Dissertation Topic Proposal

Walking to the Station: The Effects of Urban Form on Walkability and Transit Ridership

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INTRODUCTION

The proposed research addresses the impacts of urban form on transit ridership, in general, and the relationship between public transportation and walking, in particular. Urban form is defined in terms of three core dimensions: densities, land use patterns, and street networks. Existing literature suggests that population, employment and development densities (Holtzclaw 1994; Quade and Douglas Inc. 1996b; Cervero 1996); number of non-residential destinations and the mix of land uses (Cervero 2002; Kockelman 1997); density of street networks (Moudon et al. 2006; Handy 1996); and attitudinal factors (Kitamura et al. 1997; Krizek 2000) support walking and contribute to transit ridership.

The aim of the thesis is to contribute to a clearer understanding of the many ways in which urban form affects the decision to use public transportation and to walk to/from station after controlling for a multitude of factors, such as density, land-use mix, household income, car ownership, and the effect of walking distance from transit station. The underlying hypothesis being tested is that environments that are connected so as to support different kinds of walking also support public transportation. The focus is specifically on the relationship between public transportation and walking.

This study builds on the existing literature by investigating to what extent local conditions of station environments contribute to an explanation of variations in ridership rates and in transit-access modes of walking. The thesis aims to extend past studies in several fronts. Firstly, this study expresses walking as a proportion of total ridership. The goal is to reveal the urban form correlates of this relationship and the degree to which local pedestrian culture is receptive to changes in urban form. Secondly, by gauging the link between urban form and distances walked to/from the station, this study aims to determine the primary factors that can aid in extending acceptable walking distances. The findings of this analysis can provide researchers and planners with specific tools to design urban environments that would induce riders to walk more often and for greater distances. Clearly, this has implications for concomitant positive health effects on travelers as well as transportation benefits. Thirdly, this thesis explores the association of walking distances with the proportion of walking and ridership. The underlying objective is to develop a typology of urban conditions and cultures around transit stations in the city of Atlanta in order to identify how stations may contribute to culture of walking. Differences in travel patterns among urban areas may have implications for shaping policy on public health and environmental welfare as well as transportation.

SIGNIFICANCE OF RESEARCH

The aim of many recent planning investments is to reduce automobile dependence and induce non-auto commuting by implementing various urban design principles along with the ideals of New Urbanism and smart growth in re-shaping the urban form. How can urban form support pedestrian and transit-friendly development? What are the determinants of the link between urban form and non-motorized travel, namely walking and transit usage? Specifically, which urban form characteristics have a more explanatory power in revealing this relationship? These motivating questions have given rise to numerous studies on how design of built environment can change travel behavior by shaping urban form. To date, studies of built environment's impact on individual travel behavior have focused on land use mixes and densities, yet there has been relatively little research on the explicit role of street layout.

Existing measures of street connectivity, such as the density of street intersections per area (Lee and Moudon, 2006; Kerr et al. 2007; Frank et al. 2005), block size per area (Hess et al. 1999; Krizek 2000), cul-de-sacs per road mile (Handy 1996), and the links-nodes ratio (APA 2006), describe the average properties of street systems, but they fall short in capturing the variations in spatial structure of urban areas. Pedestrian Route Directness, which measures the ratio between a chosen pedestrian route distance and the 'crow-fly' distance to a particular destination (Lee and Moudon 2006; Hess 1997; Randall and Baetz 2001), as well as comparative typological schemes of layout patterns (Southworth and Owens 1993; Crane and Crepeau 1998) are used to describe the structural differences in street networks. Thus, rich descriptions of street networks may reveal insights into pedestrian movement, transit patronage, and land use compositions as impacted by those activities.

The assumption that the ordering of connectivity, or the spatial structure of an area plays an important role in movement is based on research findings in spatial cognition which suggest that direction changes, as an aspect of configuration, are related with the cognitive effort required to navigate through an area (Baileson et al. 2000; Crowe et al. 2000; Jansen-Osman and Widenbauer 2004; Hillier and Iida 2005; Montello 1991; Sadalla and Magel 1980). Since most transit trips involve some degree of pedestrian movement, understanding the ways in which people move through and conceive street networks is useful to planners and architects. Hence, this study concerns itself with both potentiality (density of streets) and structure (directional bias based on configuration). Connectivity measures applied in this research (Peponis et al. 2008) offer a systematic framework through which to evaluate the urban fabric in terms of its potentiality and structure. The analysis is based on standard GIS-based representations of street networks according to street center-lines. The unit of analysis is the road segment. Road segments extend between choice nodes, or street intersections at which movement can proceed in two or more alternative directions. Road segments may contain one or more line segments. A line segment is the basic unit of the map drawn and is always defined as a single straight line. Thus, the analysis treats the unit of analysis (the road segment, for which the individual values are computed) and the unit of computation (the line segment which provides the base metric for values) as different entities. Figure 1 illustrates the new unit of analysis by clarifying the difference between road segments and line segments.

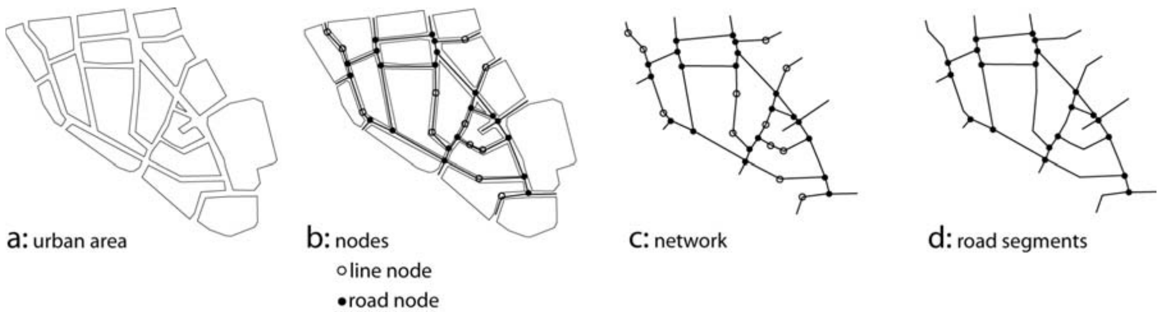

Figure 1. Definition of line segments and road segments.
Source: Peponis et al. 2008.

Analysis is based on finding the subset of street center-lines and parts of lines that can be reached subject to some limitation. When the limitation is metric distance, the total length of street reached is called metric reach, R_v, and the set of segments S_v. The average metric reach of an area is collinear with but not equivalent to number of intersections per area or the average distance between intersections. When the limitation is a number of permissible direction changes, the total length of streets reached is called directional reach, R_u, and the set of street segments S_u. When combined metric and direction-change thresholds are applied, the total length of street reached is called Metric-Directional Reach, R_w, and the set of street segments S_w. Figure 2 illustrates the new measures and analysis.

Since the analysis is based on GIS-based representation of street networks, it allows for the analysis of large commonly accessible data bases, including the street networks of US metropolitan areas. Accordingly the new measures express the density of street connectivity directly. Here the term density refers to the amount of street which is available within a given metric range. The values can be assigned to individual road segments so that spatial urban structures can be differentiated by streets, block faces or parts of block faces. Thus, they offer a systematic discrimination of urban conditions throughout the network, describing both the internal spatial structure of urban areas and their average properties.

