HEALTHY TRANSPORTATION – HEALTHY COMMUNITIES: DEVELOPING OBJECTIVE MEASURES OF BUILT-ENVIRONMENT USING GIS AND TESTING SIGNIFICANCE OF PEDESTRIAN VARIABLES ON WALKING TO TRANSIT

A Dissertation

by

PRAVEEN KUMAR MAGHELAL

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

August 2007

Major Subject: Urban and Regional Sciences

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Approved by:

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ABSTRACT

Healthy Transportation – Healthy Communities: Developing Objective Measures of Built-Environment Using GIS and Testing Significance of Pedestrian Variables on Walking to Transit. (August 2007)

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Walking to transit stations is proposed as one of the strategies to increase the use of transit. Urban planners, transportation planners, environmentalists, and health professionals encourage and support environmental interventions that can reduce the use of cars for all kinds of trips and use alternative modes of travel such as walking, biking, and mass-transit.

This study investigates the influence of the built-environment on walking to transit stations. Transit-oriented communities at quarter and half-mile distances from the Dallas Area Rapid Transit (DART) station in Dallas, Texas, were analyzed to identify the relation of various constructs of built-environment on walking to the DART stations.

Twenty-one pedestrian indices were reviewed to develop a comprehensive list of 73 built-environment variables used to measure the suitability to walk. This study aims to objectively measure built-environment using spatial data. Based on this criterion the total number of variables was narrowed to 32. Walking to transit, calculated as a percentage of transit users who walk to the DART LRT stations, was used as the dependent variable. The number of stations in operation and used for analysis in this study is 20(n). Therefore, bootstrapping was used to perform the statistical analysis for this study.

The final pattern of variable grouping for the quarter-mile and the half-mile analysis revealed four principal components: Vehicle-Oriented Design, Density, Diversity, and Walking-Oriented Design. Bootstrap regression revealed that density ($\beta = -0.767$) was the only principal component that significantly ($p<0.05$) explained walking to transit station at quarter-mile distance from the station. At half-mile distance built-environment variables did not report any significant relation to walking to transit.

The present study revealed that mere increase of density should not be taken as a proxy of increase in walking. Environmental interventions that can promote walking should be identified even at locations with high density. Further studies should use advanced statistical techniques such as Hierarchical Linear Modeling or Structural Equation Modeling to test the relationship of both the principal components and the individual variables that define the principal component to clearly understand the relationship of built-environment with walking to transit station.

DEDICATION

To my brother

ACKNOWLEDGEMENTS

First and foremost, I would like to thank the people who made it possible for me to be here against all odds, my parents. Even after all the expected and unexpected challenges that our family experienced in the last six years you have been a source of emotional support to me. I cannot thank you enough for this opportunity. I would like to thank Rekha, my sister, who has been a source of much needed strength for me. Most important, I would like to thank my better half, Prathiba Natesan, for tolerating me through this process of education and life. Without her, I would not have achieved this important milestone in my life.

I would like to thank my committee chairs, Dr. Christopher Ellis and Dr. Byoung-Suk Kweon for being a source of inspiration and advice. Thank you for encouraging me through both my academic and personal progress at Texas A&M. Thank you Chris, for accommodating my never ending demand for recommendation letters that won me my first research grant, and various other university awards. Thank you Byoung-Suk, for detangling the research method of all the research projects on which we worked together.

I thank my committee members, Prof. Jody Naderi, Prof. Bruce Thompson, and Prof. Srinivasan Raghavan. Thank you Jody for being a kind ear to the personal and professional happenings of my life and being a source of encouragement throughout my education at Texas A&M. Thank you Dr. Thompson for agreeing to be a part of my committee at the eleventh-hour and guiding me through my analysis. Last but not the least, I would like to thank Dr. Srini, with whom I have shared and discussed the importance of personal and professional achievements. I am sure those discussions will be immensely useful in my career ahead.

This list would not be complete without thanking Dr. Walter Peacock and Dr. Samuel Brody. I have learnt so much from you both. You were always easily approachable and helped me have a wonderful experience working at HRRC. I will cherish the ‘Friday discussions’ for life. My heartfelt gratitude to Dr. Forster Ndubisi, Dr. Douglas Wunneburger, my friend and guide Dr. Chanam Lee, the staff, and my colleagues in the College of Architecture.

