinct concentrations of employment-related activity. This process resulted in the identification of 224 TAZs as "Cores" or activity centers for building Centered Communities around.

In general, I joined adjacent Core TAZs into a single Core. Many Core TAZs were close but not adjacent; therefore, if two Core TAZs were within a 10 minute drive time from each other, I also joined them into a single Core (all drive times were provided by CMAP (CMAP, 2012)). I separated the City of Chicago into three distinct Centered Communities, one for the central business district, one for the side of the city north of I-290 Eisenhower Expressway, and one for the side of the city south of the expressway because the population of Chicago was too large to be considered as a single Centered Community.

In order to associate residential areas with these Cores, I connected each non-Core TAZ with the Core TAZ that it was closest to using off-peak drive times. However,

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LODES identifies both employment and resident worker locations at the Census Block level, however some of the resident worker locations are synthesized in order to maintain household confidentiality (Andersson, Freedman, Roenmer, & Vilhuber, 2008).

[3]Retail and service jobs included the following NAICS codes: Sectors 44-45 (Retail), Sector 72 (Accommodation and Food Services), and Sector 81 (Other Services)

residential TAZs were only connected to a Core TAZ if the drive time was less than 15 minutes. Therefore the 'radius' of each Centered Community is about 15 minutes of auto-based travel time. In addition, I re-categorized a handful of TAZs into different Centered Communities in order to make each community contiguous and reasonably convex. Once this process was complete, there were a total of 50 Centered Communities which included 2,649,053 resident workers out of a total of 4,262,245 in the 19-county metropolitan region (See Figure 2-1).

2.3.b Measuring Urban Form

I measured community urban form with three types of variables: size and density variables, mixed use variables (including jobs-worker balance), and accessibility variables. The jobs-housing balance literature suggests that the jobs-housing ratio and the jobs-housing balance index may be relevant to measuring complete communities (Cervero, 1996a; Ewing et al., 2011); here I substitute counts of resident workers for counts of housing units. Likewise, the literature on internal trip captures suggests that other measures of mixed use, such as Entropy, as well as size and density variables, may help explain community completeness (Ewing, Dumbaugh, & Brown, 2001; Greenwald, 2006). In addition to more traditional measures of mixed use, I test two proposed measures of mixed use, the Dissimilarity Index and the Exposure Index (Horner & Marion, 2009; Y. Song & Rodriguez, 2005). Also, I introduce a variety of accessibility variables that have not previously been used to predict internal trip capture or community completeness.

Accessibility measures are intended to capture the ease of travel to desired destinations (Geurs & Van Wee, 2004; Handy & Niemeier, 1997). I use three related accessibility measures in this study. "Regional accessibility" is the measure of accessibility from a specified point to all of the destinations of interest in the metropolitan region. "Local accessibility" is the measure of accessibility from the same point, but only to destinations located within the boundaries of a particular local geography. And finally, "Accessibility share" corresponds to the proportion of these two measures, i.e. how much of regional accessibility is provided locally.

Accessibility measures are distinct from conventional mixed use measures in two key ways: 1) Mixed use measures are strictly internal measures, and do not take into account regional context; and 2) accessibility measures incorporate some measure of travel cost, distance, or time (otherwise known as 'travel impedance'). In particular, accessibility measures reflect that travel costs increase with increasing travel time, whereas mixed use measures typically do not. Although mixed use measures, such as jobs-housing balance, have generally been used to identify complete communities, I hypothesize that accessibility measures may be more appropriate and therefore I compare the effectiveness of accessibility measures with mixed use measures for predicting community completeness.

Size and density variables (*S*). Size variables for each of the geographies under analysis include land area in acres, resident worker counts (as a proxy for the size of the resident population), total job counts, and resident worker and job densities per acre.

Mixed use variables (*M*). Mixed use variables include Jobs-Workers Ratio, Jobs-Workers Balance Index, Entropy Index (Ewing et al., 2011), Dissimilarity Index (Horner & Marion, 2009), and the Exposure Index (Y. Song & Rodriguez, 2005). The Jobs-Workers Ratio, Jobs-Workers Balance Index, Dissimilarity Index, and Entropy

Index measure levels of land use mix at the aggregate scale of the entire geography. The Exposure Index takes advantage of the variable proportions of workers to jobs within each TAZ to describe how well residents and workers are mixed together at a finer scale. The formulas employed are as follows, with j_i corresponding to the number of jobs and r_i corresponding to the number of resident workers located in a Place or Centered Community, and i=1, … n indexing the geographies under study.:

- "Raw" jobs-workers ratio:

$$Jobs\ Workers\ Ratio_i = \frac{j_i}{r_i}$$

- Jobs-Workers Balance Index, where a is the regional jobs-to-resident-worker ratio (Ewing, et al., 2011):

$$Jobs\ Workers\ Balance\ Index_{\ i} = 1 - \left|\frac{j_i - a * r_i}{j_i + a * r_i}\right|;$$

- Entropy Index[4], where all jobs within the geography have been divided into m employment categories, with each category indexed by c, i.e. $j^c{}_i$ is the number of jobs of category c in geography i (Ewing, et al., 2011):

$$Entropy_i = -\frac{\sum_{c=1}^{m}\left(j_i^c/j_i\right) * LN\left(j_i^c/j_i\right)}{\ln(m)}$$

- Dissimilarity Index, calculated as follows (Horner & Marion, 2009):

$$Dissimilarity_i = \frac{j_i}{\sum_{i=1}^{n} j_i} - \frac{r_i}{\sum_{i=1}^{n} r_i}$$

[4]For the calculation of the Entropy Index, I used the following employment categories: 1 - Resident workers; 2 - Transportation/ Communications/ Utilities = NAICS 22, 42, 48, 49, and 51; 3 - Retail = NAICS 44 and 45; 4 - FIRE = NAICS 52 and 53; 5 - Professional/Office = NAICS 54, 55, and 56; 6 - Education, Health Care, Government = NAICS 61, 62, and 92; and 7 - Other Service = NAICS 71, 72, and 81. Agriculture, Mining, Construction, and Manufacturing were omitted from all of these categories.

- Exposure Index, which measures the average residential exposure to jobs within a given geography's boundaries. In this formula, TAZs are indexed by the subscript z, while communities are indexed by i.

$$Exposure_i = \sum_{z \in i} \frac{j_z}{j_i} \frac{r_z}{j_z + r_z}$$

Accessibility variables (*A*). The accessibility measures in this study are intended to capture the ease of reaching nonwork destinations for an average community resident. In practice, the origin point for measuring accessibility for each geography was the center point of the TAZ with the highest retail and service employment density within it. I define three types of accessibility measures corresponding to three potential sets of destinations for non-work activity: All jobs; retail and service sector jobs only; and weighted nonwork destinations, as measured through a non-work index (*N*), defined below. I use gravity-based accessibility measures, as these correspond well to aggregate destination choice behavior at the regional scale. Travel impedance is captured with travel times; I use off-peak driving times between TAZs from the year 2010 (CMAP, 2012). Higher travel times to destinations correspond with lower levels of accessibility.

Nonwork attractiveness index. I follow the example of Grengs and Levine in constructing a nonwork attractiveness index by linking information on job types with trip frequencies for various nonwork travel purposes (Grengs, Levine, & Shen, 2010). Nonwork attractiveness (*N*) is calculated for a particular purpose *p* based upon the job types *k* present in a particular geography *i*, with a conversion factor based upon the metropolitan area *m*. Table 2-1 displays how I associate NHTS trip purposes with NAICS job types.

$$N_{i,p} = \frac{\sum_m t_p}{\sum_m j_k} \sum_{k \in p} j_k$$

Table 2-1: NAICS Job Types Associated with NHTS Trip Purposes

NHTS Trip Purpose (NHTS)	Associated NAICS Codes
Visit friends/relative	Resident workers
Shopping/errands	44-45
Buy goods: groceries/clothing/hardware store	44-45
Buy gas	44-45
Buy services: video rentals/dry cleaner/post office/car service/bank	52, 81
Family personal business/obligations	52, 81
Use professional services: attorney/accountant	54
School/religious activity	61
Go to school as a student	61
Day care	62
Medical/dental services	62
Social/recreational	71
Go out/hang out: entertainment/theater/sports event/go to bar	71
Visit public place: historical site/museum/park/library	71
Social event	71, 81
Get/eat meal	72
Coffee/ice cream/snacks	72
Go to religious activity	81
Attend funeral/wedding	81
Use personal services: grooming/haircut/nails	81
Attend meeting: PTA/home owners association/local government	81, 92

Constructing the non-work index in this way should yield a rough estimate of the number of trips of purpose p that find a destination within zone i, due to the number of trip attractors (i.e. jobs) located within that zone. Next, I sum over trip purposes p to derive a total non-work attractiveness for each specific geography i. Note that conceptually the units of the nonwork index N are nonwork trips:

$$N_i = \sum_p N_{i,p}$$

Accessibility share. Once the counts of the three types of destinations were established, I calculated local accessibility, regional accessibility and accessibility share for each geography. For a geography *G*, the gravity-based formula for local accessibility to nonwork destinations <u>within the geography</u> is (aka "local accessibility"):

$$A_G^G = \sum_{j \in G} E_j e^{-\delta t_{Gj}} \qquad 1$$

Where $A^G{}_G$ is the local nonwork accessibility provided to residents of geography *G* (subscript indicates that *G* is the community whose accessibility is being measured; the superscript indicates that *G* is also the relevant geography of destinations), E_j is the count of nonwork destinations in each of the zones $j \varepsilon G$, t_{Gj} is the off-peak drive time from the center of geography *G* to zone *j*, and δ is the impedance of driving time for nonwork travel. I used TransCad to calculate a doubly-constrained impedance coefficient for home based other auto trips, deriving an impedance coefficient of 0.1638 (units in minutes^{-1}) (CMAP, 2012).

Next, I examined the level of accessibility from a geography *G* to the region at large. For a geography *G*, the gravity formula for accessibility to nonwork destinations <u>throughout the metropolitan region *R*</u> is (with similar variable definitions as Equation 1):

$$A_G^R = \sum_{j \in R} E_j e^{-\delta t_{ij}} \qquad 2$$

Given that $A^G{}_G$ is the local nonwork accessibility, and that $A^R{}_G$ is the total regional nonwork accessibility, then I define the ratio of these two accessibilities, $A^G{}_G / A^R{}_G$, as the local nonwork accessibility share, or "accessibility share" for short. Note that this ratio is bounded by $0 \leq A^G{}_G / A^R{}_G \leq 1$. Corresponding to the three different types of destination counts, I name these accessibility share variables "Share Jobs" for accessibility share to all jobs, "Share Retail" for accessibility share to retail and service jobs, and "Share N" for accessibility share to non-work index destinations.

2.3.c Internal Tour Capture/Internal Trip Capture

Internal tour capture reflects what percentage of the time a nonwork tour was completed locally. An internal nonwork tour best represents the idea community completeness because it reflects a household being able to make all of its nonwork stops within the boundaries of its home community. I use internal trip capture as a secondary dependent variable in order to check for robustness in the results. Internal trip capture differs from internal tour capture in that it includes stops that occur within a traveler's home community while on the way to a destination outside of that community. Therefore I deem internal tour capture to be a superior variable for identifying complete communities. Note that I use the variable name ***C*** to refer to both dependent variables – internal tour capture and internal trip capture – whereas I spell out each variable to identify just a single one.

Household travel data comes from CMAP's Chicago Regional Household Travel Inventory, a household travel survey conducted for 11 Chicago metro area counties in Illinois and Indiana from January 2007 to March 2008 (CMAP, 2008)[5]. Internal tour capture for nonwork tours does not include tours that have a work destination or purpose. Likewise, this measure does not include tours that exclude the traveler's home location as part of the tour. After excluding irrelevant tours and trips, there were 25,480 nonwork

[5]The CMAP travel survey included the following Chicago metropolitan area counties: Cook, IL; DuPage, IL; Grundy, IL; Kane, IL; Kendall, IL; Lake, IL; McHenry, IL; Will, IL; Lake, IN; Porter, IN; LaPorte, IN.

tours and 54,566 nonwork trips for Centered Communities; and there were 37,243 nonwork tours and 79,195 nonwork trips for Places.

2.3.d Analysis

Regression techniques are appropriate for this analysis in that they allow us to compare the relative strength of the various urban form measures in explaining self-containment; I use linear regression because the dependent variables take on continuous rather than discrete values.

Let **C** represent the two dependent variables of internal tour capture and internal trip capture for each geography. Let **S** represent a vector of urban form variables describing size and density. Let **M** represent a vector of one or more urban form variables describing various measures of land use mix and **A** represent a vector of one or more local, regional, and accessibility share variables.

The purpose of the first set of equations is to determine which **M** and **A** urban form variables best describe each of the two **C** variables. Note that size and density variables (**S**) are used as controls for these equations, since these variables have the most obvious relationship with internal trip capture and have been verified in past research. That is for each *individual* variable $m_j \varepsilon \mathbf{M}$ and $a_k \varepsilon \mathbf{A}$, I examine:

$$\boldsymbol{C} = \beta_0 + \beta_1 \boldsymbol{S} + \beta_2 m_j \qquad 3$$

$$\boldsymbol{C} = \beta_0 + \beta_1 \boldsymbol{S} + \beta_2 a_k \qquad 4$$

These equations help determine which **M** and **A** variables are predictive of **C**, and how strong these relationships are. Then, once statistically significant variables have been identified, I run a combined model with both **M** and **A** variables to determine if there is redundancy between these sets of variables. In particular, I am interested in whether mixed use variables **M** remain statistically significant once accessibility variables **A** are included in the model. Once again, size and density variables are used as controls. This is tested by the following equations:

$$\boldsymbol{C} = \beta_0 + \beta_1 \boldsymbol{S} + \beta_2 \boldsymbol{M} + \beta_3 a_k \qquad 5$$

$$\boldsymbol{C} = \beta_0 + \beta_1 \boldsymbol{S} + \beta_2 m_j + \beta_3 \boldsymbol{A} \qquad 6$$

Finally, I develop a policy-relevant model that describes which urban form variables best describe $\boldsymbol{C}$ for each type of geography. In this case, I use a combination of theoretical expectation and stepwise regression to develop a streamlined model for predicting $\boldsymbol{C}$. The form of this equation is:

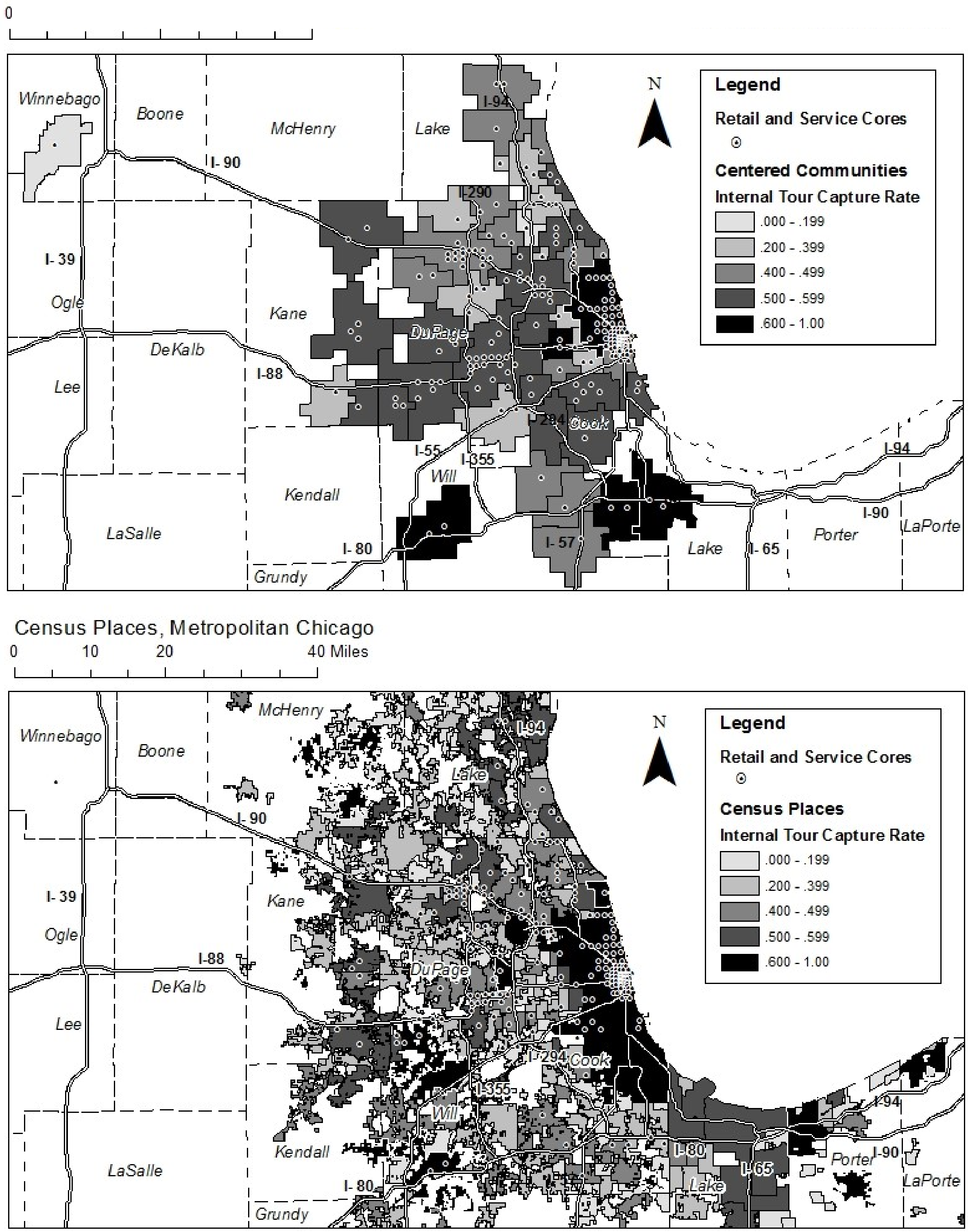
$$\boldsymbol{C} = \beta_0 + \beta_1 \boldsymbol{S} + \beta_2 \boldsymbol{M} + \beta_3 \boldsymbol{A} \qquad 7$$

2.4 Results

2.4.a Descriptive Statistics

Summary statistics for the 49 Centered Communities and the 259 Places are in Table 2-2 and Table 2-3. One Centered Community and 74 Places were dropped from the analysis because fewer than 10 tours that took place, therefore making $\boldsymbol{C}$ calculations were unreliable. Places comprise 80.2% of the resident workers, 86.4% of the jobs, and 23.5% of the land area of the 19-county Chicago metropolitan region. The Centered Communities comprise 63.3% of the resident workers, 75.8% of the jobs, and 15.7% of the land area of the Chicago metropolitan region. The Centered Communities are on average much larger and denser than the Places under analysis; the average Centered Community has 54,062 resident workers, 21,630 acres, and an average job density of 7.5 jobs per acre, whereas the average Place, on the other hand, has an average of 12,814 resident workers, 5,800 acres, and 2.2 jobs per acre.

Figure 2-1: Maps of Complete Communities and Census Places for Metropolitan Chicago



As a result, I treat these differing versions of the accessibility variables as mutually exclusive in subsequent analysis.

Table 2-2: Places, Descriptive Statistics (n=259)

Variable	Mean	Std. Dev.	Min	Max
Travel Measures				
Internal Tour Capture	33.3%	18.5%	0.0%	79.9%
Tours	143	520	10	8,109
Internal Trip Capture	34.3%	17.9%	0.0%	80.9%
Trips	303	1,139	15	17,822
Size				
Acres	5,800	10,295	220	147,608
Resident Workers	12,814	49,643	132	791,019
Jobs	15,118	75,396	8	1,205,004
Resident Density/Acre	2.18	1.44	0.11	8.15
Job Density/Acre	2.20	1.99	0.01	11.29
Accessibility				
Share N[a]	14.8%	14.7%	0.2%	97.5%
Share Retail	14.5%	15.0%	0.2%	98.6%
Share Jobs	14.2%	14.4%	0.3%	98.2%
Regional N[b]	67,482	63,323	787	750,906
Regional Retail	3,884	6,276	36	92,596
Regional Jobs	24,310	26,758	233	327,738
Local N[c]	11,529	46,065	2	732,284
Local Retail	815	5,683	0	91,326
Local Jobs	4,160	20,104	1	321,815
Mixed Use				
Jobs-Worker Ratio	1.02	0.76	0.02	6.20
Jobs-Workers Balance Index	0.72	0.22	0.03	1.00
Dissimilarity * 1000	0.01	4.56	-66.87	5.50
|Dissimilarity|[d] * 1000	1.40	4.34	0.01	66.87
Entropy	0.61	0.20	0	0.93
Exposure	0.39	0.12	0.06	0.84

a - Accessibility share for non-work index
b - Regional accessibility for non-work index
c - Local accessibility for non-work index
d - Absolute value of the Dissimilarity Index

Table 2-3: Centered Communities, Descriptive Statistics (n=49)

Variable	Mean	Std. Dev.	Min	Max
Travel Measures				
Internal Tour Capture	47.6%	11.0%	15.8%	68.0%
Tours	527	617	13	3,882
Internal Trip Capture	49.1%	11.3%	18.7%	68.2%
Trips	1,114	1,385	21	8,940
Size				
Acres	21,630	15,631	1,788	63,685
Resident Workers	54,062	55,179	1,994	354,220
Jobs	71,095	91,387	7,233	490,667
Resident Density/Acre	3.0	2.0	0.6	10.3
Job Density/Acre	7.5	29.6	0.7	210.0
Accessibility				
Share N[a]	43.1%	17.3%	12.0%	82.1%
Share Retail	42.6%	20.6%	4.9%	87.3%
Share Jobs	40.8%	18.2%	10.5%	84.3%
Regional N[b]	123,303	127,189	4,502	750,906
Regional Retail	9,255	15,471	233	92,596
Regional Jobs	45,911	54,039	1,160	327,738
Local N[c]	53,983	84,082	3,696	580,363
Local Retail	4,215	11,525	191	80,804
Local Jobs	19,633	39,108	863	276,304
Mixed Use				
Jobs-Worker Ratio	1.70	2.91	0.45	20.48
Jobs-Workers Balance Index	0.82	0.18	0.10	0.99
Dissimilarity * 1000	-0.05	20.45	-129.73	24.89
|Dissimilarity|[d] * 1000	8.75	18.44	0.35	129.73
Entropy	0.75	0.09	0.51	0.96
Exposure	0.42	0.11	0.23	0.87

a - Accessibility share for non-work index
b - Regional accessibility for non-work index
c - Local accessibility for non-work index
d - Absolute value of the Dissimilarity Index

Table 2-4: High Variance Inflation Factors (Size and Density as Controls)

Variable	Places[a]	Centered Communities[b]
Dissimilarity	~2,460,000.0	~50,300,000.0
Local Jobs	299.3	130.4
Local Retail	169.6	152.7
Local N[c]	87.3	72.8
|Dissimilarity|	15.2	33.2
Regional Retail	11.5	8.3
Regional Jobs	5.7	7.7
Regional N[d]	5.1	7.6
Jobs-Worker Ratio	4.0	13.2
Share Jobs	2.2	2.1
Entropy	2.1	2.4
Share N[e]	2.1	1.7
Share Retail	2.0	2.1
Exposure	1.4	1.9
Jobs-Worker Balance Index	1.2	1.8

a - Control variables include Acres, Jobs, Resident Workers, Job Density, and Resident Worker Density.
b - Control variables include Acres, Jobs, Resident Workers, and Job Density.
c - Local accessibility for non-work index
d - Regional accessibility for non-work index
e - Accessibility share for non-work index

2.4.b Regression Results

The first series of regressions attempts to answer the question: After controlling for size and density, what is the relative contribution of various individual urban form variables in predicting ***C***? That is, in order to limit the influence of multicollinearity, each urban form variable is examined one at a time with size variables as controls. Table 2-5 summarizes the results for both Places and Centered Communities, sorting variables in order of descending influence. Because the sample size was much smaller for Centered Communities (n=49), I only use statistically significant size variables ($p<.20$) as controls in that case (See Table 2-5 footnotes).