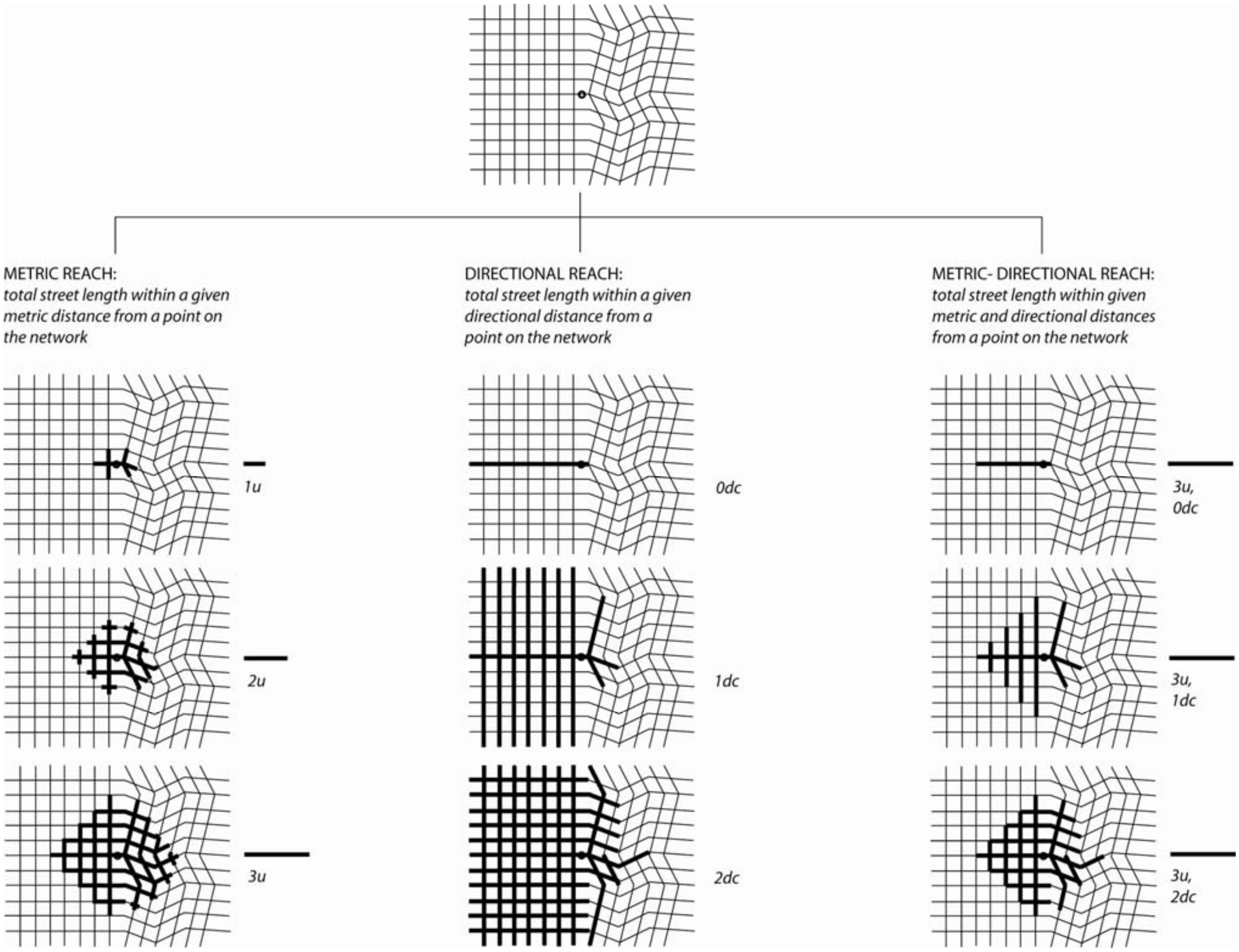

Figure 2. Diagrammatic definition of GIS-based connectivity measures.
Source: Peponis et al. 2008.

Street connectivity, as discussed above, is the interface between design and planning variables. It is related to land use and population density (Peponis et al. 2007) and movement patterns (Ozbil and Peponis 2007) as well as to architecturally significant factors such as block size and intersection distances. Architectural research has shown that urban liveliness is a function of street connectivity (Hillier et al. 1993). By better understanding the effect of street connectivity upon transit use, we can better integrate the knowledge base that informs not only planning but also architectural design. This link becomes even more important if we are to develop more sustainable cities. Also, it can contribute to an understanding of the ways in which transit systems can become integrated within urban culture. Implementation of these new measures will help define more clearly how connectivity encourages walking and thus supports transit shares.

RESEARCH BACKGROUND

Empirical literature dealing with how urban form can influence travel behavior has been framed around three attributes of built environment: *density, land use* and *design of street network*. Figures 3 to 5 summarize the findings of previous research regarding the causal links between urban form and ridership. (For a more detailed discussion, please see Appendix 1.) In spite of the plethora of studies on the influences of land use and density on transit use, no conclusions emerge on the relationships between street networks and travel. A limitation of these studies is the difficulty to develop well-specified statistical models that allow researchers to accurately evaluate the individual magnitude and importance of street structure. Part of the reason is due to collinearity between urban conditions. Fairly compact neighborhoods in US cities generally have more varied land-uses, on average shorter block lengths with more grid-like street patterns. Another drawback of existing measures of connectivity is that they only describe the average properties of street networks, failing to discriminate between the internal differentiation of spatial structure. Thus, the effect of street network design on overall travel remains unclear. Robust and universally acceptable connectivity measures of GIS-based representation can provide alternative means to quantify urban systems. They capture both the interaction between street connectivity and land-uses, and the relational properties of urban network. In addition, since the new measures reflect already relativized values of street connectivity within the entire system of connections, they discard the hurdle of impacts of the surrounding regional circulation patterns on neighborhood-scale evaluations.

PRELIMINARY WORK :street connectivity and walking/ street connectivity and ridership

In my preliminary work I have shown that street connectivity affects the distribution of walking in an area (Ozbil and Peponis 2007; Ozbil, Peponis and Stone 2008). (A full range of multiple regressions for movement rates, measures of street connectivity and land use compositions is presented through Tables 1– 5 in Appendix 2.) In order to better understand how connectivity affects the decision to use pubic transportation controlling for a multitude of factors, I ran city-level analysis which examine the impact of street network connectivity on transit patronage (Ozbil, Peponis and Bafna 2009). To the extent that the results of this study hold more generally, I confirm the importance of including the density of street connections in transit-oriented studies. Results suggest that metric reach has significant impact on ridership levels jointly with population density and two attributes of transit service features. In particular, the estimates indicate that metric reach is a stronger predictor of transit use than station area population densities. (A full range of multiple regressions for measures of street connectivity,