My time in College Station would have been like a travel through a dry desert, had it not been for my friends and their families. Hereon, it will not be the same without you guys-Miriam, Sudha, Wes and Linda, ‘the only’ Kim, Paula, Meghan, Himanshu, Sarah, Kang, Sandy, David, and my ex-roommates Vivek, and Krishna. Thank you Miriam, for introducing me to weekend parties and taking me as your friend. Also, I would like to thank my friends from India – Rajpal, Prashanth, KB, Sidd, Bharath, Rakesh, Bhoo, Vinodh, and Prad for supporting and inspiring me throughout my stay in the US.

Finally and most importantly, this dissertation is supported by the Robert Wood Johnson Foundation through their Active Living Research Dissertation Award. I would like to thank the program director Dr. James Sallis and his staff, and the reviewers of my proposal for sharing their views on my dissertation.

NOMENCLATURE

BART – Bay Area Rapid Transit

CBD – Central Business District

CDC – Center for Disease Control and Prevention

COOP – Cooperative Rain gage Station

DART – Dallas Area Rapid Transit

GIS – Geographic Information System

LUTRAQ – Land-Use Transportation Air Quality

LRT – Light Rail Transit

NCTCOG – North Central Texas Council Of Governments

PSI – Pedestrian Suitability Index

PWI – Pedestrian Walkability Index

TOC – Transit Oriented Communities

USDHHS – United States Department of Health and Human Services

USDOT – United States Department of Transportation

VMT – Vehicles Miles Traveled

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CHAPTER I

INTRODUCTION

Background of the Study

Walking to transit stations is proposed as one of the strategies to increase the use of transit. The increase in use of transit and walking is expected to alleviate the amount of trips made in private cars. Urban planners, transportation planners, environmentalists, and health professional encourage and support environmental interventions that can reduce the use of cars for all kinds of trips and use alternative mode of travel such as walking, biking, and mass-transit. Walking and biking short distances to destinations such as community stores, parks, school, or transit station is encouraged. This can increase the activity level of the community and improve the overall health of the community. Therefore walking in general, and walking for transportation is especially encouraged in communities across the United States.

Studies in the last decade have investigated the effect of built-environment on walking in the community (Ball et al., 2001; Booth et al., 2000; CDC, 1999; Troped et al, 2001; Handy, 2002; and Greenwald, Boarnet, 2002). Various environmental correlates have been identified that influence walking in general (Sallis et al., 1999; Sallis et al., 1997; Giles-Corti and Donovan, 2002a; CDC, 2001; Brownson et al., 2001; Giles-Corti and Donovan, 2002b; Saelens et al., 2003a; and Pikora et al., 2003). Walking, especially to transit, is influenced by other demographics and socio-economic variables

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This dissertation follows the style of *Journal of Planning Education and Research.*

including the built-environment. It is therefore important to take a holistic view to investigate the effect of built-environment on walking to transit.

This study investigates the influence of built-environment which includes the density, urban-form and other walking related variables identified from the literature on walking to transit stations. Transit Oriented Communities (TOC) at quarter and half-mile distance from the Dallas Area Rapid Transit (DART) station in Dallas, Texas will be analyzed to identify the relation of various constructs of built-environment on walking to the DART stations.

Problem Statement

Neighborhood communities are being redesigned and revitalized into attractive, safe, and more livable places. Currently, new communities are designed based on the principles of New Urbanism which includes medium to high density, mixed land-use, and sidewalk facilities. The central premise of these design principles is to reduce automobile usage and to encourage and accommodate transit-use and other non-motorized mode of transportation such as walking and biking. Therefore, transportation planning and planning for alternative modes of travel play a critical role in designing communities today.

Also, transportation plays a critical and effective role in improving the livability of communities, since it is tied to our daily activities. People travel in their auto, by transit, by walk or on bike to their destinations. Availability of alternative modes of travel, its location, design of streets and sidewalks affect how these daily activities of transportation are performed in the community. Of all the modes of travel, transit as an alternative mode of travel is particularly encouraged by federal and local transportation, planning, and health related agencies such as Federal Transit Administration, Federal Highway Authority, and Center of Disease Control and Prevention. This is because transit-use improves community health by reducing negative environmental impact such as air, water, and land pollution, and reducing the congestion resulting from extensive use of private automobile for work or non-work related trips for both long and short distance trips. The core reason to reduce the trips made by cars is because the US census[1] reports high and increasing use of cars for all kinds of trips in comparison to other alternative modes of travel. The percentage of total trips in cars has increased from 86.5% in 1990 to 87.9% in 2000 of all the trips (Figure 1). Walking and the use of transit have been low and have actually reduced even more in the last decade. Only 4.7% and 2.9% of the trips in 2000 were made by public transit and walking respectively.