For Places, both accessibility share and mixed use variables are statistically significant for both dependent variables, with accessibility share variables appearing to explain more of the variation in ***C*** overall, as indicated by larger increases in R^2. For Places, the results across the two ***C*** dependent variables are quite consistent. For

Centered Communities, the results are more complex. Accessibility share variables appear to best explain internal tour capture, while Jobs-Workers Balance Index appears to best explain internal trip capture. Meanwhile, in one of the equations, Jobs-Workers Ratio is statistically significant and has a sign contrary to expectations, i.e. higher concentrations of jobs relative to workers *reduce* internal trip capture; however it should be noted that this variable has a high VIF (VIF=13.2) in this regression.

While it is somewhat surprising that the results between two such similar dependent variables (internal tour capture and internal trip capture, ρ=.94 for Places, ρ=.95 for Centered Communities) would vary so greatly, it is likely that some of this variability is due to the small sample size (n=49) of the Centered Communities data set; the results for Places are highly consistent across the two regressions. Multicollinearity may also be a factor (see Table 2-4).

Table 2-5: Individual Urban Form Variables Predicting Internal Capture at p<.10

Variable	Standardized Coefficients	95% CI	*t*	ΔR^2
		Places, Internal Tour Capture (n=259)[a]		
Share N[b]	.74***	[.60, .89] [e]	10.39	.168
Share Jobs	.77***	[.62, .92] [e]	9.93	.162
Share Retail	.70***	[.56, .83] [e]	10.08	.157
Entropy	.31***	[.17, .44]	4.49	.054
JWB Index[c]	.16**	[.07, .26]	3.41	.032
Exposure	.27**	[.08, .45]	2.78	.022
		Places, Internal Trip Capture (n=259)[a]		
Share N[b]	.75***	[.61, .88] [e]	10.86	.181
Share Jobs	.77***	[.63, .92] [e]	10.53	.175
Share Retail	.71***	[.57, .84] [e]	10.36	.173
Entropy	.39***	[.27, .51]	6.41	.094
JWB Index[c]	.20***	[.11, .29]	4.52	.050
Exposure	.28**	[.11, .46]	3.22	.027
		Centered Communities, Internal Tour Capture (n=49)[d]		
Share Jobs	.25*	[.04, .46][e]	2.43	.082
Share N[b]	.22*	[.02, .42][e]	2.19	.069
JWB Index[c]	.19	[-.01, .38]	1.93	.052
		Centered Communities, Internal Trip Capture (n=49)[d]		
JWB Index[c]	.25**	[.08, .42][e]	2.92	.087
Jobs-Worker Balance	-.024*	[-.047, -.001][e]	-2.1	.029

Note: CI = Confidence Interval.
N.B: Similar results were obtained when area income ratio was added as an additional control variable.
a - Control variables include Acres, Jobs, Resident Workers, Job Density, and Resident Worker Density
b - Accessibility share for non-work index
c - Jobs-Workers Balance Index
d - Control variables include Acres, Jobs, Resident Workers, and Job Density.
e - Robust standard errors used because heteroskedacity was detected.
*p<.05 **p<.01 ***p<.001.

In the next set of regressions, I set out to examine whether mixed use and accessibility share variables are redundant in explaining complete communities, or whether they both contribute to predicting ***C***. The results were consistent and straightforward and so I report them only in text. In every case where an accessibility share variable is statistically significant and mixed use variables are added to the regression, the accessibility share variable remained statistically significant. Likewise, in every case where Jobs-Workers Balance Index and Entropy are statistically significant and accessibility variables are added, these mixed use variables remained statistically significant. Finally, in every case where Exposure is statistically significant and an accessibility share variable is added, the Exposure variable is no longer statistically significant. This last result suggests that measuring Exposure may be superfluous when accessibility share variables are included.

I built a final set of regression equations to guide policy development for the design of complete communities. The urban form variables reported here can be used to evaluate the completeness of existing communities and to consider how proposed plans might affect such communities' completeness (See Table 2-6). For these models, my objective is to explain as much of the variation in ***C*** as possible with urban form variables which correspond with current theories and earlier phases of the analysis. For this process, I require that all variables have signs in accordance with previous evidence and expectation. Furthermore, I expect that both mixed use variables and accessibility variables would both likely play a role. In order to select between the various highly correlated mixed use and accessibility variables, I made use of stepwise regression methods. In addition, the stepwise method determined whether size and density variables, such as job density, should be included in the policy model; many of these have little or no influence once appropriate accessibility and mixed use variables have been included. Finally, I pare away variables whose regression coefficients are heavily influenced by multicollinearity (i.e.VIFs>10). This procedure results in a set of relatively intuitive and consistent models which explain how urban form can influence internal tour/trip capture (See Table 2-6).

First note some consistencies across the results. Although different variables are statistically significant in the different equations, accessibility share (Share Jobs or Share *N*), mixed use (Entropy or Jobs-Workers Balance Index), and density (Job Density or Residential Density) positively influence ***C*** in all of the equations. The accessibility share variable is the most influential in three of four cases, and is the second most influential in the remaining case.

Now note some discrepancies and unusual results. Larger land size promotes higher ***C*** for Places but not necessarily for Centered Communities; note, however, that the average Centered Community size is about 3.7 times larger than the average Place size (see Table 2-2 and Table 2-3). In terms of the accessibility share variables, Share Jobs is the most predictive variable for the internal tour capture of Centered Communities but Share *N* is more predictive for the remaining three regressions; however these two accessibility share variables are highly correlated and serve as adequate substitutes for each other (ρ=.97 for Places; ρ=.95 for Centered Communities). For the mixed use variables, Jobs-Workers Balance Index is more predictive for Centered Communities but Entropy is more predictive for Places. Job density is a predictor of community completeness for Centered Communities, while residential density is for Places. Perhaps the most surprising result is that even after accessibility share is taken into account, higher levels of regional accessibility appear to reduce ***C*** for Places (but not for Centered Communities). Finally, it is interesting to note that size variables such as the number of resident workers, appear to contribute to ***C*** for Centered Communities but not necessarily for Places.

2.5 Discussion and Conclusions

For a geographically diverse set of communities, increased accessibility share, higher levels of mixed use (and in particular better jobs-worker balance), and higher levels of development density all promote community completeness. It appears that the single most important variable predicting community completeness, when defined as the ability to complete a nonwork tour without leaving one's home community, is accessibility share.

What does it mean for a community to have a high accessibility *share*? It means that it is easier to access a variety of activities locally than it is to access those same activities elsewhere within the region. In other words, it is not sufficient to have access to one coffee shop or one grocery store; rather, the range and variety of destinations available locally should rival that available regionally, taking into account a community's regional location. Computing the local share of accessibility to all jobs ($A^G{}_G / A^R{}_G$) is one way to estimate how well a community performs in this measure.

Table 2-6: Influence of Urban Form on Internal Tour/Trip Capture

Variable	Estimated Coefficients	Standardized Coefficients	95% CI
Places, Internal Tour Capture (n=259)[a], R^2=.47			
Share N[b]	.57***	.083	[.38, .75]
Regional N[c] (100,000s)	-.09***	-.057	[-.14, -.04]
Entropy	.28***	.056	[.17, .38]
Residential Density (10s)	.27***	.039	[.10, .44]
Acres (100,000s)	.34*	.035	[.06, .62]
Constant	.06*		[.00, .12]
Places, Internal Trip Capture (n=259)[a], R^2=.56			
Share N[b]	.56***	.082	[.39, .72]
Entropy	.36***	.072	[.27, .45]
Regional N[c]	-.08**	-.048	[-.12, -.03]
Residential Density (10s)	.23**	.033	[.08, .38]
Acres (100,000s)	.27*	.028	[.01, .53]
Constant	.03		[-.02, .08]
Centered Communities, Internal Tour Capture (n=49)[a], R^2=.54			
Share Jobs	.37***	.067	[.20, .54]
JWB Index[d]	.33***	.059	[.16, .50]
Resident Workers (100,000s)	.09***	.050	[.06, .12]
Acres (100,000s)	-.17	-.026	[-.37, .03]
Job Density (10s)	.005*	.014	[.001, .008]
Constant	.04		[-.13, .21]
Centered Communities, Internal Trip Capture (n=49)[a], R^2=.55			
JWB Index[d]	.38***	.068	[.19, .57]
Share N	.32***	.055	[.16, .47]
Job Density (10s)	.011**	.034	[.004, .019]
Resident Workers (100,000s)	.06**	.031	[.01, .09]
Constant	.002		[-.19, .19]

Note: CI = Confidence Interval.
N.B.: Similar results were obtained when area income ratio was included as an additional control variable.
a - Robust standard errors used because heteroskedacity was detected.
b - Accessibility share for non-work index
c - Regional accessibility for non-work index
d - Jobs-Workers Balance Index
*p<.05 **p<.01 ***p<.001

Furthermore, the level of mixed use, either in terms of jobs-worker balance or in terms of the balance across many different activity types within a community (Entropy) also facilitates community completeness, even after controlling for accessibility share.

Indeed, for all four ***C*** variables, the Jobs-Workers Balance Index variable was statistically significant and positive in influence, *even though raw Job-Workers Ratios were not*. This suggests that it is not merely the richness of jobs or destinations that promotes complete communities; too many jobs appear to be as problematic for community completeness as too few jobs. It is the actual *balance* between the number of residents and the number of jobs that matters to some significant degree. The balance between various types of jobs, as measured by an Entropy Index, also appears to facilitate community completeness.The scale and type of geography also matter, as the results for Places and Complete Communities were somewhat different. When comparing Centered Communities to Places, it is clear that Centered Communities are more complete, with an average internal tour capture of 47.6% as compared to 33.3%. The main differences between Centered Communities and Places appear to be larger land area, higher levels of mixed use, and higher accessibility share; Places that have these same characteristics are also likely to be more complete. These results suggest that the proper scale for conceiving of a complete community is probably somewhere between the average size of a Place (5,800 acres) and the average size of a Centered Community (21,630 acres). In short, planners need to plan for complete communities at a substantially larger scale than the neighborhood, which are typically in the range of 150-500 acres.

So what do these findings suggest for planners attempting to make their communities more complete? Firstly, it suggests that regional planners should promote a network of robust activity centers distributed throughout the metropolitan region. Many metropolitan agencies already have this goal as part of their regional land use planning efforts, such as metropolitan Portland's Mixed Use Centers program or metropolitan

Atlanta's Livable Centers Initiative program (ARC, 2009; Buliung & Kanaroglou, 2006). Effective activity centers should strive for jobs-housing balance and should contain a variety of activities beyond retail, such as recreation, social activities, education, health care, and some types of basic employment. In addition, each activity center should be thought of as a hub for its surrounding residential hinterlands, so the transportation links between adjacent residential areas and activity centers should be emphasized. At the same time, too much regional accessibility undermines complete communities; therefore it may be more effective to try to reinforce the completeness of historical activity centers than to try to remake a large-scale, interstate-adjacent retail development into a complete community. In other words, the transportation infrastructure, including adequate support for nonmotorized modes, should focus on the community rather than the regional scale in order to reinforce the goal of more complete communities.

These findings may not apply precisely to other metropolitan areas because they are based upon data from a single metropolitan area and from a single household travel survey. In addition, this study focuses on an aggregate measure of travel behavior, internal tour/trip capture, and therefore results may differ when focusing on specific segments of the population. Additional research focusing on different contexts and on specific demographics would help provide a more thorough picture of the composition of complete communities for researchers and urban planning practitioners.

Now I turn to some of the more technical implications of the results, such as how to measure mixed use. The measurement of land use mix using the Entropy Index is both interesting and perplexing. It is interesting that a wide diversity of activities appears to promote community completeness. On the other hand, the particular formula I use for measuring Entropy appears to be largely arbitrary and without a thorough theoretical basis (Rodriguez, Evenson, Diez Roux, & Brines, 2009), though it is similar to that employed in similar studies (Ewing et al., 2011; Greenwald, 2006). Why should an exact equal distribution of various employment categories be the one that represents the ideal balance of uses? An empirical investigation of alternative forms of the Entropy Index is warranted.

Additional research to refine these results and measures and to generalize them to a variety of contexts or populations would be helpful. This paper is the first that I am aware of which focuses on how urban form influences internal tour and internal trip capture at the community scale. In general the community scale has been neglected as a scale for the analysis of urban form variables. Additional research at this scale is needed to help guide urban planners in their efforts at community design.

Chapter 3 Does Accessibility Influence Nonwork Activity Participation? An Analysis with National Data

3.1 Abstract

Most of the research on accessibility has focused on reducing the impacts of travel, but one of the primary benefits of accessibility is the ability to engage in a greater range of activities. This study examines a national travel data set to see if high-accessibility built environments facilitate household participation in out-of-the-home, nonwork activities. Although several studies have examined the relationship between the built environment and nonwork trip generation in the past, none have looked at such a wide range of built environments as a national data set can provide. Built environment variables are associated with higher than expected impacts on household participation in nonwork activities, increasing or decreasing activity levels in the range of 8-47%, depending largely upon the level of household vehicle ownership. For households without vehicles, high residential and employment densities appear to support greater nonwork activity. Households with full access to vehicles appear to be supported by higher than average residential and employment densities and small urban and metropolitan area sizes. In a contrary finding, activity participation in households with limited vehicle access is for the most part not affected by the built environment in a statistically significant way. In sum, these results suggest that the built environment may play a larger role in facilitating activity participation than previously presumed.

Keywords: activity participation, trip generation, built environment, nonwork travel, accessibility

3.2 Introduction

The primary purpose of the cities, and of the transportation systems that help them function, is to facilitate social and economic interactions. Indeed, most of the theories about why cities form include explanations of how proximity facilitates a variety of social and economic exchanges (Glaeser, 2011; Jacobs, 1969). Therefore, when examining urban transportation systems, one important measure of their success is their ability to facilitate desired interactions. However the concern of how the built environment can support households' preferred activity participation patterns remains a relatively understudied problem.

By far, most of the research on the relationship between the built environment and travel behavior has centered on the role of reducing vehicle miles traveled (Ewing & Cervero, 2001, 2010). In an era when transportation is one of the major contributors to anthropogenic climate change and fossil fuel dependence, this emphasis makes a great deal of sense. However reducing VMT should not and cannot be the sole goal of transportation systems; ideally, sustainable transportation systems should facilitate greater travel opportunity while at the same time minimizing environmental and social impacts (Zegras, 2011). The need for a dual focus is particularly relevant to the developing world, where the challenge of increasing opportunity through the transportation systems may be a higher political and development priority than the need to reduce vehicular travel. Despite the central importance of transportation systems in increasing travel opportunity, research on how the built environment can help to facilitate desired travel activity has not generated a great deal of attention.

In particular, since influential studies by Hanson and Ewing, most of the research on built environment-transportation relationships has examined the effect of the built environment on mode choice or travel distances and has not addressed the question of the number of trips (Ewing, Deanna, & Li, 1996; Hanson & Schwab, 1987). However, a different influential research piece by Handy suggests that higher accessibility environments may increase levels of nonwork trip-making (Handy, 1996). Nevertheless, the question of how the built environment influences the frequency of trips or activity participation has received relatively scant attention in recent years.

On the other hand, the concept of travel opportunities has been addressed through the growing body of research on accessibility and accessibility measures (Geurs, Krizek, & Reggiani, 2012; Levinson & Krizek, 2005). Accessibility measures attempt to capture both how the built environment can serve to decrease travel costs and increase destination opportunities; therefore several researchers have argued that accessibility measures are superior evaluative measures of transportation systems (Bertolini, 2005; Grengs, Levine, & Shen, 2010). However, accessibility measures are truly measures of *opportunity* or potential; they are not measures of realized travel behavior. Therefore there remains an unaddressed need for connecting accessibility measures with outcome measures, illustrating how greater travel opportunity is linked to associated travel behaviors.

If accessible built environments provide greater access to opportunity, one way this may be revealed is that households in such environments may engage in greater levels of activity. As the monetary and time costs of travel on a per-trip basis decrease, the total number of trips taken by a household in a fixed period of time should increase (Boarnet & Greenwald, 1999; Crane & Crepeau, 1998). In order to explore the question of how the built environment can facilitate desired interactions, this study examines how variations in the built environment across the US influence levels of household nonwork activity.

The paper proceeds as follows: The next section, the Literature Review, evaluates the research literature concerning the built environment's relationship with activity participation and/or trip generation. The third section on Methods and Measures lays out the national data source used, the measures of activity participation at the household level, the built environment variables, and other variables related to travel demand, as well as presenting the regression techniques employed. The fourth section, the Results, covers how various built environment features influence activity participation directionally and in aggregate, and also identifies built environments associated with high and low levels of activity participation. The fifth section, the Discussion, synthesizes the results, their policy implications, and their limitations; and then finally the Conclusion briefly summarizes the research procedures and the primary findings.

3.3 Literature Review

Most studies focused on the question of travel demand elasticity and the built environment have examined nonwork travel, under the assumption that households have a relatively inelastic demand for work travel on a day-to-day basis. If the built environment influences work travel, it is more likely through longer term decisions such as where to live and/or how many vehicles to own. Several of these studies have found at least some evidence that households residing in higher accessibility environments face reduced travel costs and engage in greater travel (Helling, 1996; Krizek, 2003; Limanond & Niemeier, 2004; Thill & Kim, 2005). However this general finding has often been quite limited to particular circumstances and contexts. For example, both Krizek (2003) and Limanond and Niemeier (2004) find that only the number of simple nonwork tours increases, with other types of tours remain unaffected by variation in the built environment. Moreover, there are as many studies which find that the built environment has little effect (Ewing et al., 1996; Hanson & Schwab, 1987; Kitamura, Akiyama, Yamamoto, & Golob, 2001; Kitamura, Mokhtarian, & Laidet, 1997).

Most of this research has made use of accessibility measures, but a significant portion has examined densities as well. The examination of gravity accessibility measures to employment-based opportunities has been most common (Ewing et al., 1996; Golob, 2000; Helling, 1996; Kitamura et al., 2001; Thill & Kim, 2005), but there have also been studies that examine cumulative opportunity accessibility measures (Golob, 2000; Hanson & Schwab, 1987; Thill & Kim, 2005), utility versions of accessibility measures (Kitamura et al., 2001; Limanond & Niemeier, 2004), and density measures (Boarnet & Greenwald, 1999; Kitamura et al., 1997; Lin & Yang, 2009), and in addition a few studies have distinguished between local and regional accessibility measures (Handy, 1996; Krizek, 2003). Accessibility measures are preferred over density measures for theoretical reasons in that they are more closely related to travel costs and travel time. Furthermore there is some evidence that time-based accessibility measures may be preferable to distance-based ones (Kitamura et al., 2001; Thill & Kim, 2005).

Although the theoretical reasoning behind expecting more nonwork travel with higher household accessibility or density is strong, the empirical results to date have been on the whole weak or mixed. Studies of the built environment and trip generation have usually found a statistically significant effect on nonwork, shopping, or discretionary trip levels (Golob, 2000; Handy, 1996; Hanson & Schwab, 1987; Krizek, 2003; Leake &

Huzayyin, 1980; Lin & Yang, 2009; Thill & Kim, 2005). However, a few studies have also found negligible effects, and some have even found negative effects on trip generation for built environment variables such as density (Ewing et al., 1996; Kitamura et al., 2001; Kitamura et al., 1997; Limanond & Niemeier, 2004). . Even if we examine solely automobile-based travel, the results are mixed, with some researchers finding a positive effect (Boarnet & Greenwald, 1999; Helling, 1996), and others finding negative or negligible effects (Ewing et al., 1996; Kitamura et al., 2001; Limanond & Niemeier, 2004). In general, the results have not been strong enough to indicate a need to use measures of the built environment in trip generation models (Ewing et al., 1996; Kitamura et al., 1997; Leake & Huzayyin, 1980; Limanond & Niemeier, 2004). In many cases built environment variables were found to have been statistically significant, but the actual size or range of influence, its substantive impact, was either negligible or unmeasured (Krizek, 2003; Limanond & Niemeier, 2004; Thill & Kim, 2005).