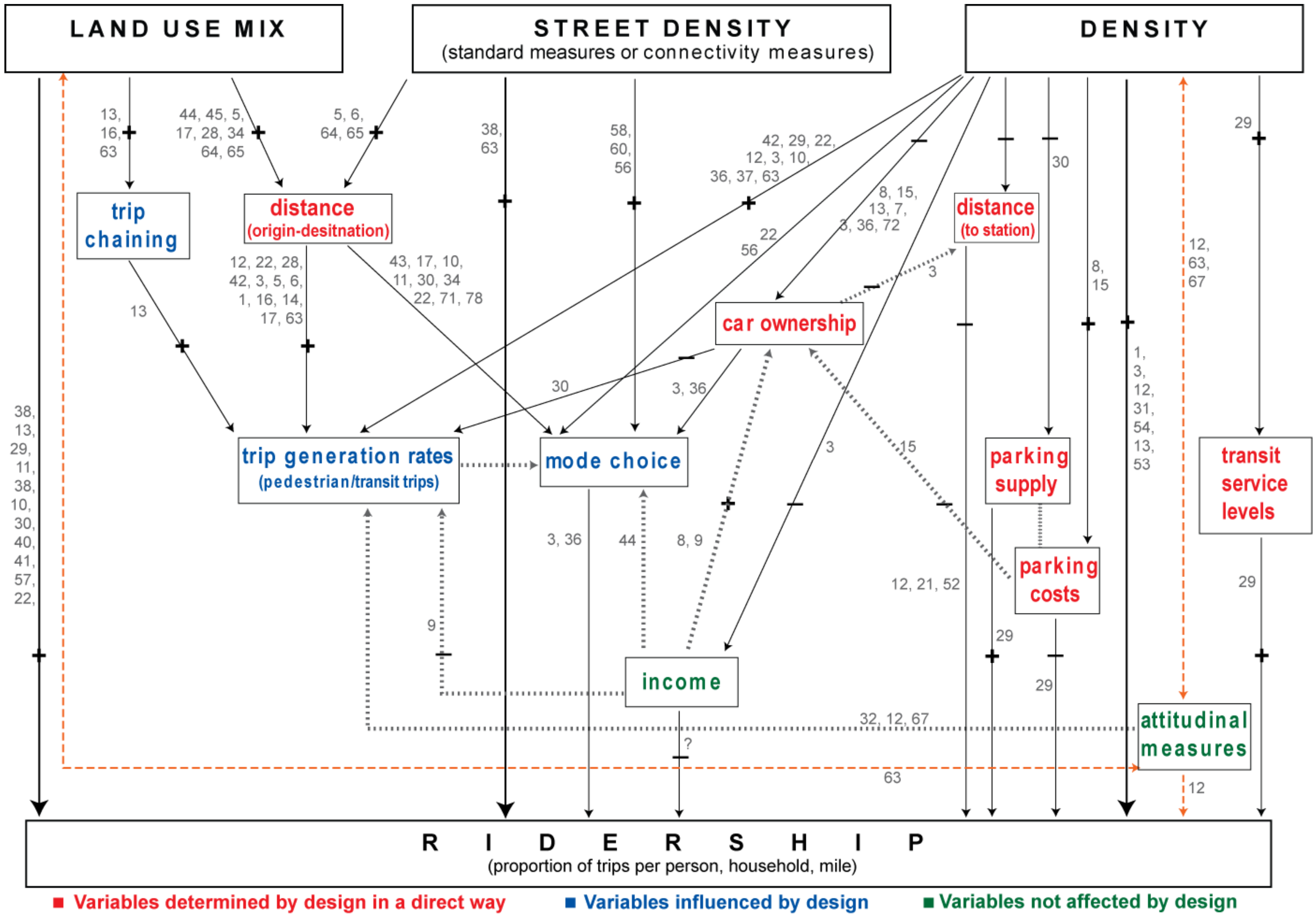

Figure 3. Summarized literature review illustrating 3 primary factors and multitude of variables affecting ridership as proportion of trips.
***** Please see figure references at the end of Appendix 1.

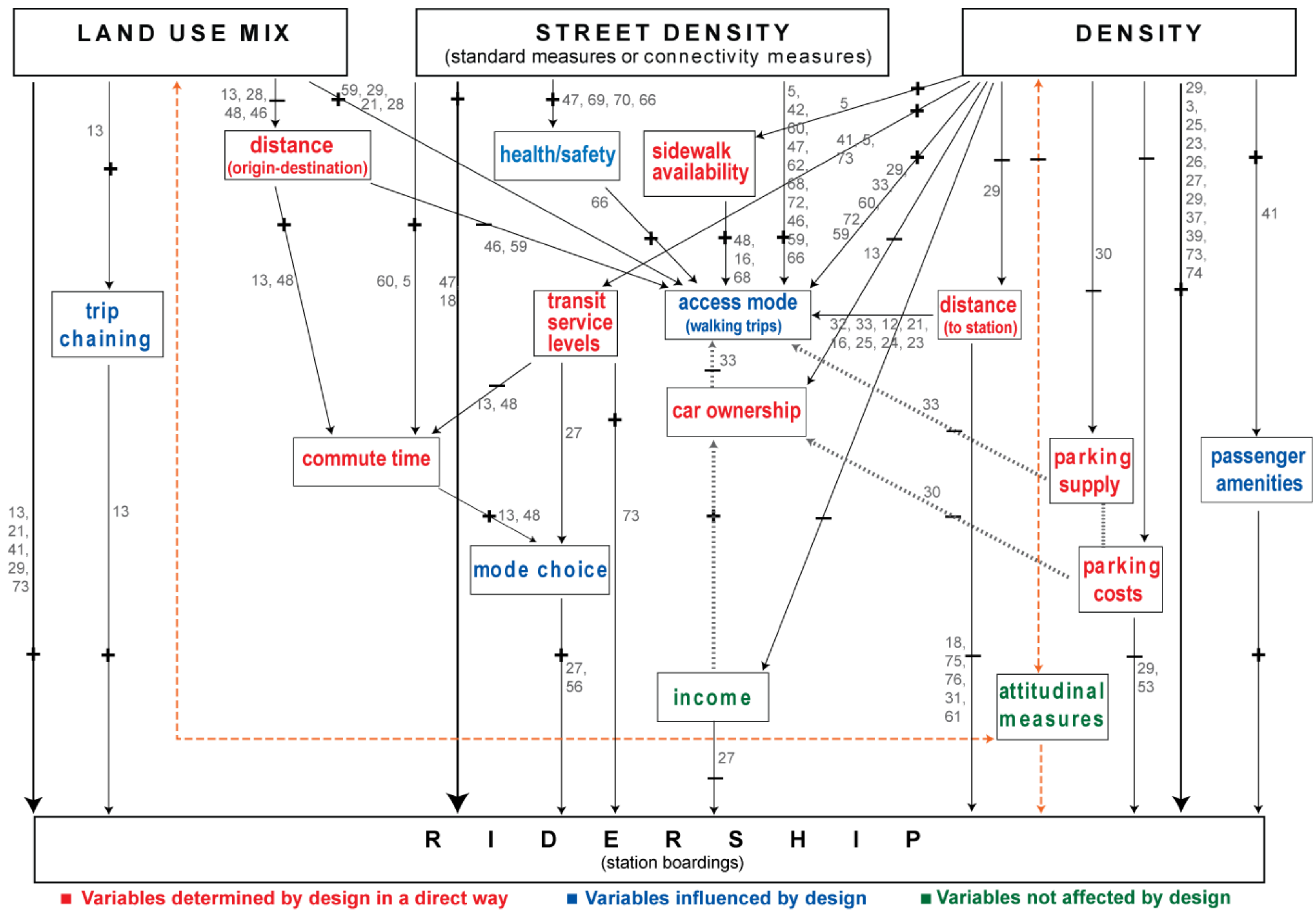

Figure 4. Summarized literature review illustrating 3 primary factors and multitude of variables affecting ridership as mere numbers

* Please see figure references at the end of Appendix 1.

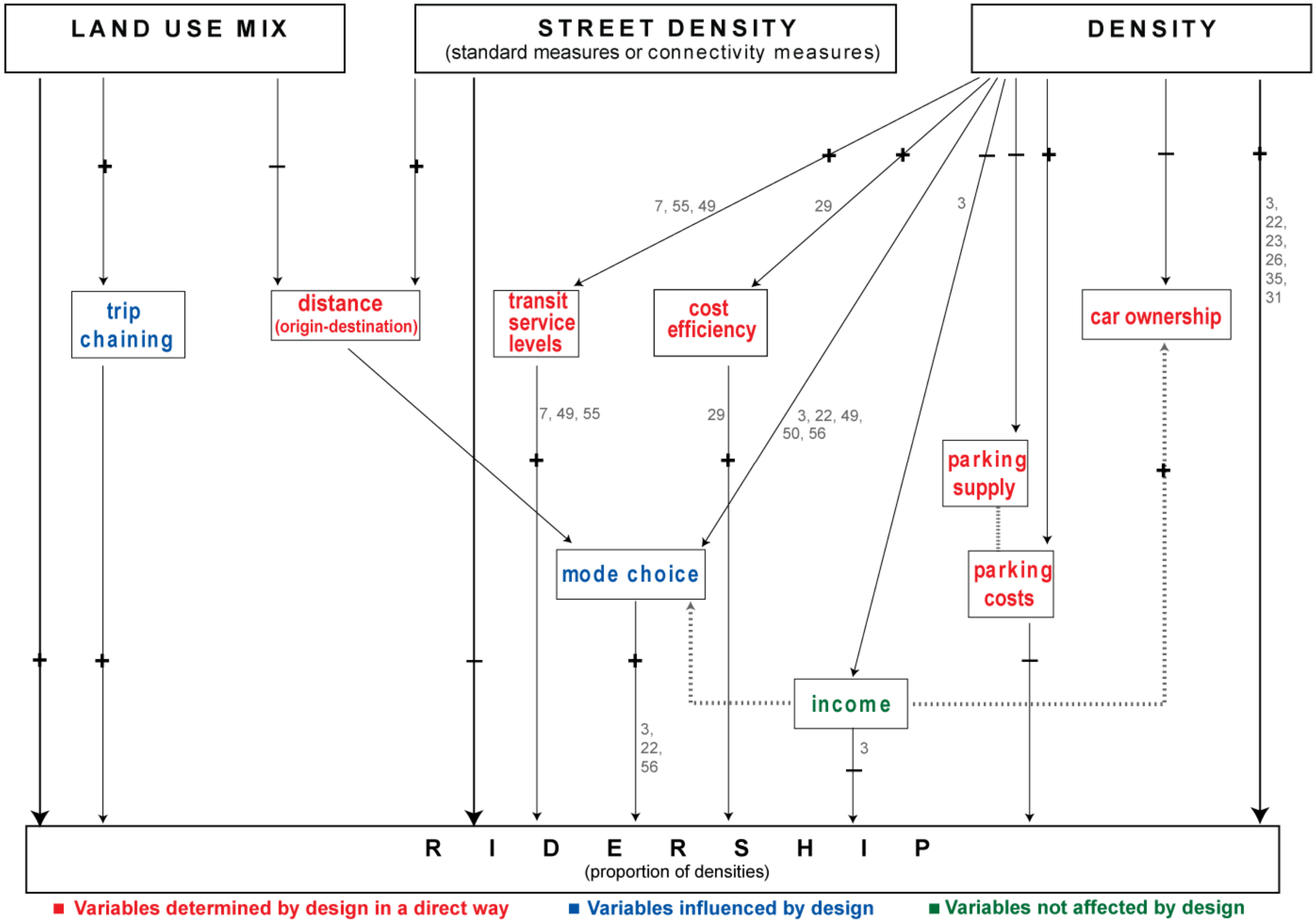

Figure 5. Summarized literature review illustrating 3 primary factors and multitude of variables affecting ridership as proportion of densities.
* Please see figure references at the end of Appendix 1.

land use compositions and socio-demographic variables is presented in Tables 6 – 7 and Figures 1–2 in Appendix 2). However; we note that these results, at this stage, largely confirm and complement existing models that have been reviewed above. Finer grain research, including parcel information on land use as well as field studies of pedestrian movement, are needed before design and planning decisions aimed at increasing the likelihood of transit usage through the creation of lively walkable environments around transit stations can be informed.

PROPOSED WORK : walkability as a function of ridership

The aim of the thesis is to explore the relationship between public transportation and walking by focusing on how urban form characteristics influence this link. Hence, by building on the above-discussed preliminary studies, I intend to conduct a fine-grained research on walkability as a function of transit ridership.

case context and data inputs

I will focus on City of Atlanta (Fulton and DeKalb counties) as a case context. The travel data are the 2001-2002 Atlanta Household Travel Survey developed jointly with Atlanta Regional Commission and NuStats. The sample includes 8,069 households in the 13 county area and contains information about work and non-work travel, trip generation, trip distribution, and modal choice as well as data on transit use, neighborhood preferences, health and activity over a 2-day travel period. This travel data is supplemented by the 2001-2002 Regional On-Board Transit Survey conducted among fixed route riders (of both bus and rail) of MARTA, CCT, Clayton County, and Gwinett County transit systems. The dataset contains 31,244 records providing origin-destination data, demographics (including household size and vehicle availability), access and egress modes, and public transit use.

study framework

I will try to address the link between public transportation and walking within the scaffold of 3 main questions. Below-diagrams (Figures 6-8) clarify the model frameworks proposed to address each question. The first question concerns itself with the proportion of riders choosing walk as access mode of transit and its association with the proportion of total ridership, defined as percentage of population density. The first part of the question will be studied using the Household Travel Survey as well as On-Board Transit Survey; the latter will be examined based on the Household Travel Survey if there are large samples available within the catchment areas of a sufficient number of stations and/or by combining these two datasets.

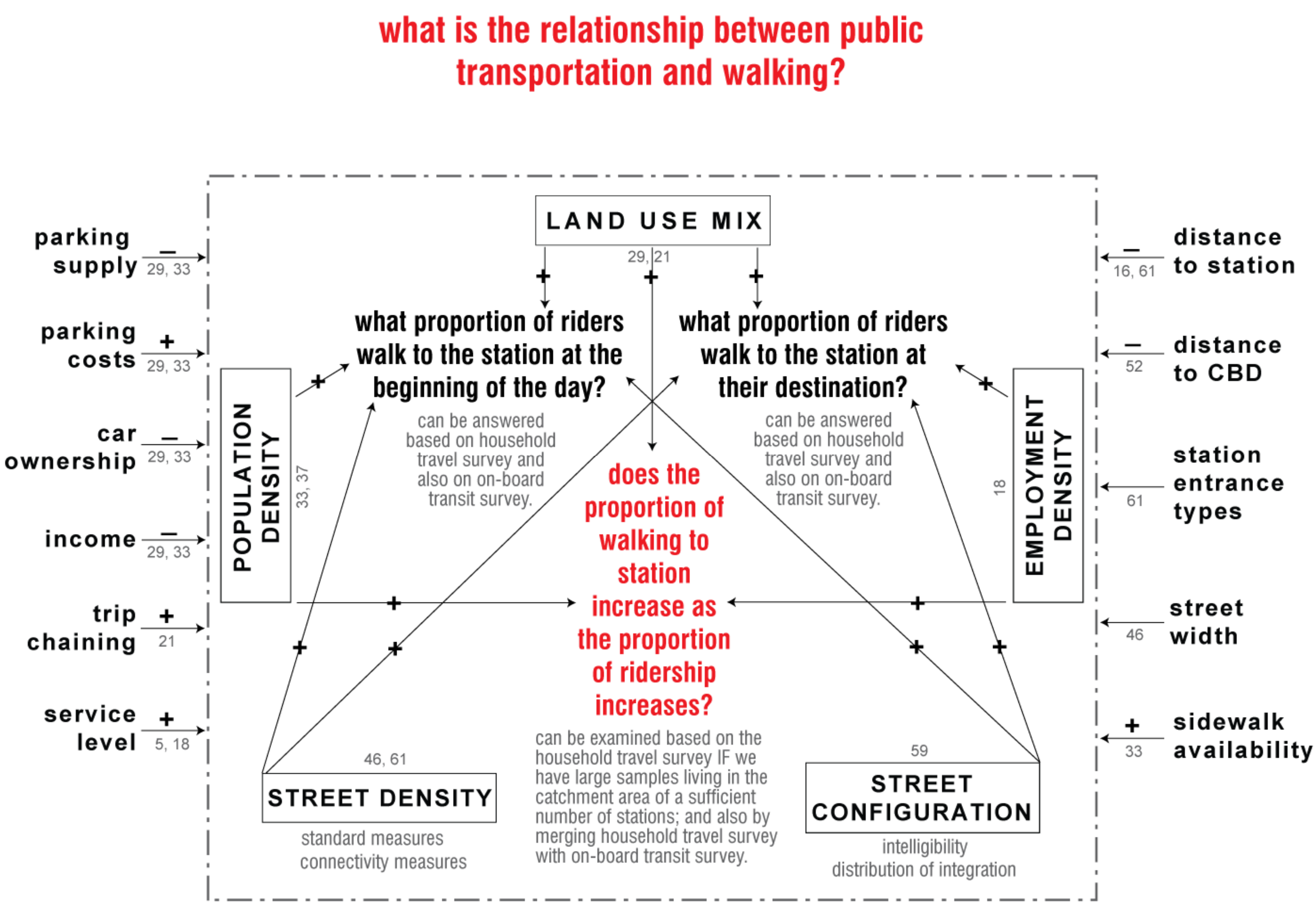

Figure 6. Proposed model framework for analyzing the relationship between proportion of walking as access mode and proportion of ridership.
* Please see figure references at the end of Appendix 1.