Several conclusions can be drawn from previous studies, with varying levels of confidence. With a high level of certainty, prior evidence suggests that the socioeconomic and demographic characteristics of households explain more of the variation in nonwork travel activity than does accessibility or other aspects of the built environment. This is evident from the fact that trip generation models rely primarily on the former and very rarely include the later. Secondly, it appears that the built environment has a smaller effect on the number of trips taken than on the distance and mode of travel, especially in environments where multiple modes provide viable alternatives (Hanson & Schwab, 1987; Helling, 1996; Kitamura et al., 2001). Thirdly, time availability may be more important than built environment features in determining the level of participation in nonwork activities (Golob, 2000; Kitamura et al., 2001). This makes sense because without free time no nonwork activity can take place, regardless of the efficiency of the transportation system.

However, one question that emerges from these results is why is the evidence for the influence of the built environment on nonwork travel activity weak when the theoretical basis appears strong? One possible explanation is that the demand for nonwork travel may be relatively inelastic (Ewing et al., 1996; Kitamura et al., 2001). Travel for household maintenance functions is a fundamental need and households may adapt to ensure that these basic needs are met. Households can adapt to their urban environment in various ways – for example, through selecting a residential location that is suitable to their needs, through purchasing an additional vehicle, or through undergoing longer travel distances and times. Therefore the benefits of an accessible built environment, and likewise the costs of lack of accessibility, may not necessarily be reflected in the number of trips generated by a household; the influence of accessibility may instead be more apparent through other metrics, i.e. lower levels of vehicle ownership and/or shorter travel distances and times. However, a second possible explanation is that the range of built environment covered by many of these studies has not contained enough variation.

Kitamura puts forward such an explanation with his "Metropolitan Effect" hypothesis that travel behavior is relatively homogenous within particular metropolitan areas, and therefore intra-metropolitan variations in the built environment will elicit only small effects on travel behavior (Kitamura et al., 2001). Most households seek a wide range of metropolitan access, extending far beyond the neighborhood where they reside

(Handy, 1996; Krizek, 2003). Therefore it may be that households adapt to the type of transportation infrastructure provided by their metropolitan environment – purchasing additional motor vehicles in metro areas that are largely vehicle-oriented, or relying on multimodal access in metro areas that provide viable transportation alternatives. If levels of travel demand are relatively constant within a metropolitan area in accordance with this hypothesis, then it may be necessary to make inter-metropolitan comparisons to discern the effects of the built environment on household activity participation.

Accordingly, this study extends the existing research in several ways. Firstly, here I try to identify the *size* of the built environment's effect on activity participation, which is an important omission from previous studies. Secondly, one of the limitations of existing studies is that they typically examine a narrow range of built environments – nearly all are limited to a single metropolitan area and some examine just a few neighborhoods. If Kitamura's Metropolitan Effect hypothesis is correct, then the most important differences in accessibility may occur between metropolitan areas, or between metropolitan and nonmetropolitan areas. Therefore this study examines a wide range of built environments provided by a national data set, including urban and metropolitan areas of various sizes; on the other hand, the built environment measures available here are limited and do not include theoretically preferred accessibility measures. Finally, this study will be somewhat different than most previous studies in that the focus will be on levels of *activity participation* rather than numbers of trips (Bhat & Koppelman, 1999b; Chapin, 1971). While understanding the forces that influence travel behavior are essential for practical purposes, it is also valuable to hone in on the fundamental question of how the built environment can facilitate or hinder desired social and economic interactions.

In particular, the primary research questions are:

- Does the built environment have a substantive effect on households' levels of activity participation?
- What average directional effects do variations in specific built environment variables have on household activity participation?
- What types of built environments are most and least supportive of different households' activity participation?

3.4 Methods and Measures

The key variables incorporated in this paper include: 1) Three measures of activity participation; 2) three household types differentiated by vehicle ownership level; 3) A variety of built environment measures; and 4) other variables influencing household activity participation. In addition, here I outline two distinct regression techniques. The first is used to analyze the influence of individual built environment variables, while the second is used to predict the total influence of the built environment on activity participation.

Both travel and household variables are derived from the National Household Transportation Survey (NHTS) 2009. The NHTS is a representative survey of household travel behavior for the United States (U.S. Department of Transportation, 2011). It includes 24-hour period with coverage of travel modes, times of day, trip purposes, and a variety of individual and household socioeconomic data. The NHTS has a sample size of 150,147 households in 2009, corresponding with a weighted national household count of

113,101,330 households (U.S. Department of Transportation, 2009). Sampling weights are incorporated in all data descriptions and regressions. As a national survey, it includes a much wider range of built environments than most metropolitan area surveys; in particular, it includes households from metropolitan and urban areas of all sizes as well as nonmetropolitan areas. NHTS data on socioeconomics, household composition, and vehicle ownership provide a rich set of control variables for modeling activity participation. In addition, because the NHTS travel file contains the amount of time spent at each location, time constraint variables are readily developed.

Because the NHTS reflects travel for a single day, and because household location is central to the analysis, I exclude out of town persons from all household member counts and from all counts of activity participation. In addition, the correct calculation of relationship variables requires that all household members respond to the survey. Excluding households where all household members or where all household members are out of town did not respond reduces the sample size from 150,147 down to 118,710 households.

Three measures of household nonwork activity participation are developed: Individual activity episodes (IAEs), household activity episodes (HAEs), and individual tours (Bhat & Koppelman, 1999a). The individual measures of activity participation are summed to household totals for analysis. An individual activity episode is defined as an individual person arriving at any nonwork, nonschool location outside of the home. This definition of activities is consistent with the theory of derived demand, that the purpose of travel is typically participation in activities, not travel itself (Meyer & Miller, 2001). Household activity episodes, on the other hand, are defined at the household level, so that when multiple members of a household travel to the same destination together it is counted as a single household activity episode. In addition, individual tours are also examined in this study, as the number of tours provides an alternative measure of travel convenience (Krizek, 2003; Limanond & Niemeier, 2004). Tours are distinguished from trips as tours involve a full circuit of travel beginning and ending at the home, whereas nonwork activity episodes include travel from any origin to any nonwork, nonhome destination.

Two different schemes are generally used for the analysis of nonwork travel. In one scheme, all travel not associated with work is considered under the general heading of nonwork travel. The second scheme distinguishes between three kinds of travel: Work travel, maintenance travel, and discretionary travel which correspond with work, maintenance, and discretionary activities (Golob, 2000; Krizek, 2003; Rashidi & Mohammadian, 2011). Here I report my results for total nonwork activity, although I also examined maintenance and discretionary activity separately in my analysis.

Households rather than individuals are the unit of analysis. The assumption underlying this choice is that household structure imposes travel constraints and opportunities on individual household members. For example, one household member may make a shopping trip instead of another. Or one household member may defer participation in a discretionary activity until other household members are available to join. Household structure may also create non-linear interactions with other variables influencing travel demand. For example, a priori, it is not clear if large households or small households would see their activity participation increase more in a high accessibility location.

Because I expect that the built environment would have a different influence depending upon households' level of vehicle ownership, I examine households by dividing them into three separate groups: households without vehicles ("Zero Vehicle Households"), households with just one vehicle but two or more drivers ("Limited Vehicle Households"), and households with at least two vehicles or with exactly one vehicle and one driver ("Full Vehicle Households").

I categorize the independent variables under four conceptual groupings – variables related to household travel demand (D), variables related to household travel supply (S), household relationship variables (R), and built environment variables (B).

The household demand variables are:

- Number of children in the household (age<16)
- Number of adult nonworkers in the household (age>=16)
- Number of adult workers in the household (age>=16)
- Household income (Imputed for 9,952 households)[6]
- Median adult household age
- Percent of adults female

Household median age and percent female are calculated using only adults over 21 if there is an adult in the household 30 years or older; otherwise, these variables are calculated on all persons of age 16 or greater.

The household supply variables are:

- Number of drivers in the household
- Number of people who worked or went to school on the travel day
- Number of people who drove to work or school on the travel day
- Average time adults spent at work (in minutes)

The household relationship variables are:

[6]I imputed income using ordered logistic regression, regressing income against number of vehicles owned, number of workers in the household, home ownership, housing unit type, life cycle stage, and urban area size.

- Presence of a married couple
- Presence of related adults other than by marriage
- Presence of unrelated adults
- Age of youngest child (4 categories: no children present; 0-5 year old; 6-15 year old; 16+ year old)

The built environment variables are:

- Population density of the household's Block Group (8 categories)
- Population density of the household's Census Tract (8 categories)
- Residential density of the household's Block Group (8 categories)
- Residential density of the household's Census Tract (8 categories)
- Employment density of the household's Census Tract (8 categories)
- Urban area size, coded 0-4, with 4 being the largest (5 categories)
- Metropolitan area size, coded 0-5, with 5 being the largest (6 categories)

Note that household supply variables include time constraints. In particular, these variables include the number of household members who traveled to work or school on a travel day, and the average time spent at work and/or school across adult household members. Some previous research has suggested that time constraints may be important determinants of nonwork activity participation (Golob, 2000; Kitamura et al., 2001). Demographic, relationship, and time constraint factors all serve as controls for the regressions.

Although ideally I would prefer to use accessibility measures, traditional accessibility measures, i.e. cumulative opportunity, gravity, and utility measures, are not possible with NHTS data. The ability to use more appropriate accessibility-based measures is sacrificed for the opportunity to examine a wider range of built environments. In particular, for this study the built environment is measured through residential and employment densities in each household's Census Tract or Census Block Group, and through measures of each household's urban area and metropolitan area size.

One of the drawbacks of using local densities is that these do not reflect the specifics of the surrounding transportation system.

The expected influence of local residential and employment density on nonwork travel is ambiguous. Increased density increases the availability of nearby destinations, but also increases the amount of congestion, so any particular increase in density could lead to a increase or decrease in activity participation (Boarnet & Crane, 2001; Levine, Grengs, Shen, & Shen, 2012). I expect an inverse U-shaped influence of density, with densities increasing activity participation up to a point, and then decreasing it afterwards. However, as density increases, a shift of modes from the automobile to transit and nonmotorized modes may occur, and activity participation may again increase as these modes become more convenient at higher densities.

In general larger metropolitan regions provide a greater and more concentrated array of destinations, but this is counterbalanced by higher levels of competition and congestion. Therefore metropolitan and urban area sizes may also have an inverse U-shaped effect on levels of activity participation. At first, as urban or metropolitan area size increase, activity participation may increase in response to the greater availability of opportunities. However, for very large urban or metropolitan areas, household activity participation may decrease as congestion and competition effects become dominant. So none of the built environment variables under analysis is expected to have a simple monotonic relationship with levels of household nonwork activity participation.

All built environment variables are coded categorically, but with numeric values. For the most part, I treat built environment variables as categorical variables to allow for nonlinear effects. However, for the first set of regressions regarding directional effects, I make use of their numeric values.

In order to determine the direction of influence of built environment (B) variables, it was important to identify a subset of B variables without excessively high variance inflation factors. When all B variables are included, block and tract population density and block and tract residential density all have VIFs > 9.0, whereas the other built environment variables all have modest VIFs < 3.0. Therefore, I drop block population density, tract population density and block residential density and only make use of tract residential density in the regressions.

Table 3-1: Variance Inflation Factors for Built Environment Variables[a]

Built Environment Variables	Variance Inflation Factor
Block Population Density	9.0
Tract Population Density	9.6
Block Residential Density	10.8
Tract Residential Density	10.1
Tract Employment Density	1.9
Urban Area Size	2.6
Metropolitan Area Size	2.3

[a] – Other variables included in regressions are number of workers, number of adult nonworkers, number of children, imputed income, median adult age, median adult gender, number of workers who drove to work, number of workers who went to work, average minutes spent at work for adults, married household, related, household, unrelated members in household, and age of youngest child.

With appropriate variables identified to capture the concepts of demand, supply, relationships, and the built environment, the relationships between these variables are explored through a series of regressions. In particular, cross-sectional regression models are used in two distinctive ways in this analysis. In the first set of models, I examine the influence of individual built environment variables on activity participation outcomes. Then, in a second set of predictive models, I examine the total influence of all built environment variables in aggregate and the aggregate size of their influence on activity participation.

For the first approach, I examine the activity participation outcomes (T) based on the household demand (D), supply (S), relationship (R), and built environment (B) variables. I conducted an extensive investigation of the appropriate functional form to use in predicting activity participation outcomes, which is discussed below. One equation is run for each of the three household types (Zero Vehicle Households, Limited Vehicle Households, Full Vehicle Households), for each of the three activity participation variables, and for each of the built environment variables (4) for a total of thirty-six (36) regressions. This first set of equations make use of reported interval values for built environment data, even though the data is recorded as categories. Each regression is fit with a hierarchical, negative binomial model. I use a negative binomial model to fit the activity participation outcomes because they are all count data (See APPENDIX II – Negative Binomial vs. Quasi-Poisson Model) and I use hierarchical models with errors clustered at the core-based statistical area to account for travel behavior being correlated within each metro area:

1. $T = \alpha_0 + \alpha_1 D + \alpha_2 S + \alpha_3 R + \alpha_4 B$

While this is valuable information, it is limited in that it collapses the range of marginal effects of built environment features into a single average effect. This is problematic because I expect nonlinear built environment influences, and even a possible change in the direction of influence across the spectrum of built environments.

Therefore, in the second set of regressions, I try to gather more insight into the size and nature of the influence of the built environment by building *predictive* regression models. The purpose of these models is to predict a particular household's level of activity participation if it were placed in a different (counterfactual) built environment. By building a predictive model, I can examine the total effect of the built environment variables in all of their possible combinations. That is, I can examine the distribution of expected levels of activity participation while allowing the hypothetical built environment to vary over a range of residential densities, employment densities, urban area sizes, and metro area sizes simultaneously. In addition, using these same predictive models, I am able to identify those built environments which are associated with different parts of this distribution; those built environments that are associated with higher levels of expected activity participation I assume are travel-supportive environments, while those built environments that are associated with lower expected levels of activity participation I assume are travel-inhibitive environments.

Predictive models have their advantages as well as their hazards. Regarding their advantages, a predictive model does not necessarily become less effective with the inclusion of additional terms, even if these terms are not statistically significant. The purpose of the model is not to interpret coefficients, but to employ the model in its entirety in order to predict behavior in counterfactual situations. On the other hand, predictive models can be notoriously inaccurate, particularly when they are used for extrapolation. Also, the implications of a predictive model can vary widely based upon the functional form that is used to describe how the independent variables influence the dependent variable. In order to assure the best possible results, I test a variety of functional forms using cross-validation, and I only use predictive models to make interpolations, not for extrapolations. That is, when examining predicted levels of travel, I examine only the range of built environments which actually occur for each household type within the NHTS sample.

For these predictive regressions, I tested four functional forms for each of the nine regression scenarios (i.e. three household types by three activity participation outcomes) and examined the K-fold cross-validation error for each. Cross-validation builds predictive models on a subset of the entire data set and then measures the predictive error on the set of excluded data; therefore I deemed cross-validation as the best method for identifying models with the least prediction error. This is performed at least 100 times for each functional form. The four functional forms tested were as follows:

Linear Model

1. $T = \alpha_0 + \alpha_1 D + \alpha_2 S + \alpha_3 R + \alpha_4 B$

Demand Interactions Model

2. $T = \alpha_0 + \alpha_1 D + \alpha_2 S + \alpha_3 R + \alpha_4 B + \alpha_5 D * S + \alpha_6 D * R + \alpha_7 D * B$

Group Interactions Model

3. $T = \alpha_0 + \alpha_1 D + \alpha_2 S + \alpha_3 R + \alpha_4 B + \alpha_5 D * S + \alpha_6 D * R + \alpha_7 D * B + \alpha_8 S * R + \alpha_9 R * B$

Second-Order Terms Model

4. $T = \textit{all second order terms, except between pairs of built environment variables}$

Of the four functional forms tested, surprisingly, the simple linear model was found to have the best predictive power through the use of K-fold cross-validation techniques (See Table 3-2). This is particularly unexpected since BICs were lower for models with more terms; however I deemed the results from cross-validation as most reliable for selecting the functional form that is most accurate in prediction.

Table 3-2: Cross Validation Error for Functional Forms

	Linear Model	Demand Interactions	Group Interactions	Second Order Terms
		Zero Car Households		
Nonwork IAEs	3.5	108.0	Failed[a]	Failed[a]
Nonwork HAEs	2.8	61.3	Failed[a]	Failed[a]
Nonwork Tours	1.0	8.6	Failed[a]	Failed[a]
		Limited Car Households		
Nonwork IAEs	12.6	50.3	62.3	28.4
Nonwork HAEs	5.1	7.0	10.9	17.2
Nonwork Tours	3.0	4.1	335.0	31.0
		Full Car Households		
Nonwork IAEs	9.7	10.6	16.1	12.1
Nonwork HAEs	5.6	6.0	6.5	6.6
Nonwork Tours	2.7	3.0	3.4	3.1

Adjusted cross validation prediction error from ***cv.glm*** function in R. All models Negative Binomial. K-Fold cross validation errors with K=125 for Zero Car Households, K=103 for Limited Car Households, and K=100 for Full Car Households.
a – Models failed to converge to a solution

All of the regressions are of count variables (activity episodes, tours), and dispersions are significantly larger than 1, so the appropriate maximum likelihood method could be either Quasi-Poisson or Negative Binomial. In order to test which type of model is more appropriate for this data, I create binned plots of variance vs. predicted mean and compare these plots with the estimates of dispersion from these two model types. Based on this information, Negative Binomial models are selected as being more appropriate (See *APPENDIX II – Negative Binomial vs. Quasi-Poisson Model*).

3.5 Results

3.5.a Descriptive Statistics

Tables 3-3 to 3-6 display various descriptive statistics about the NHTS population and in particular the differences between the three household types. Table 3-3 shows the sample-weighted average values for all of the variables by household type. Table 3-4 shows distributions of built environment characteristics by household type, Table 3-5 illustrates distributions of selected demographic characteristics by household type, and Table 3-6 displays distributions of the activity participation variables across the three household types.

Households without vehicles are quite distinct from the other two household types. Their average household size is smaller at 1.39 people per household, versus 2.52 for Limited Vehicle Households and 2.12 for Full Vehicle Households. Low income households are more concentrated among households without vehicles, however there are some high income households as well which do not own vehicles. Most households without vehicles do not have a worker present in the households, however about 30% do. On the other hand, about 70% of households with vehicles have at least one worker present.

As expected, households with fewer vehicles live in environments with higher residential and employment densities and within larger urban and metropolitan areas. Households without vehicles are seen across the range of residential densities and are concentrated in areas with high employment density, whereas there are few Full Vehicle households in the top two residential or employment density categories (Table 3-4). Surprisingly, although zero vehicle households are concentrated in the largest urban and metro area sizes, 16.2% of such households reside outside an urban area. Although Full

Vehicle households are also concentrated in the largest urban and metro areas, more than 1/3 do not live in any urban area and more than 1/5 do not live in any metro area. This illustrates the increased need for auto-based mobility outside of concentrated urban areas.

Table 3-3: Mean Values for three Household Types

	Zero	Limited	Full
Raw Count	6,257	6,248	107,800
Weighted Count	7,916,177	4,757,896	74,271,080
Activity Participation Variables			
Nonwork Individual Activity Episodes	1.89	4.26	3.51
Nonwork Household Activity Episodes	1.76	3.09	2.85
Nonwork Individual Tours	1.00	2.32	1.75
Built Environment Variables			
Tract Residential Density	7,374	3,431	1,761
Tract Employment Density	2,576	1,674	1,168
Urban Area Size (0-4)	2.80	2.36	1.99
Metropolitan Area Size (0-5)	3.63	3.24	2.99
Travel Demand Variables			
Number of children under 16	0.12	0.34	0.28
Number of drivers	0.55	2.10	1.56
Percent of adults, female	68.3%	53.0%	57.4%
Number of adults not employed	0.88	1.20	0.66
Number of employed adults	0.41	1.02	1.09
Imputed Income (1-18)	4.8	8.7	10.3
Median age of adults	61.7	56.3	56.7
Relationship and Time Constraint Variables			
Percent married	9.5%	76.9%	49.4%
Percent with related adults	10.0%	15.8%	7.6%
Percent with unrelated adults	1.8%	4.7%	1.9%
Number of people who drove to work	0.00	0.46	0.62
Number of people who worked on travel day	0.25	0.71	0.67
Average minutes worked or in school for adults	72.5	130.8	159.7

Source: National Household Transportation Survey, 2009.
Urban Area Size 0 = Not in an UA; 1 = UA = 50,000-99,999; 2 = UA 200,000-499,999; 3 = UA 500,000 – 999,999; 4 = 1,000,000 +
Metropolitan Area Size 0 = Not in an MSA; 1 = MSA < 250,000; 2 = MSA 250,000-499,999; 3 = MSA 500,000 – 999,999; 4 = MSA 1,000,000-2,999,999; 5 = MSA 3 million +

Table 3-4: Distributions of Built Environment for three Household Types

	Zero	Limited	Full
Residential Density			
50	8.3%	16.8%	22.9%
300	10.9%	15.6%	19.4%
750	8.1%	13.6%	14.3%
1500	15.9%	21.1%	19.7%
3000	20.9%	16.3%	16.0%
7000	13.9%	8.5%	5.7%
17000	11.0%	4.6%	1.5%
30000	11.1%	3.5%	0.6%
Employment Density			
25	6.7%	16.0%	22.9%
75	2.7%	4.8%	19.4%
150	3.7%	7.6%	14.3%
350	7.7%	8.2%	19.7%
750	12.1%	16.3%	16.0%
1500	16.7%	16.3%	5.7%
3000	17.3%	14.7%	1.5%
5000	33.1%	16.0%	0.6%
Urban Area Population			
Not in an Urban Area	16.2%	27.6%	35.5%
50,000-99,999	10.0%	9.5%	10.2%
200,000-499,999	7.7%	8.0%	9.0%
500,000 – 999,999	9.8%	8.6%	8.3%
1,000,000 +	56.3%	46.4%	37.0%
Metro Area Population			
Not in a Metro Area	12.7%	17.2%	21.1%
< 250,000	5.6%	6.7%	7.3%
250,000-499,999	5.6%	8.4%	8.7%
500,000 – 999,999	7.8%	7.9%	8.0%
1 million – 2.99 million	19.2%	21.0%	22.3%
3 million +	49.1%	38.8%	32.4%
Presence of Rail in Metro Area?	44.5%	30.7%	25.8%

Source: National Household Transportation Survey, 2009.