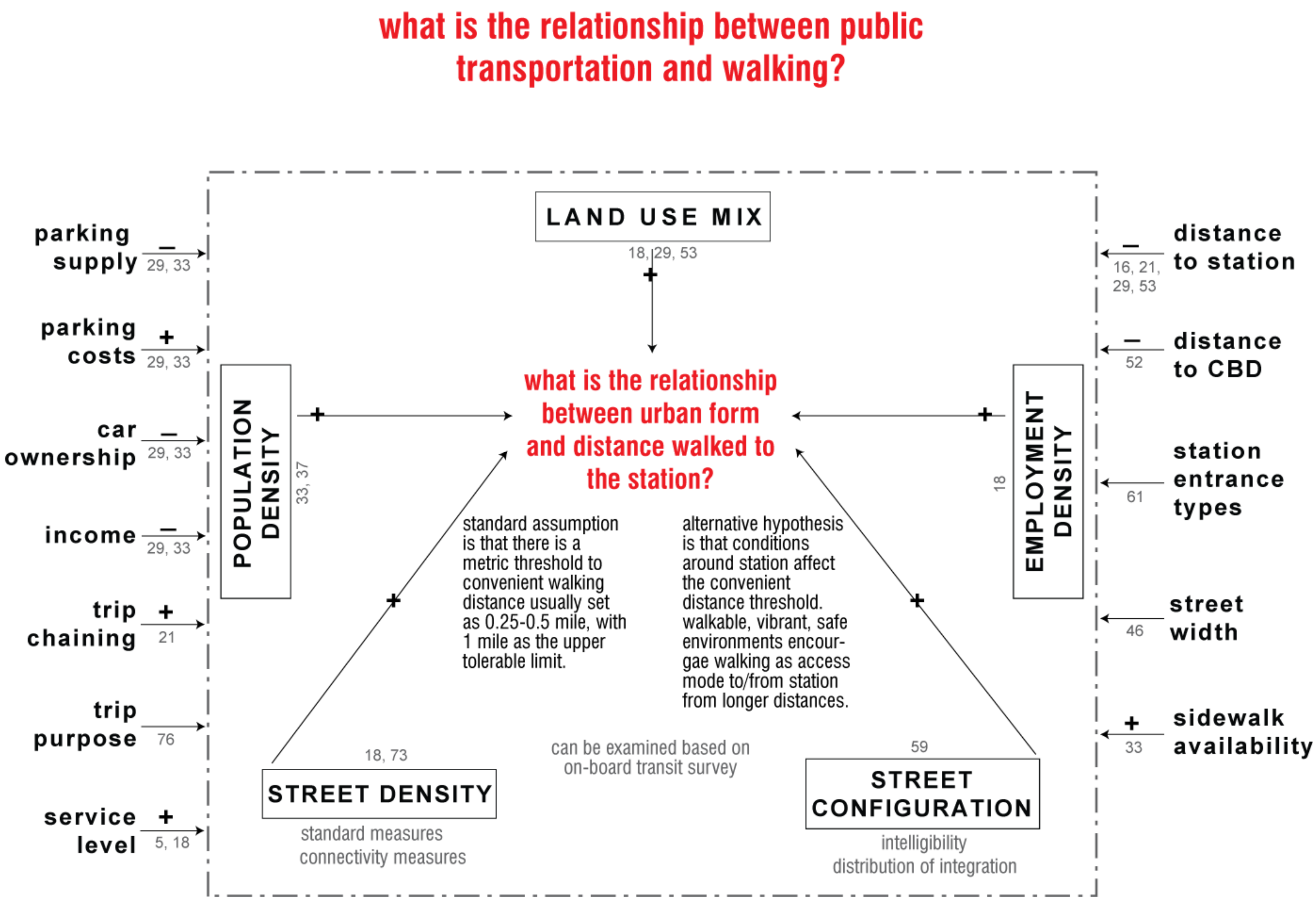

Figure 7. Proposed model framework for analyzing the relationship between urban form and distance walked to/from station.
* Please see figure references at the end of Appendix 1.

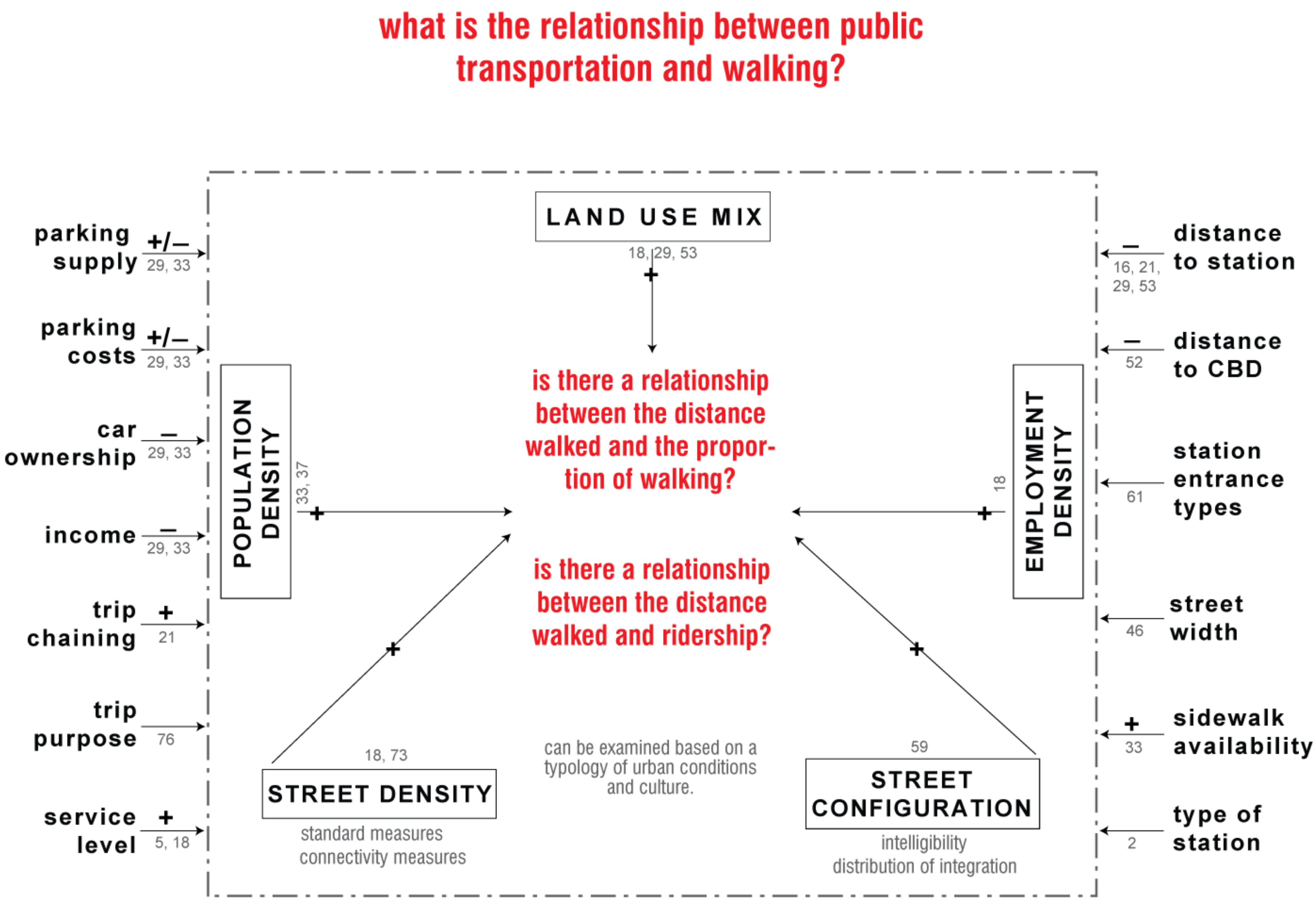

Figure 8. Proposed model framework for analyzing the relationship between distance walked and proportion of walking as well ridership.
* Please see figure references at the end of Appendix 1.

Multivariate and bivariate regression equations will be estimated within 0.25, 0.5, and 1 mile catchment areas around stations controlling for a multitude of factors, such as station-area densities[1], household income, housing densities[2], and transit service features like supply of park-and-ride facilities[3], service frequency[4], feeder bus services[5], and service potential[6]. Using currently available GIS-based land use compositions at the parcel level, I will use mixed-use entropy index[7] to measure the impact of land use mix around stations on ridership rates and walking levels. The aim is to develop comprehensive models which will specify the correlation between proportion of walking and proportion of ridership. Empirical research on access mode shares have estimated variation in walk mode share by station as a function of population density and proximity (Quade and Douglas Inc. 1996b; Cervero 1993a). This analysis seeks to extend past studies by considering walkability as a proportion of ridership, through a normative description of street network. Findings of this analysis are relevant in assessing the sensitivity of transit-access mode choices to changes in urban form.

The second question that this thesis addresses is related to the link between urban form and distance walked to/from the transit station. The volume of literature on how built environments influence ridership has concluded that pedestrian access gradient –how quickly walking mode shares fall off with walking distances to stations– is set at $^1/_3$ of a mile to a ¼ of a mile, with 1 mile being the upper limit (JHK and Associates 1987; Bernick and Cervero 1997; Stringham 1982). While several studies have examined the relationship between ridership elasticities and catchment areas around stations (Cervero 1993; Frank and Pivo 1994), research on whether and how the distance people are willing to walk can be increased has been very limited (Untermann 1984; Fruin 1992). This line of investigation requires that individual trips are categorized in terms of their specific purposes (shopping, work, recreational, etc.) since past studies have demonstrated systematic differences between distance-decay curves for different

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[1] Natural log of population and employment per gross acre within catchments of stations.
[2] Number of dwelling units per gross acre within catchment of stations.
[3] Natural log of number of station parking spaces
[4] Natural log of number of inbound trains in am peak hour (7am-9am)
[5] Natural log of feeder buses arriving at station (7am-9am)
[6] number of intersecting rail routes at each station
[7] $$Mixed-use\ entropy = -1 \times \left(\frac{\left(\sum_{i=1}^{k} p_i \times \ln(p_i) \right)}{\ln(k)} \right)$$

where: p_i = proportion land in use i of total of all land; and k = 6 categories of land use (single family housing units, multifamily housing units, basic commercial employment, service employment, industrial employment, public employment).

types of trips, suggesting that travelers perceive metric distance differently in different conditions (Hanson and Schwab 1995). More often than not, empirical literature has failed to account for the differentiation between metric distance and perceived distance (Handy 1996a), and the role of street configuration on distance walked. The underlying premise is that station-area characteristics affect convenient distance thresholds and that walkable environments encourage higher average walking distances by creating vibrant and safe urban conditions. This prospect of extending walking distances through design has significance beyond pedestrian concerns of mobility. Defining walkable urban conditions provides social benefits of interaction which likely affect personal health and activity issues. Consequently, extending acceptable walking distances to generate more walking trips represents a real economic benefit, measured in increased transit mode shares and reduced vehicle miles traveled.

The third question that this thesis aims to analyze is whether and to what extent there is a relationship between the distance walked and the proportion of walking and ridership. The hypothesis is that environments are not isotrophic. Some are more conducive to walking due to different density of interface generated by connectivity patterns and local spatial structure of street networks, as well as diverse land use patterns. The aim is to better understand how station-areas contribute to culture of walking, separating the influences of personal attributes from built environment on travel. The answer to this question has to encompass a typology of urban conditions and cultures (i.e. primacy of street versus primacy of privacy) around stations. This typology will include a standard classification of stations (i.e. high intensity urban node, mixed use regional node, neighborhood station) and their geographic locations (CBD, central city, edge city, suburb) as well as typologies of spatial structure of urban areas (i.e. sparse, linear integration core versus denser, grid-like integration core; well-distributed local integrators versus small hubs of high integrators). The results of this analysis can provide a useful basis for assessing the extent to which a policy aimed at increasing public transportation patronage and thus reducing energy consumption can also directly impact on health targets.

DISCUSSION

The aim of this thesis is to understand the impacts of urban form, in general, and street network, in particular, on transit patronage and to get a better grasp on the relationship between public transportation and walking through a fine-grained study at the neighborhood-scale. Findings of this research can address some of the subtleties and complexities embedded in travel decisions by distinguishing basic constraints and thresholds (i.e. what are the required residential density thresholds for a transit system to be viable?) from subtler affordances (i.e. which cultures produce a transit oriented propensity?). This thesis is built on the premise that local urban conditions affect not only transit riding and transit access walk mode shares but also the distance people are willing to walk to/from a station. Well structured and differentiated street networks can expand the catchment areas around stations by offering a variety of choices for meeting people's daily travel needs and creating more opportunities for shorter, purpose-driven walks. To this end, existing local urban conditions can inform cultural choices people make (pedestrian culture), which, in return, can support ridership.

Apart from theory building, this research can also hold validity for more practical implications. It can help policy makers to assess the likely impacts of transportation-related policies on environmental and health issues as well as travel. Such small-scale place-oriented policies can help to create energy efficient environments and overcome individual health issues related to low activity levels, such as obesity and cardiovascular problems. I envision that the findings of this research can aid in designing effective policies that would encourage new designs to provide the option to walk.

PROPOSED TIMELINE

May –June 2009	· analysis of question 1: the correlation between proportion of walking and proportion of ridership · preliminary literature review
July –September 2009	· analysis of question 2: the relationship between urban form and distance walked · critical review of the literature
October –January 2010	· analysis of question 3: the relationship between distance walked and proportion of ridership; the relationship between distance walked and proportion of ridership
February –March 2010	· preliminary draft completed · editing & image preparation
April 2010	· dissertation defense

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A P P E N D I X 1

Extended Summary of Knowledge

impacts of density on travel behavior

There is substantial amount of literature that has acknowledged *density* as a significant predictor of travel choice (Pushkarev and Zupan 1977; Smith 1984; Marshall and Grady 2005). A plethora of recent studies have suggested that compact developments with higher densities degenerate vehicle trips and encourage non-motorized travel by reducing the distance between origins and destinations; offering a wider variety of choices for commuting and a better quality of transit services; and by triggering changes in the overall travel pattern of households (Cervero and Kockelman 1997; Krizek 2003; Holtzclaw 1994; Ewing et al. 1994). Recent policy initiatives have focused on developing urban-form strategies with attempts to reduce auto-dependence rates by encouraging densification of development infrastructure (Washington State Growth Management Act 1990; Central Puget Sound Vision 2020).

In a study where they analyzed the variations in transit demand in Portland, Nelson and Nygaard (1995; 31) concluded that "…of 40 land-use and demographic variables studied, the most significant for determining transit demand are the overall housing density per acre and the overall employment density per acre. These two variables alone predict 93% of the variance in transit demand among different parts of the region". Similarly, Pushkarev and Zupan (1977) documented that residential densities in transit corridors, together with the size of downtown and distance of stations from downtown, explained demand for a variety of transit modes.

Data from a national sample showed that doubling of station-area residential densities yield in an increase in light-rail boardings of almost 60% (Badoe and Miller, 2000). Evaluating transit-oriented land use proposals for Charlotte, the San Francisco Bay Area, and south St. Louis County, Cervero (2006) found that the ridership-to-density elasticities (% increases in rail boardings as residential densities increase by 1%) were substantial in the estimate of ridership as a function of station environments. Cervero demonstrated that raising density within half-mile of a station by one dwelling unit per gross acre increased weekly boardings by nearly 1,100.

Studying how residential built environments around 27 rail stations in California influenced transit usage, Cervero (1993) found that station area residents are five to seven times more likely to travel by rail. Therefore, he concluded that neighborhood density and proximity are the primary factors influencing ridership. Some generalized conclusions that can be inferred from recent studies about pedestrian access to transit are that between a distance of 0.5 and 1.5 miles, the proportion of transit riders who walk to and from transit steadily decreases (Untermann 1984; Pettinga 1992).