Table 3-5: Distributions of Demographic Characteristics for three Household Types

	Zero	Limited	Full
Workers			
0	66.5%	33.1%	28.5%
1	28.9%	35.5%	41.3%
2	4.1%	28.6%	25.4%
3 or more	0.5%	2.7%	4.7%
Other Adults			
0	23.6%	24.6%	47.9%
1	65.1%	34.8%	38.5%
2	10.0%	36.1%	12.5%
3 or more	1.3%	4.4%	1.1%
Children			
0	93.0%	78.9%	84.0%
1	4.5%	12.7%	7.9%
2	1.4%	6.2%	6.3%
3 or more	1.1%	2.2%	1.8%
Household Income Category			
< $10,000	32.4%	5.9%	6.9%
$10,000 - $19,999	34.6%	16.3%	13.2%
$20,000 - $29,999	12.9%	21.4%	13.1%
$30,000 - $39,999	6.8%	14.0%	11.1%
$40,000 - $49,999	4.6%	12.7%	10.3%
$50,000 - $59,999	1.6%	7.3%	8.5%
$60,000 - $69,999	1.4%	4.9%	6.7%
$70,000 - $79,999	1.0%	4.7%	6.5%
$80,000 +	4.6%	12.8%	23.6%

Source: National Household Transportation Survey, 2009.

Table 3-6: Distributions of Travel Activity for three Household Types

	Individual Activity Episodes			Household Activity Episodes			Individual Tours		
Count	Zero	Limited	Full	Zero	Limited	Full	Zero	Limited	Full
0	36.1%	12.8%	17.6%	36.1%	12.8%	17.6%	45.3%	18.4%	29.1%
1	20.9%	10.4%	15.9%	22.2%	15.6%	18.4%	31.1%	18.7%	27.5%
2	17.3%	16.4%	16.0%	17.0%	19.8%	17.6%	14.1%	25.5%	19.2%
3	9.4%	11.3%	12.2%	10.3%	14.7%	14.5%	5.5%	14.8%	9.7%
4	5.8%	12.1%	10.3%	4.8%	13.3%	10.8%	2.3%	10.1%	6.4%
5	3.7%	7.8%	7.5%	4.0%	9.0%	7.9%	0.8%	4.7%	3.4%
6	2.1%	8.6%	5.8%	2.8%	6.3%	5.0%	0.4%	4.0%	2.2%
7	2.0%	4.3%	3.5%	1.0%	3.3%	2.9%	0.3%	1.0%	0.9%
8	1.5%	4.3%	2.8%	0.9%	2.4%	1.9%	0.0%	1.9%	0.7%
9	0.2%	3.5%	2.1%	0.3%	1.2%	1.4%	0.1%	0.4%	0.3%
10	0.1%	2.6%	1.9%	0.3%	0.4%	0.8%	0.0%	0.1%	0.2%
11 or more	0.9%	6.0%	4.3%	0.3%	1.3%	1.2%	0.0%	0.3%	0.4%

Source: National Household Transportation Survey, 2009.

3.5.b Directional Influence of Built Environment Variables

The first regressions describe the average influence of individual built environment variables on household nonwork activity participation (Summarized in Table 3-7). Activity participation is correlated with higher residential and employment densities for both Zero Vehicle Household and Full Vehicle Households, but not Limited Vehicle Households. Urban area size is correlated with higher activity participation for Zero Vehicle Households and for more nonwork tours for Full Vehicle Households. Also, larger metro area size is positively related to more nonwork tours for Full Vehicle Households. Almost none of the built environment variables appear to influence the activity participation of Limited Vehicle Households.

However the meaning of these initial regressions is limited, as they are only intended to determine average directional effects. Since non-linear effects are anticipated, it is possible that these built environment features have a positive influence over part of their range and a negative influence over another part, resulting in no statistically significant effect. Non-linear effects are displayed in *Figure 3-1: Effect of Categorical Built Environment Variables on IAEs* and in greater detail in Appendix I (*APPENDIX I – Coefficients for Categorical Built Environment Variables*) by examining each built environment variable as categorical. Figure 3-1 displays the multiplicative effect of each built environment category relative to the smallest or least dense category with separate figures by household type. Statistically significant effects at the 5% level are indicated by a geometrical symbol at each point. From these figures there is evidence of a non-linear, inverse-U shaped effects for urban area size and metro area size for all three household types. For residential and employment density, both zero vehicle households and full vehicle households appear to have increased activity across the range of densities. It is unclear if the marginal effect of a density increase is increasing or decreasing rate across the range of densities, i.e. if the trend is curving up or downwards across the range of densities.

Table 3-7: Average Directional Influence of Built Environment Variables on Household Activity Participation

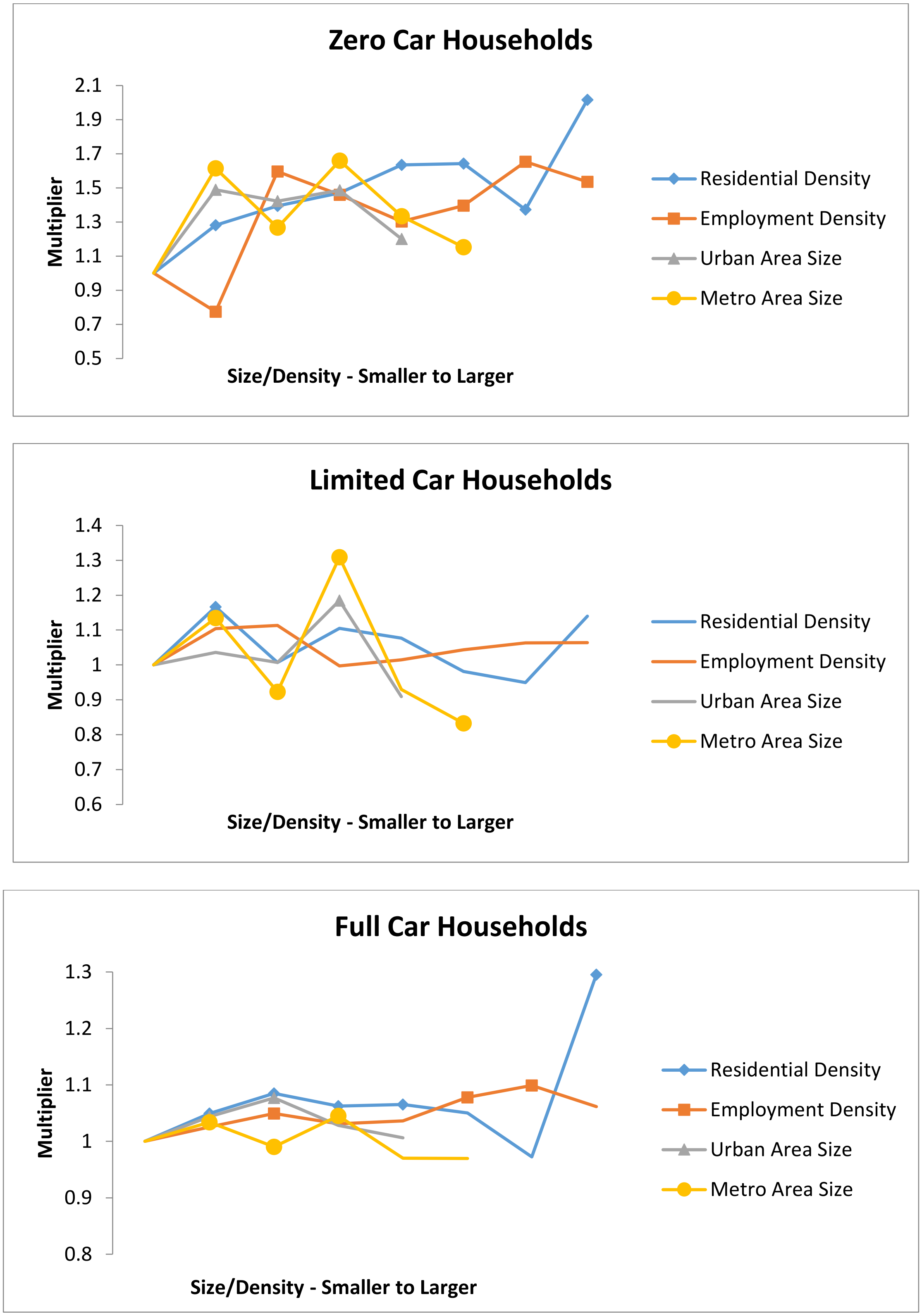
Zero Car Households	Residential Density	Employment Density	Urban Area Size	Metro Area Size
Nonwork IAEs	++	+++	+	ns
Nonwork HAEs	+++	+++	+	ns
Nonwork Tours	+	+++	++	ns

Limited Car Households	Residential Density	Employment Density	Urban Area Size	Metro Area Size
Nonwork IAEs	ns	ns	ns	ns
Nonwork HAEs	+	ns	ns	ns
Nonwork Tours	ns	ns	ns	ns

Full Car Households	Residential Density	Employment Density	Urban Area Size	Metro Area Size
Nonwork IAEs	+++	+++	ns	ns
Nonwork HAEs	+++	+++	ns	ns
Nonwork Tours	ns	+++	+++	+++

+++ positive and statistically significant at the 1% level. ++ positive and statistically significant at the 5% level. + positive and statistically significant at the 10% level. ns – not significant.
Negative Binomial models with sampling weights and errors clustered at the core based statistical area used to predict activity participation outcomes.
Control variables include presence of heavy rail in the metro, day of the week, household income, reported household income (Y/N), number of adult workers in household, number of nonworking adults in household, number of children in household, percent of adults female, number of drivers in household, median age of adults, number of people who worked on travel day, number of people who drove to work on travel day, average time spent at work or school for adults, presence of married adults, presence of related adults, presence of unrelated adults, and age of youngest child.

Figure 3-1: Effect of Categorical Built Environment Variables on IAEs



Effect of various built environment variables relative to base category. Statistically significant categories are indicated by a point marker. Coefficients with statistical significance are reported in.

3.5.c Aggregate Effect of Built Environment Variables

However, examining the directional influence of particular variables is only one way to understand the influence of the built environment on activity participation. Another approach is to examine the total effect of all built environment variables in aggregate, through the use of predictive regression models. For each type of activity participation, Table 3-8 presents how levels of activity participation vary across the range of built environments, from the built environments associated with low levels of activity participation (i.e. the 5^{th} percentile) to those associated with high levels of activity participation (i.e. the 95^{th} percentile). To capture the size of the influence of the built environment, I use three summary statistics, listed under the columns "Ratio of SDs" and "50^{th}-95^{th} Percent Increase" and "50^{th}-5^{th} Percent Decrease."

The"50^{th}-95^{th} Percent Increase" and "50^{th}-5^{th} Percent Decrease" columns show how much each type of household's activity participation would vary when moving from the 50^{th} percentile built environment to one of the extremes – either the 95^{th} percentile or 5^{th} percentile.

The "Ratio of SDs" column shows how much of the variance in each type of household's activity participation is due to variation in the built environment. This is done by taking the ratio of the standard deviation of the predicted levels of activity participation with only the built environment varying, and dividing by the standard deviation of predicted levels of activity participation with all variables varying (including all demographic and relationship variables). Conceptually, assume that the expected level of activity participation T is a function of the built environment B and other variables V, and let V_0 be a set of constant values representing a typical household:

$$\frac{sd\left(E\left(T(B, G = V_0)\right)\right)}{sd\left(E\left(T(B, V)\right)\right)} = percent\ of\ variation\ due\ to\ B$$

Table 3-8 suggests that variation in the built environment can induce a sizable change in activity participation – generally in the range of 10-50%. This is an interesting result, in that previous research has suggested a much smaller or even insignificant influence of the built environment on levels of activity participation.

Zero Vehicle Households are the most sensitive to the built environment, followed by Limited Vehicle Households, and then Full Vehicle Households. A Zero Vehicle Household moving from a median built environment to a more extreme built environment would see a 30-67% change in activity participation, whereas a Limited Vehicle Household would see a 13-42% change in activity participation and a Full Vehicle Household would see an 8-18% change in activity participation. The results from the ratio of standard deviations are similar, except they are somewhat higher for Limited Vehicle Households. Perhaps the constrained nature of travel for these households means that demographic factors play a more limited role in the range of travel activity they display, and so the built environment hold a proportionately larger influence. On the other hand, the influence of built environment variables on these households' activity participation is often not even statistically significant (See Table 3-7)

In order to gather further insight, these same predictive models are used to identify what types of built environments appear to be most supportive of nonwork activity for each type of household; these results are summarized in Table 3-9. This table compares the built environments which correspond with the top 5% and bottom 5% of activity participation levels with the mean built environment for each household type.

For Zero Vehicle Households, the most supportive built environments in terms of density are quite like the mean built environment for these households – with moderately high levels of residential and employment density. Low density environments are the least favorable for these households. The metro and urban area sizes do not appear to play a major role if all other factors, including the presence of heavy rail, are held constant.

For Limited Vehicle Households, more nonwork activity participation occurs with lower than average residential densities and slightly higher than average employment densities. The least favorable densities and urban area sizes appear to be either very high or very low, perhaps illustrating some unexpected behavioral heterogeneity within this household type. Large metro area sizes appear unfavorable for activity episodes for these households.

For Full Vehicle Households, higher than average residential and employment densities increase nonwork activity participation and lower densities are related to less activity participation. Smaller metro and urban area sizes increase nonwork activity episodes, but nonwork tours appear to increase with larger metro and urban area sizes.

It is interesting that the built environments associated with higher numbers of activity episodes are not necessarily the same as those associated with higher numbers of tours. Indeed, for the most part, the built environments that support individual and household activity episodes are similar, but those that support increased tour-making are not necessarily the same. In fact, fewer, more complex tours may be a sign of households adapting or compensating for a less supportive built environment (Krizek, 2003).

The next section steps back from the detailed results and attempts to discern more general patterns regarding what types of built environments support activity participation for differing household types.

Table 3-8: Variation in Nonwork Activity Participation Associated with Built Environment

Zero Car Households

	Ratio of SDs	5%	25%	50%	75%	95%	50th-95th Increase	50th-5th Decrease
Nonwork IAEs	30.1%	1.07	1.29	1.52	1.81	2.22	47%	30%
Nonwork HAEs	35.9%	1.02	1.20	1.48	1.73	2.17	47%	31%
Nonwork Tours	36.2%	0.44	0.60	0.70	0.87	1.17	67%	38%

Limited Car Households

		5%	25%	50%	75%	95%	50th-95th Increase	50th-5th Decrease
Nonwork IAEs	53.2%	3.43	3.83	4.23	4.73	6.00	42%	19%
Nonwork HAEs	52.4%	2.58	2.97	3.12	3.42	4.11	32%	17%
Nonwork Tours	39.9%	1.77	1.88	2.03	2.22	2.66	31%	13%

Full Car Households

		5%	25%	50%	75%	95%	50th-95th Increase	50th-5th Decrease
Nonwork IAEs	8.0%	2.69	2.88	2.92	3.06	3.25	12%	8%
Nonwork HAEs	11.6%	2.39	2.55	2.60	2.72	2.89	11%	8%
Nonwork Tours	11.4%	1.19	1.31	1.45	1.51	1.58	9%	18%

Negative Binomial models with sampling weights and errors clustered at the core based statistical area used to predict activity participation outcomes. Control variables include presence of heavy rail in the metro, day of the week, household income, reported household income, number of workers in household, number of nonworking adults in household, number of children in household, percent of adults female, number of drivers in household, median age of adults, number of people who worked on travel day, number of people who drove to work on travel day, average time spent at work or school for adults, presence of married adults, presence of related adults, presence of unrelated adults, and age of youngest child. For predictions, all non-built environment control variables held at mean or median values for each household type. Built environments are only permitted to range over those observed for each type of household.

Table 3-9: Built Environments Associated with Highest (95th Percentile) and Lowest (5th Percentile) levels of Nonwork Activity Participation

	Residential Density	Employment Density	Urban Area Size	Metro Area Size
Min	50	25	0	0
Max	30,000	5,000	4	5
Zero Car Households				
Mean	7,128	2,548	2.80	3.62
95th Nonwork IAEs	6,985	2,606	2.30	3.07
95th Nonwork HAEs	7,445	2,619	2.22	3.03
95th Nonwork Tours	3,038	1,987	1.98	2.24
5th Nonwork IAEs	1,547	706	1.92	3.07
5th Nonwork HAEs	518	445	2.29	3.40
5th Nonwork Tours	254	296	1.61	3.14
Limited Car Households				
Mean	3,388	1,655	2.37	3.25
95th Nonwork IAEs	1,614	1,933	2.28	3.00
95th Nonwork HAEs	1,740	1,998	2.22	2.87
95th Nonwork Tours	1,605	2,134	2.78	3.30
5th Nonwork IAEs	11,916	2,981	3.37	4.99
5th Nonwork HAEs	233	258	0.68	3.73
5th Nonwork Tours	2,028	1,009	1.18	3.23
Full Car Households				
Mean	1,793	1,180	2.01	3.01
95th Nonwork IAEs	5,417	2,680	1.78	2.14
95th Nonwork HAEs	5,132	2,682	1.76	2.16
95th Nonwork Tours	2,452	2,141	2.60	3.02
5th Nonwork IAEs	4,134	1,148	1.24	4.54
5th Nonwork HAEs	146	43	0.20	3.71
5th Nonwork Tours	50	25	0.21	2.40

Negative Binomial models with sampling weights and errors clustered at the core based statistical area used to predict activity participation outcomes. Control variables include presence of heavy rail in the metro, day of the week, reported household income, household income, number of workers in household, number of nonworking adults in household, number of children in household, percent of adults female, number of drivers in household, median age of adults, number of people who worked on travel day, number of people who drove to work on travel day, average time spent at work or school for adults, presence of married adults, presence of related adults, presence of unrelated adults, and age of youngest child. For predictions, all non-built environment control variables held at mean or median values for each household type. Built environments are only permitted to range over those observed for each type of household.

3.6 Discussion

Overall, these results suggest that the built environment has a sizeable effect on levels of household nonwork activity, with the greatest influence on households with the fewest vehicles. For example, moving a Zero Vehicle Household from the median built environment to a 95th percentile built environment could increase nonwork activity in the range of 30-38% (Table 3-8). This suggests a greater influence of the built environment than previous trip generation studies suggest, e.g. (Ewing et al., 1996).

Looking for consistencies across the results by comparing Table 3-7 and Table 3-9, it appears that greater residential and employment densities support higher levels of nonwork activity among Zero Vehicle Households and Full Vehicle Households.

The effect of built environment variables on Limited Vehicle Households is usually statistically insignificant (See Table 3-7 and Figure 3-1). Limited Vehicle Households do appear to benefit from mid-size metro areas and see decreased activity participation with large metro area sizes (Figure 3-1). However, the muted results for Limited Vehicle Households is surprising because I expect that such household would be more sensitive to the built environment rather than less. Therefore I hypothesize that there is some behavioral heterogeneity among households of this type which may be masking the influence of the built environment.

Urban area size and metro area size appear to have nonlinear effects, increasing activity participation between rural areas and small urban and metro area sizes, and then decreasing activity participation between small urban and metro area sizes and large ones (Figure 3-1). Although there is variation across the household types, most households find the highest activity participation with urban area sizes of about 2.00, which corresponds with urban areas of 200,000-499,999 in size and with metro areas of 2.00-

3.00, which correspond with metro areas of about 250,000-1 million in size. These urban and metro area sizes may be the most favorable for offering a range of proximate opportunities while at the same time experiencing relative minor congestion effects.

It should be noted that some caveats are in order based on the analysis methods employed in this study; these regression models are based upon the assumption that vehicle ownership and the built environment influence activity participation, but by including both sets of variables in the models the causal relationships between these two variables are suppressed. In specific, by controlling for levels of vehicle ownership, the regression yields a controlled direct effect of the built environment on activity participation (Imai, Keele, & Yamamoto, 2010). That is, these regressions yield an estimate of the influence of the built environment under the assumption that changes to the built environment do not induce changes to vehicle ownership levels. The controlled direct effect may be different (higher or lower) from the true “direct effect” of the built environment on activity participation.

Nevertheless, vehicle ownership is currently a cultural priority, as well as sometimes an economic necessity, in the contemporary United States. Therefore this analysis, which presumes that vehicle ownership levels will not be changed much by the built environment, yields important results for how the built environment can influence nonwork activity participation.

3.7 Conclusion

In this study, I examine a national sample of households (National Household Transportation Survey 2009) representing a wide variety of residential built environments in order to understand the influence of the built environment on household nonwork activity participation. Differing regression techniques are used to determine the influence of individual built environment variables, to examine the possibility of non-linear effects, to determine the size of the built environment's total effect, and to identify built environments which are associated with high and low levels of nonwork activity participation. Nonwork activity participation is examined through three measures: individual activity episodes, household activity episodes, and individual tours, each of which is aggregated to the household level for analysis. The regression models control for a wide range of household characteristics, including most of the conventional drivers of travel demand, and in addition incorporates time constraints, a perhaps neglected factor in explaining nonwork activity participation. I employ predictive regression models to isolate the influence of the built environment on activity participation while holding socioeconomic, demographic, and other factors constant. Households with no vehicles, households with limited vehicle access, and households with full vehicle access are examined separately.