However, others argue that residential density thresholds are interrelated with various factors such as cost and efficiency of transit service, and the supply and price of parking (Pushkarev and Zupan 1982; Institute of Transportation Engineers 1989). Analysis of the of 11 light rail and six commuter rail cities showed that a light rail station with parking has on average about 50 percent more boardings than a station without parking (TCRP Report #16 vol.1; 14). Thus, it seems imperative that conclusions regarding density should be considered in conjunction with service and parking efficiencies.

impacts of land use on travel behavior

Explanations regarding the measurable impact of *land-use characteristics* on pedestrian travel and how dense land-use patterns play a significant role in encouraging walks follow similar logics. That high density levels of mix-use and presence of retail activities near residences increase non-work trips and induce non-auto commuting (Cervero 1996; Holtzclaw 1994; Krizek 2003), and that increased levels of land-use mix at the trip origins and destinations yield in increase in walking (Frank and Pivo 1994; Cervero 1988). Upon examining residential, office and shopping developments located near five rail transit systems in California, Cervero (1993) concluded that concentrating a substantial amount of development within a quarter-mile radius of suburban rail stations acts as an inducement to transit riding. In his study, in which he analyzed travel data based on a 1991 diary-based travel survey in Palm Beach County, Ewing (1995) has concluded that development patterns had a significant impact on household travel behavior beyond their relationship with the other socio-demographic characteristics of households. Land-uses around stations represent origins and destinations, because most people walk to and from these stations. Boardings would naturally increase in areas where more people live or more activities attract people.

The general inferences that can be drawn from these studies are that the characteristics of areas around stations strongly influence the way in which patrons travel to and from transit. In employment centers mixed land use contributes to increasing levels of transit; while, in residential neighborhoods urban design that supports pedestrian movement influences the mode of access to transit. Pedestrian-friendly neighborhoods are claimed to be more congenial to transit use as well as to walking. The problem is that conclusions regarding the significance of density are limited in their scope since most of them are based on inferences drawn from single metropolitan areas. Including a relatively large database of US cities with varying urban form and non-urban form characteristics, the proposed research will arrive at reliable conclusions.

impacts of design of street network on travel behavior

Transportation and urban planners have focused on the *design of street networks*, discussing its strength as a determinant of walking. Various quantitative measures have been suggested by the urban-design literature to evaluate pedestrian accessibility and measure street connectivity. The distance between origins and destinations for walking and the total length of streets covering an area have been employed by some authors (Handy 1996; Aultman-Hall et al 1997) to describe how the character of streets differs at neighborhood and regional levels. Pedestrian Route Directness, which measures the ratio between a chosen pedestrian route distance and the 'crow-fly' distance to a particular destination, has been studied (Hess 1997; Randall and Baetz 2001) as an indicator of how accessible a neighborhood is to the pedestrians.

Some researchers have chosen to calculate the density and pattern of intersections, average block areas and block face lengths per unit area to capture the degree of network connectivity (Southworth and Owens 1993; Cervero and Kockelman 1997; Siksna 1997). Pertinent analysis has computed higher NA (neighborhood accessibility) levels for communities with higher street intersection densities or lower average block areas (Krizek 2000; Krizek 2003). It has been argued that large blocks, having fewer intersections, provide a scale consistent with the automobile (Jacobs 1985), and empirical research has demonstrated an inverse relationship between the size of blocks and the levels of pedestrian traffic (Hess et al 1999). A common theme of this body of research is that inordinate size of street blocks or the lack of a fine-grained urban network of densely interconnected streets fails to promote walking (Ewing et al 2003; Hess et al 1999).

However; most studies report no significant relationships between travel and network design. A California Air Resources Board study (Kitamura et al. 1994), which involved the examination of travel behavior in 5 selected neighborhoods in the San Francisco Bay Area, concluded that specific individual street design characteristics (i.e. sidewalk width, intersection characteristics) and neighborhood characteristics may not be significant at every site and location in influencing transit use. Thus, the effect of street network design on overall travel remains unclear.

Another limitation of these studies is the difficulty to develop well-specified statistical models that allow researchers to accurately evaluate the individual effect of street network. Part of the reason is due to collinearity between density, land use mix and urban form. For instance;

fairly compact neighborhoods in US cities generally have more varied land-uses, on average shorter block lengths with more grid-like street patterns. One facet underlying the weak explanatory power of built environment is the absence of rich land-use and urban design data. National censuses generally include travel data for large scale models at the tract level or block-group level. This is a significant barrier to carrying out small scale studies at the neighborhood level on how design of street network shapes non-motorized travel. Parcel-level or block-level land use compositions might help elucidate the different attributes of the urban network in explaining the distribution of pedestrian movement, and hence transit patronage.

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A P P E N D I X 2

Preliminary Work: street connectivity and walking

ALL AREAS

logTotal Moving/100m	+ Connectivity			+ Land Use(1)			+ Land Use(2)		
	B	t	std β	B	t	std β	B	t	std β
constant	-8.50	-6.34	0.00		-6.48			-6.40	
metric reach	0.30	**22.04**	0.87	0.29	**21.65**	0.85	0.29	**18.67**	0.84
directional distance for 1 mile metric reach	-0.33	*-2.21*	-0.11	-0.29	*-1.99*	-0.10	-0.28	*-1.97*	-0.10
directional reach for 0 direction change	0.38	1.15	0.07	0.31	0.96	0.05	0.34	1.01	0.06
directional reach for 2 direction changes	-0.01	-0.53	-0.03	0.00	-0.11	-0.01	0.00	-0.15	-0.01
directional distance for 2 direction changes	0.17	0.27	0.01	0.19	0.31	0.01	0.22	0.36	0.01
NRsqft/100m							0.00	**3.08**	0.11
Rsqft/100m							0.00	-0.12	-0.01
aggregatesqft/100m				0.00	**3.08**	0.11			
Overall Model		N= 158			N= 158			N= 158	
		R^2= 0.83			**R^2= 0.84**			**R^2= 0.84**	
		R^2adj= 0.82			**R_2adj= 0.83**			**R^2adj= 0.83**	

Note: Numbers in bold = p< 0.01; numbers in italics = p<0.05

Table 1. Multiple regressions for movement rates, measures of street connectivity, and land use compositions for Downtown, Midtown, and Virginia Highland.

DOWNTOWN

logTotal Moving/100m	+ Connectivity			+ Land Use(1)			+ Land Use(2)		
	B	t	std β	B	t	std β	B	t	std β
constant	-6.31	-1.07	0.00	-8.17	-1.41	0.00	-8.17	-1.41	0.00
metric reach	0.20	1.74	0.19	0.22	*1.97*	0.21	0.22	*1.97*	0.21
directional distance for 1 mile metric reach	-1.09	**-3.68**	-0.56	-0.95	**-3.22**	-0.49	-0.95	**-3.22**	-0.49
directional reach for 0 direction change	0.91	1.04	0.22	1.01	1.19	0.25	1.01	1.19	0.25
directional reach for 2 direction changes	-0.08	**-2.49**	-0.52	-0.08	**-2.58**	-0.52	-0.08	**-2.58**	-0.52
directional distance for 2 direction changes	3.17	*2.26*	0.33	3.37	**2.47**	0.36	3.37	**2.47**	0.36
NRsqft/100m							0.00	*2.05*	0.22
Rsqft/100m							.	.	.
aggregatesqft/100m				0.00	*2.05*	0.22			
Overall Model		N= 62			N= 62			N= 62	
		R^2= 0.36			**R^2= 0.40**			**R^2= 0.40**	
		R^2adj= 0.30			**R^2adj= 0.34**			**R^2adj= 0.34**	

Note: Numbers in bold = p< 0.01; numbers in italics = p<0.05

Table 2. Multiple regressions for movement rates, measures of street connectivity, and land use compositions for Downtown.