The results suggest that the built environment has a sizeable effect on households' levels of nonwork activity participation, with a greater influence on households with fewer vehicles. This in turn supports the hypothesis that appropriate built environments can foster greater household activity participation. The results also provide a general sketch about what types of built environments may be supportive of the activity participation patterns for different household types.

For households without vehicles, high residential and employment densities at the Census Tract level appear to support greater levels of nonwork activity participation. Full Vehicle Households appear to be supported by higher-than-average residential and employment densities and mid-sized urban area (200,000-500,000) and metropolitan area sizes (250,000-1 million in population). Limited Vehicle Households appear to be relatively unaffected by the built environment, though they do appear to have more activity in mid-sized metropolitan areas (500,000-1 million in population). The limited influence of the built environment on Limited Vehicle Households is contrary to expectation and the reasons behind this finding are unclear.

While the overall importance of the built environment in influencing household nonwork activity participation has been validated, other measures of the built environment must be examined in order to better capture the nature of travel opportunities available to households. Therefore a potential follow up to this research is to work with measures of accessibility, which account more finely for households' geographic patterns of travel cost and opportunity. In addition, it may be beneficial to try to measure levels of congestion in a household's area or include some other measure of perceived travel difficulty. This paper's results suggest that congestion effects may overwhelm proximity and choice effects in some cases – i.e. perhaps people in large metro areas may prefer to stay home rather than battle the crowds, even if the places where they live offer a great range of opportunities. Therefore, the next phase of this research should examine more appropriate measures of travel opportunity, while still incorporating a wide range of residential built environments.

Chapter 4 Changing Accessibility in US Metropolitan Areas: The Influence of Changing Urban Form and Travel Times

4.1 Abstract

Urban expansion has occurred in the US for decades, resulting in greater auto dependence, however it is unclear how this has influenced household access to activities. Examining four US metropolitan areas undergoing contrasting urban form trends, I use gravity formulas to measure how accessibility to employment is changing for the typical metro resident over time, examining both auto and transit modes. The effects of changing urban form and changing travel times on accessibility change are isolated for analysis. The research finds heterogeneous patterns of accessibility change, highlighting the importance of the varying trends and policies across the metros; moreover there is little evidence of effective urban form-transportation coordination within any of the four metropolitan areas examined.

4.2 Introduction

US cities have been expanding for at least the last 100 years, since the advent of higher speed transportation technologies such as the streetcar (Anas et al., 1998; Mieszkowski & Mills, 1993). In the post-war era in particular, population densities have been decreasing, and new population centers have formed far from traditional city centers. This paper examines this phenomenon of spatial expansion via the concept of accessibility. Rather than asking the question of whether or not residents are living farther away from some historic urban center, this paper instead asks the question of whether residents have the greater or lesser access to urban opportunities over time. This question is more relevant to residents' opportunity and convenience with respect to living in a particular metropolitan area. It also provides us with a way to evaluate whether major metropolitan areas are sprawling over time in the sense of providing diminished accessibility for residents.

Accessibility is often defined as ease of access to opportunities in the environment. Accessibility measures are increasingly accepted as relevant performance metrics for metropolitan area transportation systems. In addition, accessibility metrics have been related to both increased travel opportunity as well as decreased travel impacts, in particular VMT (Cervero & Duncan, 2006; Ewing & Cervero, 2010). Therefore understanding how accessibility is changing over time in our major metropolitan areas is relevant to greenhouse gas mitigation, quality of life, and economic development objectives for regional planning.

Only a handful of papers have examined longitudinal metropolitan accessibility change, and fewer still have examined the underlying causal factors for accessibility change. In this paper, I examine how accessibility changes over time for four major metropolitan areas experiencing contrasting trends. In particular, I focus on two primary drivers of accessibility change – changes to urban form and changes to travel times. The four metropolitan areas reflect in turn different trends with regard to urban form and travel time congestion, potentially highlighting the relative influence of each. This comparative analysis of contrasting metropolitan areas sheds light on how changing urban form and travel times influence accessibility over time.

Proximity and travel times (and costs) are the two key underlying components of access to destinations. In theory, if travel times did not change with increasing destination proximity, then closer proximity would result in higher accessibility. Likewise, if travel times were improved without any incidental changes to urban form, this would also result in increased accessibility. Therefore proximity and travel times can be thought of as two potential policy levers for increasing access to opportunities. The picture becomes more complex, of course, when you consider the feedback mechanisms between these two, but conceptually and practically each feature can be thought of individually.

However, in recent decades, US metropolitan areas are likely to have become both lower in proximity due to sprawl and have slower travel times due to congestion. If this is indeed the case, then most metropolitan areas are potentially delivering less accessibility to their residents over time. Metropolitan-scale smart growth efforts, however, could potentially channel development into existing built-up areas, and therefore lead to higher proximity and higher accessibility relative to their more sprawling counterparts. The relative influence of and general trends in evolving urban form (proximity) and travel times – is explored in this paper on longitudinal accessibility change.

4.2.a Literature Review

This work builds upon a body of recent work where accessibility metrics have been used to evaluate the performance of transportation systems at the metropolitan scale. Accessibility measures have been increasingly used compare various metropolitan areas to each other as well as to examine longitudinal accessibility change within a specific metropolitan area (Cervero, Rood, & Appleyard, 1999; El-Geneidy, 2010; Grengs, Levine, & Shen, 2010; Helling, 1998). The accessibility concept is rooted in the idea that transportation is a derived demand, i.e. that the primary purpose of the transportation system is to provide access to destinations of interest. Accessibility metrics account for both travel costs and destination choices, integrating into a single measure the number, size, and location of destination choices with the travel cost of reaching those choices. In short, they offer a succinct measure of the performance of the transportation system in providing access to a particular kind of opportunity for a particular study population.

In their 2010 paper, "Intermetropolitan Comparison of Transportation Accessibility," Grengs and Levine compare metropolitan San Francisco and metropolitan Washington DC for the work and nonwork accessibility these metropolitan areas offer via auto and transit modes. They make use of gravity-based accessibility measures with travel time as the primary measure of travel cost. This paper concludes that San Francisco provides higher work and nonwork accessibility than Washington DC by auto, whereas both areas provide similar levels of transit-based accessibility. In addition, the analysis separates the effects of mobility and proximity on accessibility by equalizing travel speeds across the two metropolitan areas (Levine, Grengs, & Shen, 2010; Levine et al., 2012). In a follow on paper, "Does accessibility require density or speed?" Levine and Grengs conclude that density contributes more to accessibility by making destinations closer than it detracts by reducing the speed of auto travel (Levine et al., 2012). This result suggests that metropolitan areas that grow with more compact urban forms are likely to provide greater employment accessibility over time, a hypothesis explored further in this paper.

While Grengs and Levine have considered intermetropolitan comparisons of accessibility from a number of perspectives, they have not examined longitudinal changes in accessibility for metropolitan areas. However, a handful of previous studies have tracked longitudinal changes to metropolitan accessibility (Cervero et al., 1999; Helling, 1998; Levinson & Marion, 2010). Cervero, Rood, and Appleyard track changes to work accessibility over time in the San Francisco Bay Area for the 1980-1990 period, breaking down their analysis by occupational grouping (Cervero et al., 1999). They use gravity accessibility measures, but are unable to distinguish auto and transit accessibility because their accessibility measures are based upon highway distances rather than travel times. Cervero et al.'s approach emphasizes the equity aspects of accessibility analysis, noting that accessibility had increased for high skill occupations while decreasing for lower-skill occupations in the Bay Area during the 1980-1990 period.

Helling conducts a very thorough exposition of accessibility change in metropolitan Atlanta over the 1980-1990 period (Helling, 1998). She calculates accessibility to work by auto for each Census Tract, making use of travel times provided by the local metropolitan planning organization. She separates out the effects of population patterns, employment patterns, and traffic congestion on accessibility change, finding that for this period the effects of increased traffic congestion overwhelm all other effects and result in reduced accessibility. However, one drawback of her analysis is that she calculates a total rather than per capita accessibility, so her analysis does not illustrate the change in accessibility for the average or typical resident.

In another related paper, Levinson and Marion examine changes to accessibility to work by auto for Minneapolis from 1995-2005 (Levinson & Marion, 2010). Levinson and Marion employ cumulative accessibility measures based on a fixed commute time; these are more straightforward to compute than gravity measures, though they also have some theoretical drawbacks due to the arbitrary nature of the cut-off point for travel times in such measures. Taking a geographical rather than household perspective, they find that accessibility increased almost everywhere in the Minneapolis metropolitan region, and moreover that accessibility has increased more at the edge of the region than in the center. Moreover, they find that accessibility in the Minneapolis metropolitan area increased during this period despite some increases to traffic congestion primarily because of employment growth.

From these three longitudinal studies in three unique metropolitan areas, it is difficult to make any generalizations about overall accessibility trends in US metropolitan areas. It does seem that employment growth, simply by increasing the number of work destinations available, is likely to increase accessibility to jobs in growing metropolitan regions. Helling's study, which found severe effects of transportation congestion, suggests that slower travel times may have a large effect. Both Helling's work and Cervero's work suggest that changes to accessibility over time may vary depending upon the study population of interest. I follow Helling's approach in trying to determine what the effect of shifting residential location patterns is on accessibility change. Most of the existing literature suggests that residential patterns are decentralizing in major US metropolitan areas, therefore likely decreasing employment accessibility over time. Interestingly, none of the previous studies have examined whether employment location patterns are having an important effect on accessibility, independently of employment growth. Several researchers of urban form have suggested that employment decentralization is a way for employment accessibility to remain high even while the residential population is spreading out. This paper analyzes the effects of shifting employment locations independently from the effects of total metropolitan employment growth (which is almost certain to raise accessibility by its definition). In summary, this paper builds upon this previous work by examining longitudinal accessibility change for multiple metropolitan areas with contrasting urban form trends, and by examining the various components comprising changing urban form in greater detail.

4.2.b Research Questions and Hypotheses

The primary research questions concern how accessibility changes over time in US metropolitan areas, and to what extent accessibility change is influenced by changes to urban form and to travel times. More specifically, is accessibility increasing or decreasing over time in US metropolitan areas, and what are the primary underlying causes of these changes? In terms of policy, are there different trends for metropolitan areas where more compact urban form patterns prevail, versus metropolitan areas where more sprawling urban form patterns prevail?

Furthermore, the influence of urban form on accessibility is decomposed into several spatial factors – the locations of residences, and the locations of employment, and the total numbers of employment destinations. Examining each of these aspects of urban form separately provides additional insight into the drivers of accessibility change over time. In addition, previous research suggests the likely directional influence of each of these factors, namely, that shifting residential locations by themselves are likely to decrease accessibility and shifting employment locations are likely to increase accessibility over time (Anas et al., 1998; Giuliano et al., 2012; Levinson & Marion, 2010).

In addition, changing accessibility to jobs over time is analyzed for both auto and transit modes. This highlights differing modal trends, since transit accessibility is influence somewhat differently that auto accessibility by shifting urban forms and roadway travel times. Transit travel times may be somewhat less effected by congestion because they are at least partially on dedicated rights of way. Therefore transit accessibility could at least theoretically hold up better over time as a metropolitan area grows and becomes more congested.

Based on previous research to changes in accessibility over time and bid rent theories of urban form, I put forward the following hypotheses (Ahlfeldt, 2011; Helling, 1998; Levinson & Marion, 2010):

- **Compact vs. Sprawl Hypothesis**: Metropolitan areas with increasing proximity will outperform metros with decreasing proximity in terms of accessibility change.
- **Residential Decentralization Hypothesis**: Residential development patterns are reducing average household accessibility over time in most metropolitan areas.
- **Employment Follow Households Hypothesis**: Employment development patterns are increasing average household accessibility over time.
- **Traffic Congestion Hypothesis**: Auto-based accessibility is decreasing due to worsening traffic congestion in most metropolitan areas.

4.3 Methods

Four metropolitan areas were selected for study in order to maximize contrast along the independent variables of interest, changes to urban form/proximity and changes to travel times. Two metropolitan areas were selected for having urban forms with increasing proximity, and the other two metropolitan areas were selected for having urban forms with lowering proximity. It is important to note that proximity and decentralization (distance to the CBD), while correlated, are not identical concepts and it is possible for them to move in opposite directions over time. In addition, the selected metropolitan areas are also intended to demonstrate contrasts with regard to travel times, with two metropolitan areas representing trends towards worsening congestion and therefore longer travel times, and two metropolitan areas representing trends towards lessening congestion and therefore shorter travel times. In addition, the selected metropolitan areas had to be large enough to support detailed transportation modeling programs since at least the year 2000. Table 4-1 presents a conceptual summary of the selected metropolitan areas.

Table 4-1: Four Metropolitan Areas Representing Contrasting Trends

	Increasing Density	Decreasing Density
Increasing Congestion	Charlotte	Chicago
Decreasing Congestion	Seattle	St. Louis

In order to identify metropolitan areas with the greatest changes to traffic congestion, I worked with data from the Texas Transportation Institute's Urban Mobility Report (Shrank, Lomax, & Eisele, 2011b). Using total delay and total population for years 2000 and 2010 from the top 101 urban areas by population size, I identified the metropolitan areas which saw the greatest percent increase and greatest percent decrease in delay per capita between 2000 and 2010. This allowed for the identification of metropolitan areas with differing traffic congestion trends.

With respect to identifying contrasting urban forms, I employ a calculation of changing population proximity for major metro areas over time. It should be noted these are measures of *population* proximity, i.e. how close people are to each other, whereas the true object of interest in my study is *employment* proximity, or how close people are to employment locations. However past research has indicated that these two aspects of proximity are highly correlated (Cutsinger, Galster, Wolman, Hanson, & Towns, 2005). To calculate changes to proximity, I started with Census population data at the Census Tract level. Looking at the top 101 metropolitan statistical areas by population from Census 2010, each metro area was trimmed to keep only those census tracts with a population density greater than 200 persons per square mile. This makes metropolitan areas across the country more comparable spatially because it eliminates some of the variation due to differently-sized counties in different parts of the country (Wolman et al., 2005). Then, for each Census Tract centroid, I measured the total population within 10 miles; this is a kind of proximity measure (based on a 10-mile neighborhood). Next, for each metro area, I weight Census Tracts by populations (See Equation 1), resulting in a population-weighted proximity measure which captures how many people live within ten miles of the average metro inhabitant. Examining percentage change in this proximity variable from 2000 to 2010 identifies those metropolitan areas which experienced the greatest increases and decreases in proximity over time.

$$Proximity = \sum_{Census\ Tracts} 10\ Mile\ Pop * \frac{TractPop}{MetroPop} \qquad 1$$

Where *Proximity* = Metro-area population weighted density; *10 Mile Pop* = Total population count within 10 miles of the Census Tract Centroid; *TractPop* = Total Census Tract Population; *MetroPop* = Total Metropolitan Area Population.

Finally, both sets of data were examined simultaneously in order to identify four metropolitan areas with maximum contrast along the two dimensions of proximity change and congestion change. In addition, selected metropolitan areas had to be large enough to have transportation modeling programs in place since the year 2000. This resulted in the selection of metropolitan Seattle, Charlotte, Chicago, and St. Louis, as reflected in Table 4-2 below, which describes their proximity and traffic congestion change for the 2000-2010 period.

Table 4-2: Selected Metropolitan Areas for Study

Metropolitan Statistical Area	2010 Population (1000s)	Pct. Change, Per Capita Delay	2010 Delay Per Capita	2000 Delay Per Capita	Pct. Change, Proximity	Proximity 2010	Proximity 2000
Seattle	3,237	-10.2%	27.2	30.3	4.6%	624,092	596,737
Charlotte	1,052	36.6%	16.9	12.3	19.1%	374,511	314,360
St. Louis	2,341	-31.1%	20.1	29.1	-12.3%	491,925	560,679
Chicago	8,583	31.1%	42.8	32.6	-11.3%	1,276,939	1,440,181

Sources: US Census Bureau, 2010; Texas Transportation Institute, 2011.

The four metropolitan areas selected for this study represent contrasts moreso than similarities. Two metros are aging cities from the Midwest, and two are newer, faster growing cities from the West and South. Chicago stands out in particular as a metropolitan area with a significant legacy of transit use and an influential central city. The transportation investment policies across these four metropolitan regions also present marked contrasts. Charlotte is notable for a commitment to a “five transit corridor” plan for its land use and transportation investment strategy, which has been funded by a dedicated sale tax since 1998 (Mecklenburg/Union Technical Coordinating Committee, 2002). Seattle’s long range transportation plan (LRTP) from the year 2001, Destination

2030, emphasized how transportation investments should reinforce the region's regional growth plan Vision 2020. This regional growth plan emphasized channeling growth within existing urban centers (Puget Sound Regional Council, 2001). Chicago's and St. Louis' long range transportation plans are notable for their emphasis on repairing existing infrastructure first: 71.6% of the East West Gateway's LRTP budget and 80.5% of the Chicago Area Transportation Study's budget are allocated to system maintenance, preservation and restoration (Chicago Area Transportation Study, 2000; East West Gateway Coordinating Council, 2002). St. Louis' LRTP also mentions that the transit operator for the region, the Bi-State Development Agency, experienced unexpected operating budget deficits that resulted in service reductions in 2001; however data from the National Transit Database shows no decline in vehicle hours of transit service from the 2000-2010 period (Table 4-3). So in short each metropolitan area is changing under the influence of differing circumstantial and policy forces which shape their urban forms and transportation systems.

Table 4-3: Key Statistics for Four Metros, 2000-2010

	Seattle	Charlotte	St. Louis	Chicago
Population 2000 (1000s)	2,914	1,183	2,300	8,821
Population 2010 (1000s)	3,337	1,612	2,416	9,198
Population Growth	14.5%	36.2%	5.1%	4.3%
Employment 2000 (1000s)	1,647	767	1,338	4,571
Employment 2010 (1000s)	1,641	808	1,287	4,247
Employment Growth	-0.3%	5.3%	-3.8%	-7.1%
Transit Commute Mode Share 2000	6.8%	1.4%	2.4%	11.5%
Transit Commute Mode Share 2010	8.2%	2.0%	2.6%	11.2%
Change in Transit Mode Share	1.4%	0.6%	0.2%	-0.3%
Transit Vehicle Hours of Service 2000	3,812,586	765,554	1,517,225	10,882,811
Transit Vehicle Hours of Service 2010	4,867,259	991,558	1,692,380	10,832,683
Increase in Transit Vehicle Hours	27.7%	29.5%	11.5%	-0.5%

Sources: Bureau of Labor Statistics, 2013; National Transit Database, 2011; Charlotte Metrolina, 2012; Chicago Metropolitan Agency for Planning, 2012; East West Council of Governments, 2012; Puget Sound Regional Council, 2012.

4.3.a Urban Form: Residential and Employment Locations

In order to understand the influence of urban form, the combined effects of shifting residential patterns, shifting employment patterns, and changes to employment totals are examined. Population totals were used to estimate residential locations, although these totals do include group quarters populations. Metropolitan planning organizations provided population counts by travel analysis zone for the two time periods, 2000 and 2010.

Job locations were taken from metropolitan planning organization data for both time periods, however job totals were taken from the BLS. Because MPOs make use of multiple sources for their job count data, their methodology for counting jobs is not necessarily consistent over time; therefore I preferred to use the BLS data for tracking job growth because it employs a more consistent methodology. On the other hand, I did rely upon MPO data for describing the physical distribution or locations of jobs throughout the metropolitan area. One exception was that the Puget Sound Regional Council was unable to provide employment counts for the year 2000 due to legal constraints, however these counts were obtained from the Census Transportation Planning Package for the year 2000 (Bureau of Transportation Statistics, 2004).

For metropolitan St. Louis, travel model information was only available back to the year 2002, and therefore 2002 population and employment counts were used as the baseline year as opposed to year 2000.

4.3.b Accessibility Measures and Decomposition

In this section I discuss the accessibility measures used and their decomposition into various urban form and travel time components. Change in access to opportunities over time was evaluated with the use of gravity accessibility measures. One advantage of gravity accessibility measures is that they can take into account opportunities available anywhere in the metropolitan area, while discounting those opportunities by factoring in the difficulty of reaching them. The standard gravity accessibility formula was used:

$$A_i = \sum_{j=i}^{n} O_j e^{-\delta * t_{ij}} \qquad 2$$

Where A_i is the accessibility at TAZ i, O_j is the number of opportunities (total employment) available in TAZ j, δ is the impedance coefficient for travel time, and t_{ij} is the travel time from TAZ i to TAZ j in minutes.

In order to discern the impact of changes in accessibility for the residential population, population counts are associated with each TAZ, therefore creating an accessibility distribution curve for the entire metropolitan area. Medians and other percentiles (A_p) from this distribution are derived by ordering the TAZs by their level of accessibility and assigning population shares to each TAZ (See Equation 3). This means that not just spatial shifts in accessibility, but also spatial shifts in where the population lives over time, i.e. residential location patterns, can impact median metro accessibility.

$$A_p = A_{i*} \; with \; i* \;\; s.t. \frac{\sum_{A_i < A_{i*}} TAZPop_i}{MetroPop} < p \leq \frac{\sum_{A_i \leq A_{i*}} TAZPop_i}{MetroPop} \qquad 3$$

Where A_p is the pth percentile accessibility for the metropolitan region, A_{i*} is the accessibility of the particular TAZ where this population percentile is reached when the TAZs are sorted by ascending accessibility, $TAZPop_i$ is the population of TAZ I, and MetroPop is the total metropolitan population, i.e. the sum of the TAZ populations.

Accessibility is a mathematical function of the location of residences, the locations and totals of employment, and the travel times it takes to journey between them; therefore any change in residential and employment locations must necessarily result in some change in accessibility patterns. However it is an important empirical question to what degree each of these variables has an influence in changes to accessibility over time. Understanding their relative degree of influence provides insight into the potential benefits of various urban form and transportation policies for improving metropolitan accessibility.

In order to isolate the influence of these independent variables, each one – residential locations, employment locations, employment totals, and travel times – is varied independently while holding the others constant. This creates a series of contrasts that helps us to identify the degree of influence of each independent variable on accessibility over time.

The table below explains how total accessibility change is decomposed into each of the individual factors. Starting from the year 2000 situation, first I alter the residential pattern, then the employment pattern, then the employment totals, and finally the travel times. Residential patterns are shifted first in order to determine the influence of residential decentralization. Employment patterns and employment growth are examined next, to see to what degree these patterns may compensate for residential decentralization patterns. These two aspects of employment are considered separately because I want to identify the impacts of employment growth separately from the effects of land use policy, though these are no doubt intertwined. Changes to travel times are examined last, because presumably changing travel times are at least partially caused by shifting urban form patterns. Note that changing the order in which these factors are examined does create slightly different results regarding the size of influence of each factor. However regardless of the order, the product of the influence of each of these factors necessarily equals the total accessibility change.

Table 4-4: Determining the Influence of Individual Variables on Accessibility Change

Independent Variable Analyzed	Before Scenario	After Scenario
Residential Patterns	RP1 EP1 TT1 ET1	RP2 EP1 TT1 ET1
Employment Patterns	RP2 EP1 TT1 ET1	RP2 EP2 TT1 ET1
Employment Totals	RP2 EP12 TT1 ET1	RP2 EP1 TT1 ET2
Travel Times	RP2 EP2 TT1 ET1	RP2 EP1 TT2 ET2

RP1 = Residential patterns from time 1; RP2 = Residential patterns from time 2.
EP1 = Employment patterns from time 1; EP2 = Employment patterns from time 2.
TT1 = Travel Rimes from time 1; TT2 = Travel Times from time 2.
ET1 = Employment Totals from time 1; RP2 = Employment Totals from time 2.

4.3.c Travel Times

Metropolitan planning organizations also provided travel times by auto and by transit modes between all pairs of travel analysis zones for the two years under analysis, usually 2000 and 2010. In some cases, MPOs "backcasted" their current transportation model to derive travel times based upon historical transportation networks, and historical population and employment patterns. Each MPO faced unique challenges in backcasting, so the methods for obtaining travel times vary by MPO, but each MPO endeavored to use consistent methods across the two time points.

MPOs also differed in how they categorize travel times by modes and by time of day, sometimes including multiple transit modes and multiple mechanisms for reaching transit. In order to calculate a single transit travel time, I selected the fastest transit travel time for each TAZ-to-TAZ pairing. Also, I selected walk to transit travel times where available, developing my own estimated of walk time where they were not available from MPOs. Congested or morning travel times were used for calculating the accessibility to work, while uncongested or early afternoon travel times were used for calculating the accessibility to shopping.

For each metro area, a computation of intrazonal travel time was also necessary, because residents of a TAZ also have access to destinations within their home TAZ. In order to compute intrazonal travel times, I took ½ of the average of the three closest travel times, computed separately by mode and by time of day.

4.3.d Impedance of Travel Time

The impedance coefficient for travel time is assumed to be constant and based upon the metropolitan area size, with larger metropolitan areas having smaller impedances. Work travel time impedance is based upon metro population size through the following formula (Levine et al., 2010):

$$\delta = 0.109 * exp(-3.53 * 10^{-8} * metro.population)$$

A smaller impedance coefficient suggests a willingness to travel a longer time for opportunities. Larger metro areas have smaller impedances for two reasons: Firstly, they offer a greater range of opportunities, and therefore offer greater incentive to travel longer distances; and secondly, they have higher levels of traffic congestion, and therefore residents become more accustomed to dealing with longer travel times.

Impedance coefficients are held constant over time for each metropolitan areas, in order to make accessibility measures comparable over time (Grengs, Levine, Shen, & Shen, 2010). However, since different impedance coefficients are used for each metropolitan area, the accessibility measures are not comparable across metropolitan areas.

4.4 Results

4.4.a Changing Metropolitan Accessibility over Time

There is no clear overall pattern of aggregate accessibility change across these four metros, as Table 4-5 shows. Although the research data are capable of providing complete accessibility distribution curves for each of the metros and time periods selected, I report the median auto accessibility and the 90th percentile transit accessibility in order to provide a clear and succinct presentation. The 90th percentile for transit access is selected because presumably those in high transit accessibility locations are more likely to make use of transit, in consideration of the relatively low transit mode shares in each of these metros (See Table 4-3).

The most striking pattern is the lack of a pattern. There are cases where both auto and transit accessibility increase and decrease, and they do not necessarily increase or decrease together. Charlotte dominates the crowd, likely because its strong employment growth boosted accessibility to employment nearly everywhere throughout the metro area. However, slow-growing Chicago performs better than fast-growing Seattle with respect to changing auto accessibility to employment. Seattle performs by far the best with respect to transit accessibility to employment. St. Louis performs dismally with regard to changes in transit accessibility, even though there is no obvious evidence that transit service levels have declined (Table 4-3). Rather than one clear picture of accessibility change emerging, what appears is four distinctive stories, each based upon the particular trends and policy choices of the metro areas under study.

More specifically, the two primary dimensions under analysis, proximity change and congestion change, do not seem to have a decisive influence. Those metros with increasing proximity- Seattle and Charlotte – do not necessarily outperform those with decreasing proximity – St. Louis and Chicago – with respect to accessibility change. Likewise, those metros with decreasing traffic congestion – Seattle and St. Louis – do not necessarily outperform those with increasing traffic congestion – Charlotte and Chicago – with respect to accessibility change.

Table 4-5: Percent Change in Accessibility, 2000-2010, median or 90th percentile

	Seattle	Charlotte	St. Louis	Chicago
Accessibility by Auto (Median)	-11.1%	22.6%	-6.3%	1.2%
Accessibility by Transit (90th)	15.8%	-2.6%	-68.7%	-5.7%

N.B.: Change in gravity-based accessibility to all jobs, based upon interzonal travel times from MPO travel demand models.

4.4.b Accessibility Decomposition

The next series of graphs allow us to look under the hood at aggregate accessibility change, to see how much of the change is driven by changing residential patterns, employment patterns, employment growth, and travel times.

Figure 4-1 illustrates the size of the various components of change in auto accessibility to employment for each of the metropolitan areas. In most cases the largest single factor was changing travel times, and, except for Seattle, changing auto travel times improved accessibility by a fair amount, contrary to expectation. The second largest factor overall was shifting residential locations, which generally served to decrease employment accessibility. The third largest factor was usually employment growth, which of course followed the trend for each metropolitan area as a whole. The influence of changing employment patterns on accessibility was fairly marginal for all of the metros over this period.

Figure 4-2 yields a similar decomposition of accessibility change for transit access to employment for the four metros over the 2000-2010 period. Once again changes to travel times tend to have the largest influence overall, with notable decreases in transit accessibility for Chicago and St. Louis and notable increases for Charlotte and Seattle. These differences are at least partially reflective of increased investment in transit, as indicated by Charlotte's and Seattle's long range transportation plans (Mecklenburg/Union Technical Coordinating Committee, 2002; Puget Sound Regional Council, 2001). However urban form characteristics also play a major role in a few cases here. Charlotte sees a large drop in transit accessibility due to shifting residential locations; this is a bit surprising due to its large transit investments and its strong regional plan for transit-oriented growth. And Chicago undergoes a large increase in transit access to employment due to shifting employment locations. This is also surprising because Chicago's LRTP suggests an acceptance of decentralizing employment locations (Chicago Area Transportation Study, 2000).

Figure 4-1: Changes to Auto Accessibility to Employment, 2000-2010

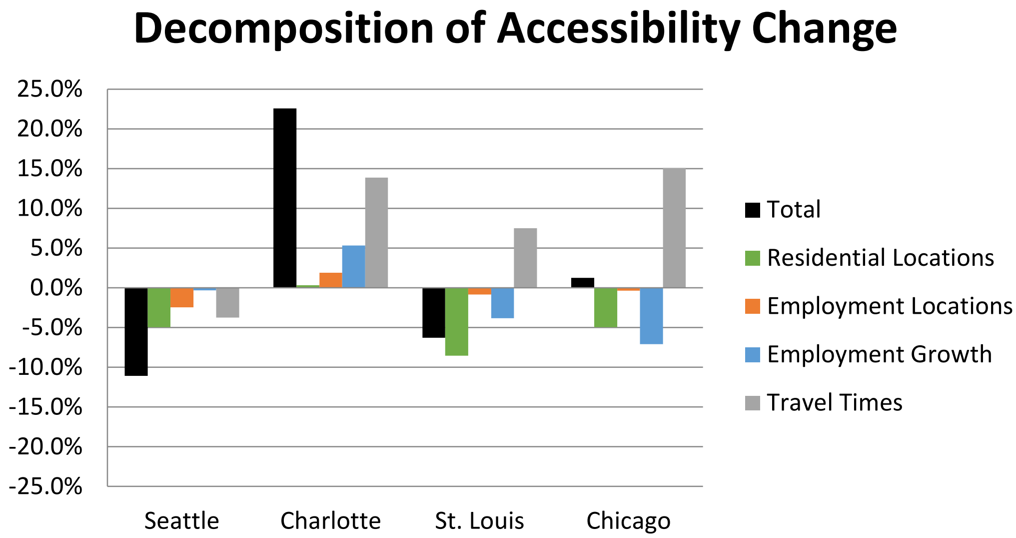


Figure 4-2: Changes to Transit Accessibility to Work, 2000-2010

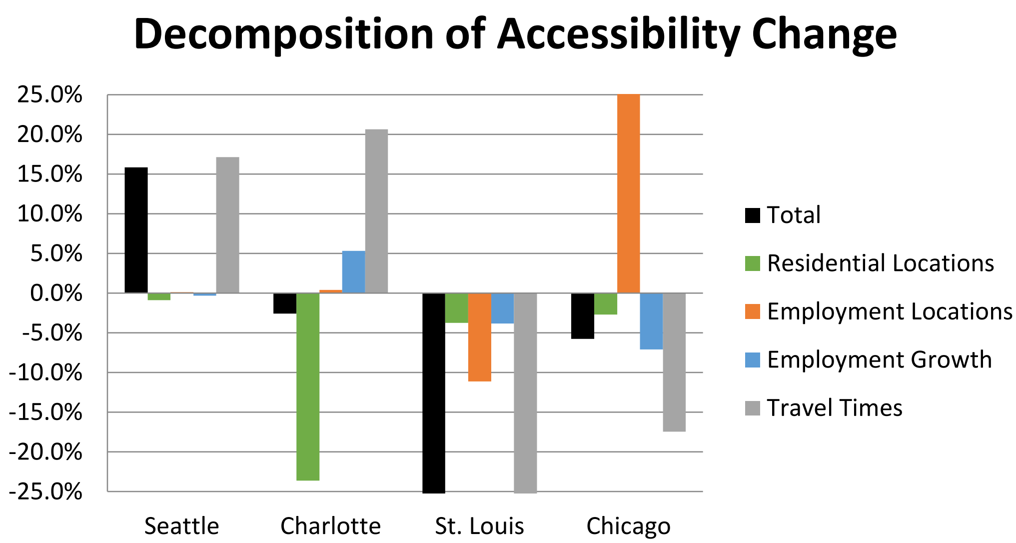


Table 4-6: Decomposition of Accessibility Change

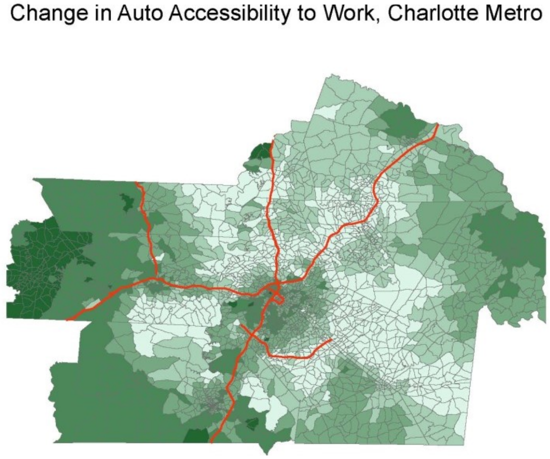
	Auto Accessibility to Work			
	Seattle	**Charlotte**	**St. Louis**	**Chicago**
Residential Locations	-5.0%	0.3%	-8.5%	-5.0%
Employment Locations	-2.4%	1.9%	-0.8%	-0.4%
Employment Growth	-0.3%	5.3%	-3.8%	-7.1%
Travel Times	-3.8%	13.9%	7.5%	15.1%
Total	-11.1%	22.6%	-6.3%	1.2%

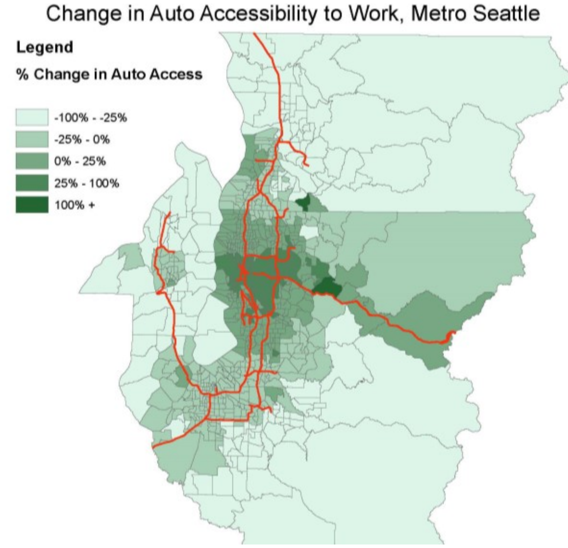
	Transit Accessibility to Work			
	Seattle	**Charlotte**	**St. Louis**	**Chicago**
Residential Locations	-0.9%	-23.6%	-3.7%	-2.7%
Employment Locations	0.1%	0.4%	-11.1%	26.3%
Employment Growth	-0.3%	5.3%	-3.8%	-7.1%
Travel Times	17.1%	20.6%	-61.9%	-17.4%
Total	15.8%	-2.6%	-68.7%	-5.7%

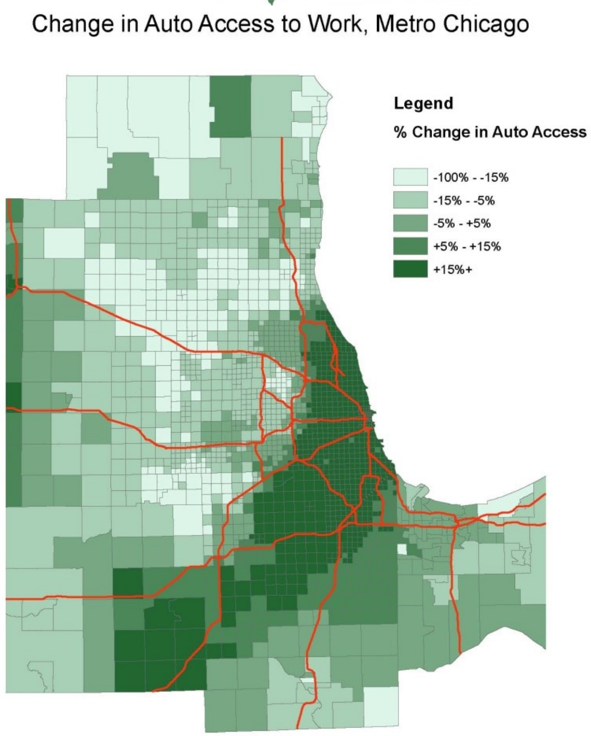
4.4.c Spatial Patterns of Accessibility Change

The maps below reflect the TAZ-by-TAZ spatial changes in accessibility to work by two modes across the four metropolitan areas (Figure 4-3 and Figure 4-4). Based upon these maps, metropolitan areas can be broadly categorized by their spatial pattern of accessibility change into three categories: Centralizing, decentralizing, or heterogeneous. Seattle has the strongest centralizing tendency, while St. Louis has the strongest decentralizing tendency, and Charlotte and Chicago have a heterogeneous pattern with accessibility increasing in central as well as in peripheral areas. The forces behind these patterns of accessibility change could potentially be multiple and complex: market forces, regional and local land use policies, investments in transportation infrastructure, and so forth. In particular, it is difficult to tell if it is transportation investments which are creating these patterns of accessibility change.

Figure 4-3: Changes in Auto Accessibility to Work, 2000-2010, by TAZ







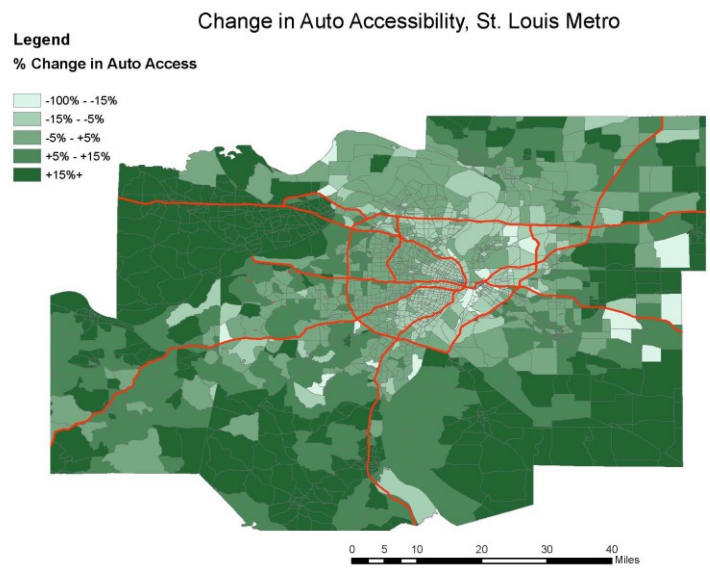
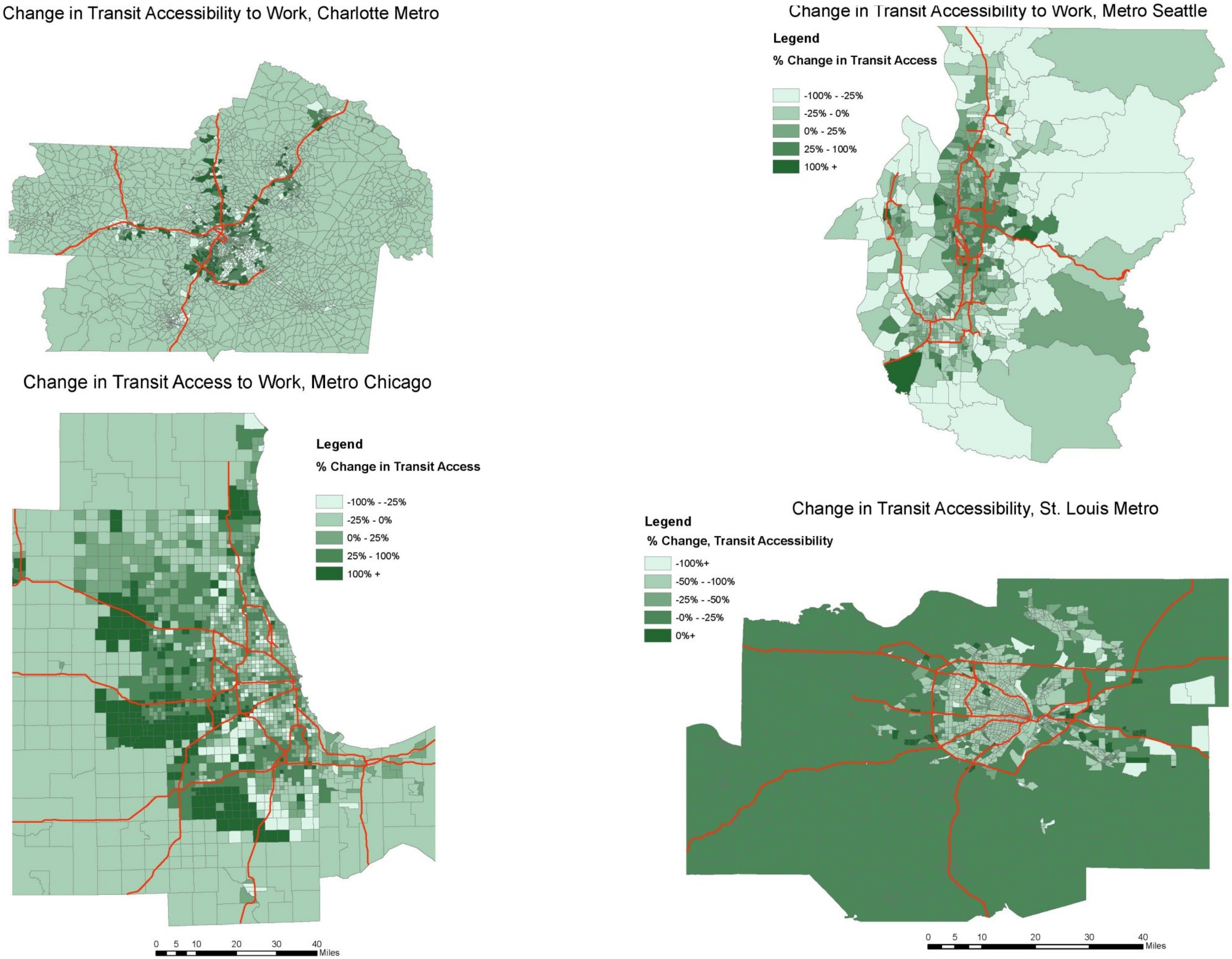


Figure 4-4: Changes in Transit Accessibility to Work, 2000-2010, by TAZ



4.5 Discussion

First, I review the results with respect to their implications for the hypotheses discussed in the Introduction section. Then differences between the results for auto and transit modes are discussed. Finally, the discussion delves into the decomposition of accessibility change and what this suggests for the coordination of regional land use and transportation policy.