MIDTOWN

logTotal Moving/100m	+ Connectivity B	t	std β	+ Land Use(1) B	t	std β	+ Land Use(2) B	t	std β
constant		-2.66			-2.19			-1.64	
metric reach	0.01	0.19	0.03	0.01	0.15	0.02	-0.01	-0.26	-0.04
directional distance for 1 mile metric reach	1.28	1.60	0.30	1.56	*2.12*	0.37	1.86	**2.38**	0.44
directional reach for 0 direction change	0.59	1.66	0.28	0.11	0.30	0.05	0.26	0.68	0.12
directional reach for 2 direction changes	0.03	1.19	0.23	0.04	1.73	0.31	0.04	1.74	0.31
directional distance for 2 direction changes	8.64	**2.48**	0.46	6.04	1.84	0.32	4.66	1.33	0.25
NRsqft/100m							0.00	**3.02**	0.46
Rsqft/100m							0.00	-0.42	-0.07
aggregatesqft/100m				0.00	**2.95**	0.44			
Overall Model		N= 54			N= 54			N= 54	
		R^2= 0.28			**R^2= 0.42**			**R^2= 0.44**	
		R^2adj= 0.17			**R^2adj= 0.32**			**R^2adj= 0.32**	

Note: Numbers in bold = p< 0.01; numbers in italics = p<0.05

Table 3. Multiple regressions for movement rates, measures of street connectivity, and land use compositions for Midtown.

VIRGINIA HIGHLAND

logTotal Moving/100m	+ Connectivity			+ Land Use(1)			+ Land Use(2)		
	B	t	std β	B	t	std β	B	t	std β
constant		-2.26			-2.43			-2.50	
metric reach	0.22	**4.40**	0.54	0.22	**4.62**	0.55	0.20	**4.32**	0.51
directional distance for 1 mile metric reach	-0.24	-1.29	-0.22	-0.18	-1.04	-0.17	-0.15	-0.89	-0.14
directional reach for 0 direction change	0.99	1.34	0.23	0.71	0.98	0.17	1.10	1.50	0.26
directional reach for 2 direction changes	0.00	0.11	0.02	0.01	0.37	0.06	-0.01	-0.21	-0.04
directional distance for 2 direction changes	-1.11	-1.63	-0.19	-1.33	*-2.00*	-0.23	-1.00	-1.50	-0.17
NRsqft/100m							0.00	**2.92**	0.30
Rsqft/100m							0.00	0.55	0.06
aggregatesqft/100m				0.00	*2.26*	0.23			
Overall Model		N= 54			N= 54			N= 54	
		R^2= 0.54			**R^2= 0.58**			**R^2= 0.61**	
		R^2adj= 0.49			**R^2adj= 0.53**			**R^2adj= 0.55**	

Note: Numbers in bold = p< 0.01; numbers in italics = p<0.05

Table 4. Multiple regressions for movement rates, measures of street connectivity, and land use compositions for Virginia Highland.

APPENDIX 2

Preliminary Work: street connectivity and ridership

Dependent variable: natural log of annual average daily station boardings

	standard model			urban form model			reduced model		
	sum of squares	F ratio	prob>F	sum of squares	F ratio	prob>F	sum of squares	F ratio	prob>F
Explanatory variables									
City*	**20.225**	**19.175**	**0.000**	**22.727**	**22.619**	**0.000**	**30.907**	**30.210**	**0.000**
Distance to CBD†: miles between station and center	1.665	3.158	0.077	0.321	0.640	0.425	—	—	—
Park-and-ride (no, yes)	1.915	3.630	0.058	**4.513**	**8.984**	**0.003**	**5.429**	**10.613**	**0.001**
Feederbus services (no, yes)	1.564	2.965	0.087	*2.916*	*5.805*	*0.017*	—	—	—
Service potential: number of intersecting rail routes at station	**16.259**	**30.830**	**0.000**	**13.460**	**26.792**	**0.000**	**13.572**	**26.533**	**0.000**
Population density: persons per gross acre within 0.5 mile of station	*2.602*	*4.934*	*0.027*	**3.919**	**7.802**	**0.006**	*2.682*	*5.244*	*0.023*
avg R_2‡				0.742	1.478	0.226	—	—	—
avg Reach				**5.791**	**11.528**	**0.001**	**6.668**	**13.035**	**0.000**
Number of cases	219			219			219		
R squared	**0.31**			**0.35**			**0.33**		

Note: Numbers in bold = p< 0.01; numbers in italics = p<0.05

* City was entered as a categorical variable into the equation to capture the differences that are due to cities.

† Measures the crow-fly distance between transit station and city center in CBD.

‡ Average 2-directional reach expresses the average length of streets within 0.5 mile radius of station that is up to 2 direction changes away from the station.

Table 6. Effect tests for multivariate regressions estimating natural log of annual average daily station boardings.

Dependent variable: natural log of annual average daily station boardings

	Reduced model		
	B	t	std β
Explanatory variables			
constant		0.000	
city [atlanta]	**0.791**	**0.000**	**0.518**
city [chicago]	**-0.267**	**0.008**	**-0.233**
city [dallas]	**-0.523**	**0.000**	**-0. 325**
Park-and-ride (no)	**-0.238**	**0.001**	**-0.241**
Park-and-ride (yes)	**0.238**	**0.001**	**0.241**
Service potential: number of intersecting rail routes at station	**0.235**	**0.000**	**0.329**
Population density: persons per gross acre within 0.5 mile of station	*0.010*	*0.023*	*0.166*
avg Reach	**0.078**	**0.000**	**0.291**
Number of cases		219	
R squared		**0.33**	

Note: Numbers in bold = p< 0.01; numbers in italics = p<0.05

Table 7. Parameter estimates for multivariate regressions estimating natural log of annual average daily station boardings.

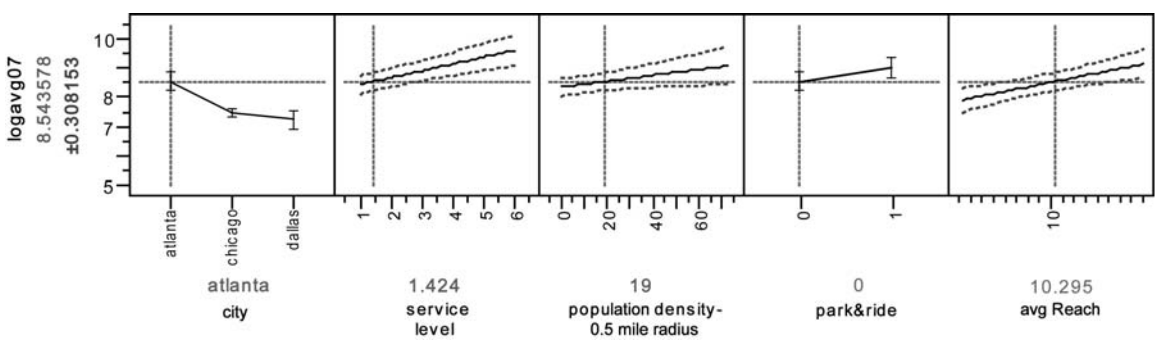

Figure 1. Prediction equations for the variables in "reduced" model[8].

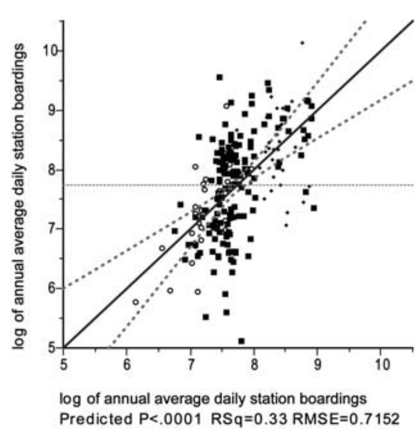

Figure 2. Scatter plot showing the natural log of annual average daily station boardings by the "reduced" model.

[8] The "reduced" model shows the extracted measures which are statistically significant at the 0.01 level in the "urban form" model. The "urban form" model is constructed by the inclusion of connectivity measures, metric reach (average metric reach) and 2-directional reach (average metric reach for 2 direction changes), in addition to controls.