- **Compact vs. Sprawl Hypothesis**: This hypothesis suggests that metropolitan areas with increasing proximity will outperform metros with decreasing proximity in terms of accessibility change. The two metropolitan areas with increasing population proximity, Seattle and Charlotte, did not perform consistently better than those metro areas with decreasing proximity, with regard to accessibility change. Seattle and Charlotte did have better performance on transit accessibility, but this seems to be more likely due to improved transit travel times (See Figure 4-2).
- **Residential Decentralization Hypothesis**: This hypothesis suggests that residential development patterns, if considered in isolation, are reducing average household accessibility over time in most metropolitan areas. Shifting residential locations decreased accessibility in 7 out of 8 cases and had a negligible effect in the remaining case (less than 2%). This suggests that there is a general trend of residents shifting towards lower accessibility areas in US metros.
- **Employment Follow Households Hypothesis**: Employment development patterns are hypothesized to increase average household accessibility over time. In fact, when separated from metropolitan growth trends, employment locations generally had a very small impact on household accessibility to work, and it was as often negative as positive. The two exceptions

to this rule were a large decrease in transit accessibility to employment in St. Louis (-11.1%) and a large increase in transit accessibility to employment in Chicago (+26.3%).

- **Traffic Congestion Hypothesis**: Here I hypothesize that auto-based accessibility is decreasing due to worsening traffic congestion in most metropolitan areas. Changes to auto-based travel times over this study period, 2000-2010, mostly show faster travel times and therefore increased accessibility over time. Only Seattle saw both decreased work accessibility due to slower auto travel times, and these decreases were modest (-4.4% and -4.1% respectively). This result runs against the conventional wisdom that congestion is increasing uniformly across major US metropolitan areas, and in particular, runs against the data from the Texas Transportation Institute's Urban Mobility Report, which indicates that metropolitan Chicago and metropolitan Charlotte had seen significant increases in auto congestion over the 2000-2010 period (Shrank, Lomax, & Eisele, 2011a).

There are several possible explanations for these counterintuitive results with respect to traffic congestion, and the foremost that comes to mind is the possible inconsistency in data sources over time. As a national study, the Urban Mobility Report cannot verify all of its original data sources, and some of the local entities they rely upon for data collection may vary their data collection methods over time.

If the data provided by MPOs on changing travel times are accurate, they suggest that auto-based travel times improved significantly for Charlotte, Chicago, and St. Louis. What are the possible explanations for this, especially in the face of limited transportation investments? Here are some possible explanations:

- Higher gas prices and the economic recession may have reduced travel demand and therefore the "normal" growth in metropolitan congestion.

- Other demographic forces, i.e. the rise of the Millennials, may have resulted in decreased travel demand during this period
- The limited transportation investments that were made may have been more effective than anticipated.
- The residential population may have shifted towards areas with lower traffic congestion, therefore reducing the level of congestion throughout the whole system.

Unfortunately, because the data under analysis here is simply travel times, this research cannot identify which out of these several possibilities is the most feasible.

4.5.a Accessibility Trends for Transit vs. Auto Modes

There were very large and variable shifts in transit accessibility due to travel times, and these shifts largely did not correspond with changes in auto travel times. These results suggest that transit investment and operations, not congestion, were the primary drivers of changes to transit accessibility for the metros covered here. Charlotte's large improvements in transit travel times are likely due to its major transit investments during this period, such as the Lynx Blue Line (Charlotte Area Transit System, 2011). Likewise, St. Louis's large decreases in transit accessibility are likely due to shifting priorities in its transit investments (i.e. shifting away from buses and towards light rail) and decreased funding for its transit operations (Bi-State Development Agency, 2010). I was able to examine St. Louis' transit travel times in detail, and they do indicate that most of the decline in transit service was due to worsening travel times by bus, even as the light rail system was extended to incorporate additional stations (East West Gateway Coordinating Council, 2002). Across all four metros, changes to transit accessibility were impacted much more by changing funding and operations than by levels of traffic congestion.

4.5.b Coordination of Land Use and Transportation

The decomposition of accessibility change into components due to changing residential locations, employment locations, employment growth, and travel times identified some surprising and perhaps disappointing trends. Both Seattle and Charlotte made major expansions to their transit systems during the 2000-2010 time period, as indicated by increased transit vehicle hours (Table 4-3) and higher accessibility due to decreased transit travel times (

Table 4-6). However in Seattle changing residential and employment locations made no contribution to transit accessibility to work, while in Charlotte shifting residential locations reduced transit accessibility to work significantly (

Table 4-6, net effect of -23.6%). To be clear, Charlotte did see positive population growth in areas with high transit accessibility; however even faster population growth occurred in areas with low transit accessibility. This suggests that these metro areas were not broadly successful in reinforcing their transit investments with land use patterns that were also supportive of transit. On the other hand, Chicago's transit accessibility was boosted significantly by shifting employment patterns (

Table 4-6, net effect of +26.3%), but much of this improvement was undermined by slower transit travel times (

Table 4-6, net effect of -17.4%). None of the metro areas under study saw both improved transit travel times and improved urban form in support of transit at the same time.

4.5.c Implications for Policy

Changes to urban form patterns and changes to travel times resulted in a wide variety of accessibility changes over time across the four metropolitan areas under study. In general, the largest and most positive changes for accessibility came about as a result of improved travel times, for both auto and transit modes. This suggests that regionally important transportation investments may be effective for increasing both auto and transit accessibility, and theoretically, the increased opportunity and economic growth that comes with greater regional accessibility.

The findings with respect to urban form patterns are less conclusive. Metro areas with increasing population proximity did not necessarily outperform those with decreasing population proximity with respect to accessibility change. It could be that residential decentralization shifted populations away from high congestion areas, improving travel times in congested corridors; therefore it is possible that residential decentralization could play a positive role in increasing auto-based metropolitan accessibility.

On the other hand, the results also suggest a disappointing lack of coordination between transportation investments and patterns of urban form change, especially with respect to transit investments. Charlotte saw major improvements in transit accessibility due to expanded transit service, but unfortunately saw decreased transit accessibility due to faster residential growth in areas with low accessibility to transit. Chicago saw major improvements in transit accessibility due to increased concentration of employment locations in transit-served areas, but saw decreased transit accessibility due to reduced levels of transit service. It is unfortunate that none of the metro areas under study appeared to coordinate both land use change and transportation investments to obtain potentially synergistic benefits.

4.5.d Study Limitations

Although these results provide us with an intriguing window into longitudinal accessibility change for major US metros, the breadth of the concept of accessibility necessarily means that these results should be presented with some caveats. Accessibility varies not just spatially but also with each individual's characteristics. Accessibility as experienced by a person depends upon their particular time budgets and personal mobility constraints (Kwan & Weber, 2003; Miller, H. J., 1999). The individual nature of accessibility is not captured by the geographic measures of accessibility used in this study. Furthermore, I consider here just the most basic forms of accessibility – accessibility to jobs – whereas other important accessibility considerations might include access to schools, parks and recreation, medical care, and healthy food options. On the other hand, accessibility to jobs has frequently been used as a proxy for generalized access to urban opportunities (Ahlfeldt, 2011; Helling, 1998). Analyzing accessibility as a spatial concept, as I do here, provides some insight into the performance of urban form, but it also masks a variety of accessibility challenges faced by different segments of the population.

By examining four metropolitan areas with contrasting urban form and traffic congestion trends, this study improves upon the external validity of previous studies of longitudinal accessibility change. However, the sample size of four is still small, and all of the study areas are major US metropolitan areas, so it is unclear how these results might apply to smaller metros or to metropolitan areas outside of the United States.

In addition, the time period under analysis, 2000-2010, is unusual in a number of respects, notably the major recession that occurred during the end of the 2000's. This recession particularly affected the housing market, depressing the construction of new housing. Therefore the amount of change to urban form during this time period may be somewhat less than would be experienced in other 10-year time periods with similar population growth patterns. Travel demand also flattened during the recessionary period, though this could be due to either short term or longer term influences (Millard-Ball & Schipper, 2010; Santos, McGuckin, Nakamoto, Gray, & Liss, 2011b).

Travel times are provided by differing metropolitan planning organizations using differing modeling platforms and modeling assumptions. For example, walk to transit travel times are not provided by CMAP, while those that are provided by Charlotte DOT appeared higher than expected. However, the focus of this analysis was on internal consistency within each MPO's data over time. In the end, the results of this analysis are only as reliable as the travel demand models which determine congested and uncongested travel times for each metropolitan area.

4.6 Conclusion

This paper examines changes in employment accessibility by auto and transit modes for four metropolitan areas, Charlotte, Chicago, Seattle, and St. Louis, over the 2000-2010 period. This is the first paper I am aware of to examine longitudinal change in metropolitan accessibility across multiple metropolitan areas. These four metropolitan areas were selected to maximize contrast with respect to changes in urban form (proximity) and changes in traffic congestion over time (Table 4-2). Overall, there was no single dominant trend of accessibility change; accessibility either increased or decreased depending upon the particular metropolitan area and the particular transportation mode under analysis. Moreover, the different patterns of metropolitan accessibility change are not well explained by either changes in proximity nor by macro-scale measures of traffic congestion.

Previous research into metropolitan urban form patterns suggest that more compact urban forms would provide greater accessibility benefits; that increased traffic congestion would usually serve to reduce employment accessibility over time; and that residential locations would tend to shift towards lower accessibility areas, while employment locations would shift in a way that re-balances this accessibility. This research did not confirm any of these hypotheses, except with regard to decentralizing residential locations.

More specifically, the areas with increasing population proximity, Seattle and Charlotte, did not necessarily outperform the areas with decreasing population proximity, Chicago and St. Louis, with regards to accessibility change (Table 4-5).

Changing travel times were the largest factor in accessibility change over time, highlighting the continued importance of regional transportation investments. Auto travel times improved in several metropolitan areas, contrary to expectations, although the primary reasons behind improved auto travel times are unclear. Transit travel times improved in some metropolitan areas while worsening in others, with little correspondence with auto travel times. The fact that transit travel times shifted independently of auto travel times suggests that difference between metros' varying transit performance was primarily due to changing transit investment and operations, rather than changing levels of traffic congestion.

The influence of urban form was decomposed into shifting residential location patterns, shifting employment location patterns, and change in total metropolitan employment. Shifting residential patterns led to decreased accessibility in most cases, whereas shifting employment patterns tended to have little overall effect. Employment patterns only had a positive effect on accessibility where there was an increase in total metropolitan employment.

There was little evidence of land use-transportation coordination to improve accessibility at the metropolitan scale for these four metropolitan areas. Indeed, in many cases accessibility gains due to improvements in one component were undermined by countervailing trends in another area. This suggests that there is still significant upside opportunity to coordinate changes to land use patterns with transportation investments in metropolitan areas. In particular, channeling both residential and employment growth into high accessibility areas remains a relatively untapped opportunity for improving employment accessibility in major US metropolitan areas.

Chapter 5 Conclusion: Implications and Future Research

5.1 Introduction

The theme of the dissertation is the complex interplay between local accessibility and regional accessibility, a theme that was notably explored by Handy (1993). The relationships between various types of accessibility and preferred travel behaviors have proven to be less straightforward than expected. Travel is more localized when local accessibility is higher and when regional accessibility is lower, i.e. a higher accessibility share. Also, travel opportunity, as measured by the number of nonwork activities household engage in, is increased more by local densities than by metropolitan area size. Both of these results suggest that planning for an accessible built environment is not simply a matter of maximizing *regional* accessibility for households. The most preferable urban forms may be those which offer a balance between high local accessibility and high regional accessibility. High local accessibility may enable more convenient participation in nonwork activities, while high regional accessibility may increase access to employment opportunities.

What constitutes "local" is an important and challenging question. Much of the research on local accessibility has focused on the "neighborhood" scale of an approximately ½-mile walk. One of the arguments I make in this research is that the "local" should be reconceived at a somewhat larger scale more aligned with the size and influence of major activity centers. I define the local area around an activity center to include the surrounding residential area contained within a ~2-3 miles radius. The primary travel mode for this local scale would not likely be walking, however travel modes for this kind of distance could include a variety of travel modes: private vehicles, transit, passenger drop offs, bicycles or car share vehicles. By thinking at this larger scale, planners are better able to incorporate the wide range of choices which residents of the contemporary city expect, and they are better able to allow for a wider range of housing types within a local community. This includes some areas dedicated to single family housing. Planning for relatively complete, mixed use activity centers and the integration of surrounding residential areas is an achievable goal for local and regional planners and one that could result in significant decreases in auto travel demand.

Regional accessibility may actually make certain types of travel, such as nonwork travel, longer in distance. This counter-intuitive result points to the importance of connecting our accessibility-based performance measures with observed travel behavior. If we plan for "accessibility" without being specific about which measures we are using and without connecting those measures with specific travel behavior outcomes, unintended consequences may result. It is for this reason that I emphasize the connection between accessibility measures and travel behavior outcomes.

As a matter of broad policy guidance, metropolitan transportation planners should strive for greater regional accessibility for households and businesses. The theoretical superiority of accessibility measures over mobility measures is clear. However, the travel behavior implications of increasing regional accessibility for households are currently only vaguely understood. If planners are expecting more localized travel, more frequent travel, shorter travel distances, and greater traveler choice, then adequate research must be conducted to to insure that higher accessibility does indeed bring about these expected outcomes..

Finally, the results from *Changing Metropolitan Accessibility in US Metropolitan Areas* suggest how difficult it may be to change urban form patterns to promote greater regional accessibility. This paper finds that changing urban form patterns in major metropolitan areas are not helping to achieve goal of increasing regional accessibility. This is true even in metropolitan areas with smart growth or transit-oriented development planning frameworks, such as Seattle or Charlotte. It is well understood by practicing land use planners that the political, economic, and infrastructure obstacles to infill development are greater than those to greenfield development. Therefore identifying high accessibility areas for infill development is only the beginning of the land use planning challenge. Despite the very real obstacles to infill development, I do believe that mapping accessibility regionally and tracking accessibility change over time can help highlight desirable infill development opportunities, and can illustrate how regional development patterns may be working against regional accessibility planning goals.

5.2 Summary of Findings

5.2.a Measuring Complete Communities

In this paper, community completeness is defined as the ability to complete a nonwork tour in one's home community. Communities are defined at two geographic scales, Census Places (i.e. towns and cities) and Centered Communities, which are based on a 15 minute auto travel shed outwards from a given concentration of employment activity. For both of these types of communities, increased local accessibility share, higher levels of mixed use (and in particular better jobs-worker balance), and higher levels of development density promote community completeness. It appears that the single most powerful variable for predicting community completeness is accessibility share to all types of jobs.

Furthermore, the level of mixed use, either in terms of jobs-worker balance or in terms of balance across many different activity types (Entropy) also facilitates community completeness, even after controlling for accessibility share. This suggests that it is not merely the richness of jobs or attractions that promotes complete communities; too many jobs appear to be as problematic as too few jobs. It is the actual *balance* between the number of residents and the number of jobs that matters to some significant degree. The balance between various types of jobs, as measured by an Entropy Index, also appears to facilitate community completeness.

5.2.b Does Accessibility Influence Nonwork Activity Participation

This paper finds that the combined features of the built environment have a substantial effect on households' levels of nonwork travel activity, with a greater influence on households with fewer vehicles. The range of this influence varies from about 8-47%, depending upon the household type and the type of travel activity analyzed. For households without vehicles, high residential and employment densities at the Census Tract level appear to support greater levels of nonwork activity participation. Full Vehicle Households appear to be supported by higher than average residential and employment densities and mid-sized urban area (200,000-500,000) and metropolitan area sizes (250,000-1 million in population). Limited Vehicle Households appear to be relatively unaffected by the built environment, though they do appear to have more activity in mid-sized metropolitan areas (500,000-1 million in population). The limited influence of the built environment on Limited Vehicle Households is contrary to expectation and the reasons behind this finding are unclear.

5.2.c Changing Accessibility in US Metropolitan Areas

Overall, there was no single dominant trend in accessibility change over time for the four major US metropolitan areas examined (Chicago, Seattle, Charlotte, and St. Louis); accessibility either increased or decreased depending upon the particular metropolitan area and mode under analysis.

More specifically, the two primary dimensions of analysis, proximity change and congestion change, do not appear to have a decisive influence. Those metros with increasing proximity – Seattle and Charlotte – do not necessarily outperform those with decreasing proximity – St. Louis and Chicago – with respect to accessibility change. Likewise, those metros with decreasing traffic congestion – Seattle and St. Louis – do not necessarily outperform those with increasing traffic congestion – Charlotte and Chicago – with respect to accessibility change.

Auto travel times improved in several metropolitan areas, contrary to expectations, although the primary reasons behind improved auto travel times are unclear. Transit travel times improved in some metropolitan areas while worsening in others; the evidence suggests that the primary cause of variation in these metros' transit travel times was differing levels of transit investment during the time period under study.

There was little evidence of effective land use-transportation coordination to improve accessibility at the metropolitan scale for these four metropolitan areas. Indeed, in many cases accessibility gains due to improvements in one aspect (i.e. urban form or travel times) were undermined by countervailing trends in another aspect. This suggests that there is still a significant opportunity to improve the coordination of land use patterns with transportation investments in metropolitan areas.

5.2.d Research Limitations

Gravity accessibility measures to employment do provide a powerful summary measure of access to many kinds of urban opportunity. However, these measures also mask a great deal of important information about the people living in a particular metropolitan area and their level of access to the opportunities they need and want. Gravity-based accessibility measures are designed to be measures of places, not of people, and so they do not account for variations in capabilities and travel preferences, such as being able and willing to drive. They do not take into account variations in time budgets that occur across the various occupations and life stages of the population.

In addition gravity accessibility measures, at least as employed in this research, fix a single impedance coefficient across the population. This is very useful for aggregating a great deal of spatial information into a single summary quantity. But no doubt the value of time and the willingness to spend time in travel also varies substantially across the metropolitan population.

These weaknesses aside, I do think that gravity accessibility measures provide us with a high quality and compact snapshot of the level of opportunity provided by a metropolitan transportation and land use system from a particular location in space. Indeed, the use of gravity accessibility measures would be a significant improvement for the second paper, which addressed how the built environment influences activity participation. Due to the limitations of the NHTS data source for that paper, tit was only able to use built environment density and urban and metropolitan area size. I hope to be able to conduct a follow-on research piece which explores how a gravity-based accessibility measures influence levels of nonwork activity participation.

5.3 Implications for Practice and Research

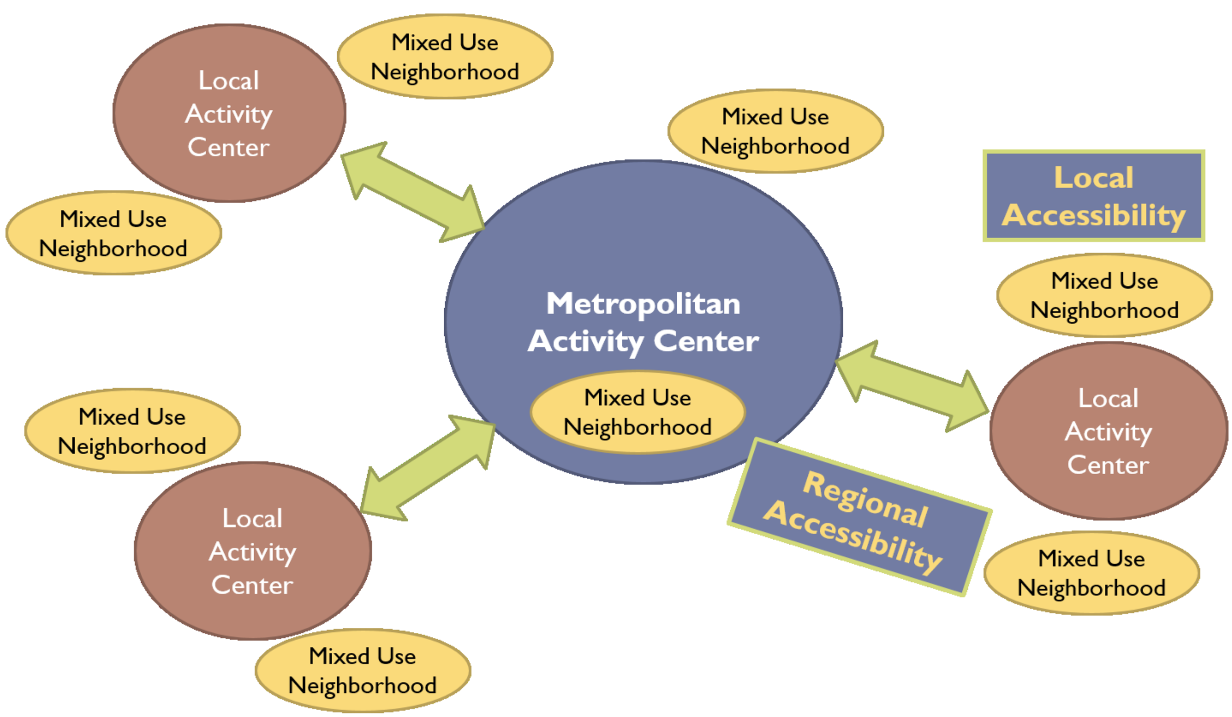
5.3.a Implications for Planning Practice

The results of *Measuring Complete Communities* suggests that it is possible to plan for meaningfully complete communities within major metropolitan areas. In other words, planners can design major metropolitan regions into polycentric forms such that the majority of nonwork travel needs can be met locally within a nearby activity center (See *Figure 5-1: A Polycentric*

Urban Form to Promote Complete Communities for an illustrative example). The paper on *Nonwork Activity Participation* also emphasizes the importance of local opportunities (at the Census Tract scale), finding that the availability of such opportunities locally is associated with greater nonwork activity participation.

In order to provide adequate local accessibility for fostering complete communities, activity centers should be planned with a diversity of activities and should be of significant size and intensity. As a point of reference, the average "centered community" analyzed in *Measuring Complete Communities* contained 71,095 jobs and had an internal trip capture of 47.6%. Residential areas should be located close to designated activity centers and connected to them via a variety of local mobility options – walking, bicycling, transit – within a highly connected local street grid. At the same time, access to large scale, regional shopping centers must be limited in order to promote locally complete communities. This suggests a variety of potential land use or

Figure 5-1: A Polycentric Urban Form to Promote Complete Communities



transportation strategies, such as pricing travel on regional facilities or limiting the growth of regional shopping centers near major interstate exits. If fostering locally complete communities is a legitimate planning goal, the need for regional accessibility must be balanced with the need for local accessibility, in some cases favoring the importance of local accessibility over that of regional accessibility.

In addition to planning for polycentric metropolitan urban forms, a second implication of the dissertation, in particular the third paper on *Changing Metropolitan Accessibility*, is that planners might benefit from mapping accessibility patterns for both regional and for comprehensive plans. Although the concept of accessibility has been well understood and a central topic of research inquiry for some time, the state of planning practice in the US has not fully incorporated accessibility measures in either land use planning nor in transportation planning. Major metropolitan areas in the US have the technical toolkit available to employ accessibility measures in their evaluations, however accessibility measures have played a relatively minor role to date (Some plans that have at least partially included accessibility measures include CMAP's Go To 2035 Plan (Chicago Metropolitan Agency for Planning, 2010) and PSRC's Vision 2040 Plan (Puget Sound Regional Council, 2008)). Given the policy environment surrounding regional planning, never has there been a more appropriate time to focus on accessibility as an outcome (See *Section 1.1* for a more detailed discussion of the policy environment). Metropolitan planning agencies are being called upon to facilitate economic growth while at the same time decreasing environmental impacts through regional transportation and land use planning efforts. A focus on accessibility performance measures has the potential to promote both of these goals simultaneously.

How might planners make a more thorough use of accessibility measures in their toolkits? Firstly, measures of accessibility to opportunity could be mapped as part of both land use and transportation planning processes, just as residential density is commonly mapped today. Examining spatial patterns of accessibility would then be a key input into both the land use and transportation planning processes. Secondly, the evaluation of various land use and transportation interventions could be considered with respect to their spatial impacts on accessibility by multiple modes. A key question for each policy intervention or scenario would be how does it alter accessibility to opportunities for the modes of interest. Thirdly, at the regional scale, residential densities could be arranged to correlate with accessibility patterns, therefore increasing the number of people living in highly accessible locations. Each of these is a relatively straightforward and practical way to incorporate accessibility measures into transportation and land use planning efforts.

Planners may think that they are coordinating transportation investments and land use patterns at the regional scale, but unless they are examining regional accessibility measurements, it is difficult to tell how effective this coordination is. If a small amount of development is channeled into mixed use centers while a large amount of new development flows to the urban periphery, then accessibility of the average household may be decreasing over time. As a result, regional planning efforts may turn out to be relatively unproductive in reducing VMT and increasing economic opportunity. The coordination of land use and transportation at the regional scale almost requires the use of accessibility measures in evaluation in order to ensure its effectiveness.

In addition to illustrating the coordination between land use and transportation, accessibility mapping also can be used to illustrate areas of opportunity for disadvantaged populations. If land is otherwise suitable for development, high accessibility, low density areas are appropriate target areas for infill development and affordable housing. In fact, areas of high density but persistent low density may represent a kind of environmental injustice – the most favorable locations within the metropolitan area preserved for the few and excluding the many. Although infill development may be challenging in such areas, such development opportunities represent an untapped resource for the region and for creating social and economic opportunity for more disadvantaged and less mobile populations.

5.3.b Barriers to Planning for Denser Infill Development

Although it is easy to identify high accessibility areas as suitable for infill development, from the local perspective promoting such infill development can be quite challenging. The obstacles to infill development in existing built up areas are many, including citizen opposition, lack of infrastructure, environmental regulations, and difficulty of land assembly (Dawkins, Sartori, & Knapp, 2012; Sirianni, 2007). Local governments in the US are usually sovereign over land use planning and their priorities and politics may differ from regional priorities. In particular, existing neighborhoods may oppose proposed infill development and densification as a threat to their quality of life, a phenomenon often referred to as "Not In My Back Yard" or NIMBY-ism (Sirianni, 2007).

The difficulty of promoting land use change is so great that the planning profession has largely accepted that the preservation of existing single family neighborhoods is a legitimate planning priority in most of the US. Perhaps this reflects the political realities that residents of high-value single family areas tend to be politically powerful and well-connected and therefore the areas where they live are not a (politically) feasible target for planning major land use change. However planners should be aware that accessibility is a scarce resource, and therefore locking that resource up in large areas of single family housing may create a system of injustice – whereby lower income workers must travel significant distances to reach affordable housing and spend a disproportionate share of their incomes on travel costs. In many ways the status quo in planning comes with a substantial, if hidden, costs on lower-income working populations.

Planners have in select circumstances made some progress in getting neighborhoods to accept their fair share of new development and housing. During the 1990's, the City of Seattle developed an intensive and collaborative neighborhood-oriented planning process which allowed local constituents to have as significant say over where and how infill development would take place (Sirianni, 2007). An important part of this collaborative planning process was mutual accountability between neighborhoods and city government – neither party had complete control over outcomes, and both had to fulfill obligations towards each other for the completion of a successful neighborhood plan. The success of neighborhood planning in this instance illustrates that planning for infill development is possible where sufficient collaborative planning capacity is in place and is nurtured carefully. In Seattle, the capacity for neighborhood planning was carefully built up over time to allow for long-term relationships between city planners and neighborhood stakeholders. Perhaps the conclusion of research such as Sirianni's (2007) is that infill development is possible in the US, but only where there is adequate patience and planning capacity to engage in the detailed process of planning for infill with neighborhoods as equal partners.

5.3.c Implications for Planning Research

With regard to planning research, each of these research papers has quite distinct implications. *Measuring Complete Communities* highlights the importance of examining intermediate-scale urban form more closely. The planning research community has spent a great deal of time on measuring and evaluating the effects of neighborhood-scale urban form, but most household activity, including most nonwork activity, ranges beyond the neighborhood. The idea of complete communities, designed at a somewhat larger scale than the neighborhood, is one that merits further investigation from a number of perspectives.

The second paper, *Does Accessibility Influence Nonwork Activity Participation*, arrives at surprising results about the sensitivity of nonwork travel demand with respect to urban form; this paper suggests that the number of trips households take may be fairly elastic with respect to the influence of the built environment. Based upon these results, there should be more research into the question of whether or not accessibility influences the amount of travel people engage in. Better measures and better research designs could shed additional light on this important question, which had long been viewed as settled.

The third paper, *Changing Accessibility in US Metropolitan Areas*, perhaps introduces the most new research questions. In retrospect, it appears that this research took place during a period of flat or declining travel demand, 2000-2010. The uniqueness of this time period means that the external validity of this research with regard to other time periods is in question. Therefore it would be interesting to investigate how accessibility changed in major metropolitan areas before this era, and to think about how it might change in the future. My expectation is that with the rapid rises in VMT in the pre-2000 period, congestion increased and proximity decreased across a wide range of growing metropolitan areas. With regard to the future, continued sprawl and limited new investment in transportation infrastructure make this a likely future forecast as well; research could investigate the future of metropolitan accessibility through scenario analysis based on an extrapolations of current trends. Furthermore, applying the same methodological approach of this paper to earlier periods and to more diverse metropolitan geographies seems warranted.

A related research question that is suggested by the *Changing Metropolitan Accessibility* paper is: What does it take to shift development patterns towards high accessibility areas? Are there specific policies which have been successful in fostering this shift? What are the most significant obstacles to the densification of high accessibility areas, and can they be effectively addressed? Some of these questions are answered in brief above (*Section 5.3.b*), but the question of what it takes to break through these barriers merits further research.

5.3.d Additional Research Inquiries into the Value Accessibility

There are strong theoretical and empirical reasons for thinking that accessibility is a useful performance measure for the evaluation of the integrated urban form-transportation system. However there is little research to date about the value of accessibility at the margin. The precise benefits of accessibility at the scale of the metropolitan region or at the scale of the individual households are poorly understood.

How much does increased accessibility lead to increased regional economic productivity? Theoretically accessibility should be a better measure than density for explaining economic productivity. But the key question is what accessibility measures are most appropriate for understanding agglomeration economies. What accessibility measures offer the best explanation for variations in economic productivity across urban regions, and what other variables should be controlled for in such an analysis?

How much does a marginal increase in accessibility benefit a particular individual or household? Does it decrease their travel time or costs significantly? Does it increase their range of choices, and if so, how should this benefit be measured? Perhaps above some threshold level of accessibility, additional increases in accessibility provide little marginal benefit. With currently high levels of auto-based mobility in the US, it is not clear that increasing general accessibility to employment would provide significant marginal benefits to households. What types of accessibility are of the highest value (work, nonwork, food, recreation, open space?), and how is this reflected in travel behavior?

Are there some populations, or some types of destinations, wherein accessibility improvements are especially valuable? Perhaps for much of the population the marginal benefit of increased accessibility is small, but for disadvantaged populations increased accessibility could result in improved employment opportunities and health outcomes. How much does equity matter in accessibility? Defining the benefits of accessibility more precisely is an area that merits additional research attention.

APPENDIX I – Coefficients for Categorical Built Environment Variables

Table 6-1: Influence of Categorical Built Environment Variables on Individual Activity Episodes, Zero Vehicle Households

Residential Density in Census Tract	Equation 1	Equation 2	Equation 3	Equation 4
300	0.248**			
750	0.332***			
1500	0.385***			
3000	0.492***			
7000	0.496***			
17000	0.317**			
30000	0.701***			
Employment Density in Census Tract				
75		-0.256**		
150		0.467***		
350		0.378***		
750		0.264**		
1500		0.334***		
3000		0.503***		
5000		0.428***		
Urban Area Size				
50,000-199,999			0.398***	
200,000-499,999			0.352***	
500,000-999,999			0.395***	
1,000,000 +			0.183***	
Metro Area Size				
<250,000				0.479***
250,000-499,999				0.236***
500,000-999,999				0.507***
1-3 million				0.288***
3 million +				0.142**
Travel Day				
Tuesday	-0.231***	-0.284***	-0.281***	-0.257***
Wednesday	-0.041	-0.057	-0.054	-0.035
Thursday	-0.15	-0.185**	-0.188**	-0.174**
Friday	-0.065	-0.095	-0.106	-0.092
Saturday	-0.044	-0.104	-0.085	-0.06
Sunday	-0.05	-0.105	-0.106	-0.075
Reported Income?	-0.346***	-0.355***	-0.359***	-0.341***
Adult Workers	0.316***	0.297***	0.304***	0.307***
Adult Non-Workers	0.34***	0.329***	0.32***	0.333***
Children	0.131**	0.105*	0.12**	0.129**
Income	0.02***	0.024***	0.026***	0.026***
Median Age of Adults	-0.011***	-0.011***	-0.011***	-0.011***
Percent Female	0.05	0.059	0.054	0.043
Drivers	0.332***	0.351***	0.347***	0.337***
Drove to Work Today	-0.064	-0.123	-0.134	-0.117
Adults Worked Today	-0.12	-0.103	-0.127*	-0.125*
Average Time Adults Worked Today	-0.001***	-0.001***	-0.001***	-0.001***
Married?	0.149	0.118	0.138	0.143
Related Adults Present	0.032	0.053	0.079	0.058
Unrelated Adults Present	0.13*	0.187**	0.16**	0.143*
Youngest Child Present				
Age 0-5	-0.274	-0.266	-0.344**	-0.365*
Age 6-15	0.373***	0.441***	0.394***	0.367***
Age 16-21	0.036	0.02	0.074	0.052
Rail present in Metro	0.073	0.123	0.229**	0.322***
Constant	0.056	0.067	0.169	0.140

*Tables 6-1 – 6-3: Coefficients from negative binomial regressions with clustered standard errors at the core based statistical area. *** = 1% statistical significance. ** 5%. * 10%.*

Table 6-2: Influence of Categorical Built Environment Variables on Individual Activity Episodes, Limited Vehicle Households

Residential Density in Census Tract				
300	0.154***			
750	0.007			
1500	0.1			
3000	0.074			
7000	-0.019			
17000	-0.052			
30000	0.131			
Employment Density in Census Tract				
75		0.099		
150		0.107*		
350		-0.003		
750		0.015		
1500		0.043		
3000		0.061		
5000		0.062		
Urban Area Size				
50,000-199,999			0.035	
200,000-499,999			0.007	
500,000-999,999			0.169**	
1,000,000 +			-0.095	
Metro Area Size				
<250,000				0.126***
250,000-499,999				-0.081***
500,000-999,999				0.269***
1-3 million				-0.073
3 million +				-0.183**
Travel Day				
Tuesday	0.023	0.017	0.015	0.01
Wednesday	0.094	0.093	0.091	0.1
Thursday	0.118	0.119	0.124	0.11
Friday	-0.012	-0.008	0	0
Saturday	0.072	0.084	0.088	0.088
Sunday	0.155	0.146	0.136	0.14
Reported Income?	0.037	0.057	0.057	0.067
Adult Workers	0.417***	0.427***	0.425***	0.409***
Adult Non-Workers	0.402***	0.412***	0.407***	0.389***
Children	0.192	0.195*	0.188	0.197
Income	0.031***	0.031***	0.033***	0.034***
Median Age of Adults	-0.005***	-0.004***	-0.004**	-0.003*
Percent Female	-0.072	-0.073	-0.101	-0.098
Drivers	-0.232**	-0.223**	-0.213*	-0.199*
Drove to Work Today	-0.046	-0.041	-0.051	-0.05
Adults Worked Today	-0.005	-0.032	-0.023	-0.027
Average Time Adults Worked Today	-0.001***	-0.001***	-0.001***	-0.001***
Married?	-0.379**	-0.393**	-0.42***	-0.429***
Related Adults Present	-0.369*	-0.392*	-0.405**	-0.382*
Unrelated Adults Present	-0.467***	-0.453***	-0.415***	-0.39***
Youngest Child Present	0	0	0	
Age 0-5	-0.198	-0.16	-0.102	-0.09
Age 6-15	-0.088	-0.089	-0.072	-0.07
Age 16-21	-0.168*	-0.166*	-0.179*	-0.14
Rail present in Metro	0.001	-0.021	0.064	0.159
Constant	1.483***	1.458***	1.528***	1.476***

*Tables 6-1 – 6-3: Coefficients from negative binomial regressions with clustered standard errors at the core based statistical area. *** = 1% statistical significance. ** 5%. * 10%.*

Table 6-3: Influence of Categorical Built Environment Variables on Individual Activity Episodes, Full Vehicle Households

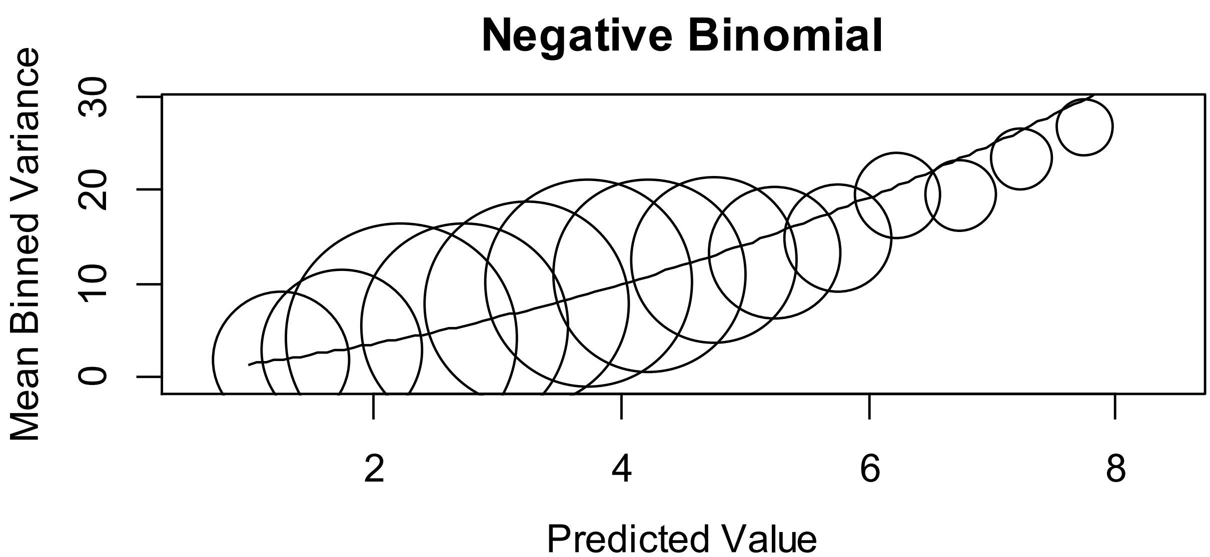
Residential Density in Census Tract				
300	0.048***			
750	0.082***			
1500	0.06***			
3000	0.063***			
7000	0.049			
17000	-0.028			
30000	0.259***			
Employment Density in Census Tract				
75		0.025		
150		0.048**		
350		0.031*		
750		0.035*		
1500		0.075***		
3000		0.095***		
5000		0.06*		
Urban Area Size				
50,000-199,999			0.043***	
200,000-499,999			0.074***	
500,000-999,999			0.028	
1,000,000 +			0.006	
Metro Area Size				
<250,000				0.033***
250,000-499,999				-0.01***
500,000-999,999				0.044***
1-3 million				-0.03*
3 million +				-0.031
Travel Day				
Tuesday	0.143***	0.143***	0.141***	0.141***
Wednesday	0.193***	0.195***	0.194***	0.193***
Thursday	0.191***	0.192***	0.19***	0.189***
Friday	0.19***	0.191***	0.19***	0.19***
Saturday	0.302***	0.304***	0.301***	0.301***
Sunday	0.288***	0.287***	0.287***	0.286***
Reported Income?	-0.182***	-0.181***	-0.179***	-0.178***
Adult Workers	0.125***	0.124***	0.13***	0.131***
Adult Non-Workers	0.111***	0.108***	0.114***	0.117***
Children	0.196***	0.196***	0.197***	0.198***
Income	0.022***	0.022***	0.023***	0.023***
Median Age of Adults	-0.004***	-0.003***	-0.004***	-0.004***
Percent Female	0.019	0.019	0.02	0.021
Drivers	0.256***	0.256***	0.25***	0.247***
Drove to Work Today	0.044*	0.043*	0.045*	0.045*
Adults Worked Today	-0.106***	-0.106***	-0.107***	-0.107***
Average Time Adults Worked Today	-0.001***	-0.001***	-0.001***	-0.001***
Married?	0.182***	0.185***	0.178***	0.173***
Related Adults Present	0.175***	0.177***	0.176***	0.174***
Unrelated Adults Present	0.102**	0.099**	0.096**	0.102**
Youngest Child Present				
Age 0-5	-0.02	-0.016	-0.02	-0.017
Age 6-15	0.116**	0.119**	0.115**	0.115**
Age 16-21	0.068***	0.071***	0.067***	0.064***
Rail present in Metro	-0.048**	-0.052***	-0.031	-0.01
Constant	0.299***	0.294***	0.318***	0.337***

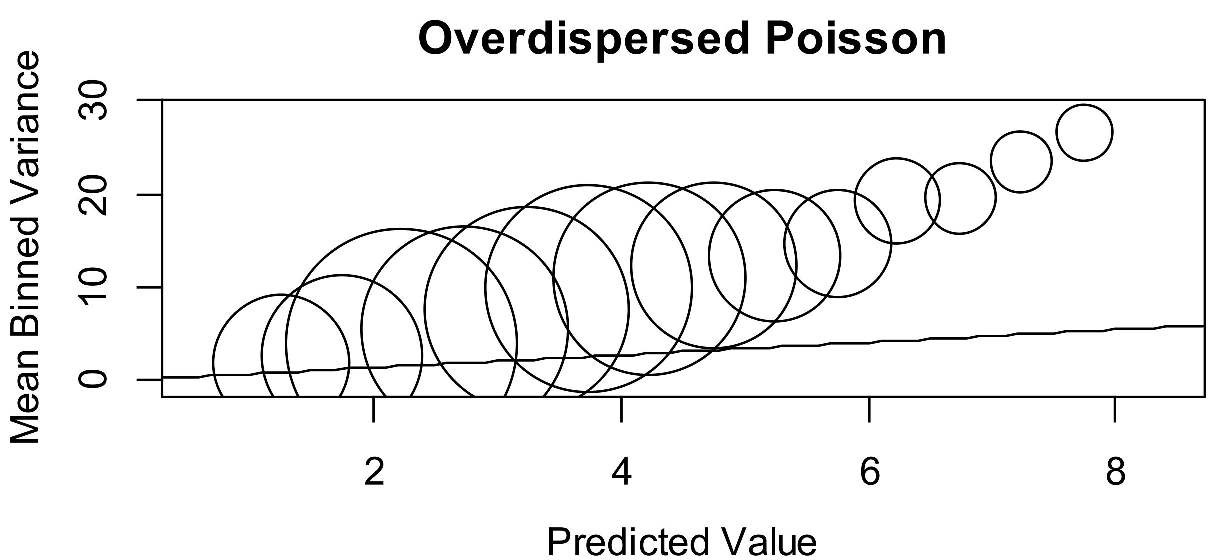
*Tables 6-1 – 6-3: Coefficients from negative binomial regressions with clustered standard errors at the core based statistical area. *** = 1% statistical significance. ** 5%. * 10%.*

APPENDIX II – Negative Binomial vs. Quasi-Poisson Model

Using all households, I examined binned mean vs. variance plots for Negative Binomial and Quasi-Poisson models of nonwork individual activity episodes (See below). The estimated dispersion from the Negative Binomial fits the actual pattern of dispersion better than estimates from the Quasi-Poisson. In general, the Negative Binomial is better suited for situations where dispersion has an approximately second-degree relationship with the predicted mean; whereas the Quasi-Poisson is better suited where there is a first-degree relationship (Hoef & Boveng, 2007).

Figure 7-1: Estimated Dispersion compared to Mean (x-axis) vs. Variance (y-axis) Bubble Plots





Models predict total nonwork Individual Activity Episodes for households. Control variables include number of household vehicles, day of the week, reported household income (Y/N), number of adult workers in household, number of nonworking adults in household, number of children in household, household income, percent of adults female, number of drivers in household, median age of adults, number of people who worked on travel day, number of people who drove to work on travel day, average time spent at work or school for adults, presence of married adults, presence of related adults, presence of unrelated adults, and age of youngest child.

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