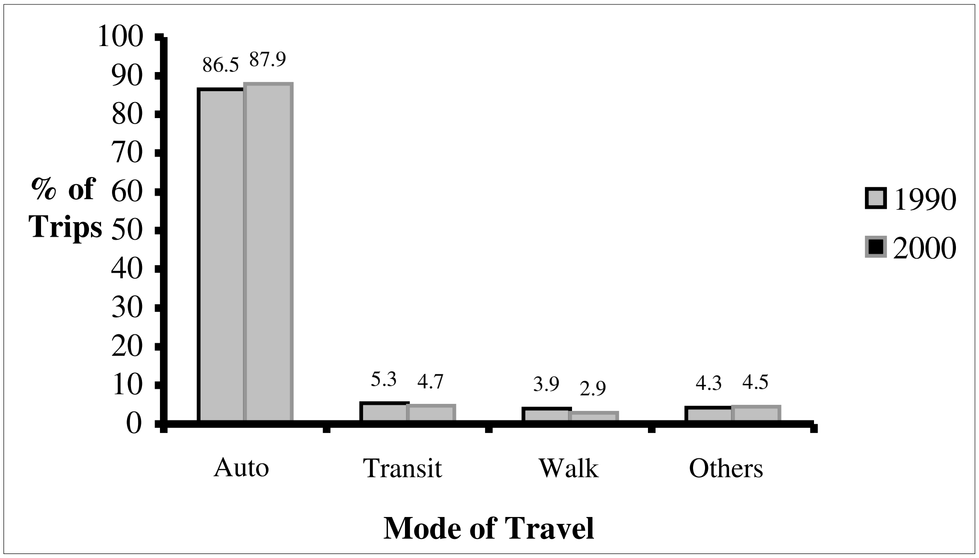


Figure 1. *Census report of mode of travel in 1990 and 2000*

One way to reduce the number of car trips is to reduce the use of private cars for short distance trips. A study by Cervero and Radisch (1996) reported that over 65% trips of less than one-mile in distance were done in cars. Choosing alternate modes such as walking and biking for the short distance trips can help reduce the total number of trips and Vehicles Miles Traveled (VMT) in car. Travel demand studies have revealed that travel by personal vehicles is lower in neighborhoods with higher rates of walking. Walkable neighborhood also helps increase use of transit for all trips as reported by Cervero and Radisch. Therefore, walking with inter-connected facilities to transit in communities needs to be encouraged.

Also, linking of transit facilities with well connected road network, sidewalk, and other physical attributed of built-environment is seen as one of the important strategies to increase transit-use. Since all transit trips involving some amount of walking, improving built-environment around transit facilities that support walking, will help increase walking and eventually the activity-level of the community.

Recent studies report that walking trips are heavily influenced by the characteristics of the neighborhood. Greenwald and Boarnet (2002) reported that characteristics of built-environment such as high density, land use mix, and street network connectivity are positively associated to walking. Thus pedestrian neighborhoods are generally defined to have relatively high densities of development, mixed land uses, and high connectivity of street network (Ewing, Haliyur, and Page, 1994). These characteristics of built-environment are similar to the built-environment characteristics of the traditional neighborhoods, planned well before early modern times.

Though recent studies have investigated certain built-environment variable's influence on walking to transit, comprehensive built-environment constructs still remains to be investigated.

Research Purpose

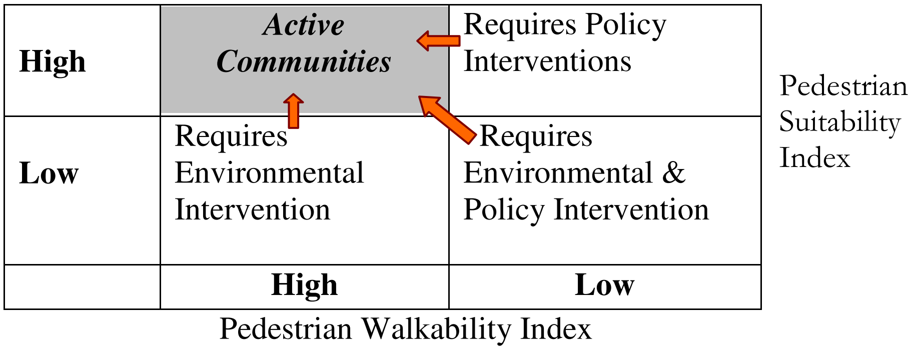
The specific objective of this research is to measure the impact of built-environment on walking to transit stations. The central hypothesis of the proposed research is that improving pedestrian built-environments in communities around transit stations will encourage people living in them to use transit as a mode of travel to work, recreation, or shopping. The rationale that underlies this investigation is to identify the built-environment variables that affect walking to transit which will help propose appropriate design interventions to encourage activity-friendly environments. The central hypothesis will be tested and the objectives of this study achieved by pursuing the following specific research objectives, which are:

1) To identify what built-environment characteristics in communities around transit stations function together as constructs of the physical environment?
2) To examine if the constructs of the physical environment in communities around transit stations affect walking to transit?
3) To investigate if the effects of these constructs vary based on the distance from the transit station?
4) To recommend design interventions in transit communities that can increase walking to transit stations

The proposed research is innovative because it uses objective measures of the built-environment around transit stations for its suitability to walk to the stations. These measures will be investigated for its influence on walking to transit stations, which is the central hypothesis of this research. Identification of these built-environment variables will help in identifying design interventions that promote walking and use of transit.

Research Premise

This study is foreseen as a part of larger study to develop two indices: (i) Pedestrian Suitability Index and (ii) Pedestrian Walkability Index, to measure the activity-level of communities. The Pedestrian Suitability Index (PSI) will the objectively evaluate the pedestrian environments of the community while the Pedestrian Walkability Index (PWI) will use subjective measures of the environment such as willingness to walk and preferred sidewalk width in communities. Disparity in the outcome of these indices, as shown in Figure 2, in the communities under investigation will help identify the specific type of intervention (Physical or Policy) that can increase activity-level of the communities. Lack of walking in communities (Low PWI) with built-environment that support walking (High PSI) suggests policy intervention will be required to educate people about the benefits of walking. Conversely, physical interventions need to be introduced in locations with low PSI and High PWI. To do so, it is important to understand the relationship of specific built-environment variables on walking. Therefore, this dissertation currently develops objective measures of the built-environment using spatial data and investigates its impact on walking to transit. These measures will be used in later studies to develop the PSI (future scope).



High	***Active Communities***	Requires Policy Interventions
Low	Requires Environmental Intervention	Requires Environmental & Policy Intervention
	High	**Low**

Figure 2. *Theoretical framework to identify appropriate intervention*

Organization of the Dissertation

This dissertation is organized in five chapters. Chapter I discusses the background of this study and identifies the specific objectives of this study. Chapter II reviews the literature related to objective of this study. This chapter is divided into three sections. The first section reviews the role of built-environment in supporting new-urbanist principles of reducing auto-travel, and using alternative modes of travel. The second section develops an inventory of built-environment variables used to measure suitability to walk by reviewing the existing pedestrian indices and the third section looks at objective measures of the built-environment variables used by studies that have used Geographic Information Systems. Chapter III discusses the data measures and research method used in this study. This chapter introduces and discusses bootstrap principal component analysis and bootstrap regression, statistical method used to analyze the objectives of this study. Chapter IV presents the results of analysis by presenting the descriptive analysis, constructs of built-environment identified by bootstrap principal component analysis and role of these constructs with walking to transit stations using bootstrap regression. Finally, discussion of the results and summary of this study is presented in Chapter V.

CHAPTER II

REVIEW OF LITERATURE

Section – I

Introduction

The literature study for this research was conducted in three parts. The first section of the literature reviewed the effect of built environment on(i) reduced use of private-auto; (ii) increased non-motorized mode of travel such as walking; and (iii) walking to transit station. The second section reviewed the literature on existing pedestrian indices to develop a comprehensive list of built-environment variables used to measure the suitability to walk and the third section synthesizes the literature that have objectively measured a few or all of these variables objectively using GIS. For ease of reporting, the following literature will identify traditional neighborhoods as pedestrian neighborhood since both have been reported to have similar characteristics.

Built-Environment for New-Urbanist Communities

Studies in the last two decades have investigated the effect of built-environment on motorized (Cervero and Radisch, 1996; Cervero and Gorham, 1995; 1000 Friends of Oregon, 1997; Holtzclaw, 1994) and non-motorized mode of travel such as walking (Cervero, 2002; Handy, 1996). However, fewer studies have looked at walking to transportation destinations at the community-level (Example: Loutzenheiser, 1997; Cervero, 1996; Besser and Dannenberg, 2005; Scholssberg and Brown, 2004). Since walking to transportation destinations such as transit station is seen as one of the strategies to increase transit-use and physical activity of the community, it is important to analyze communities with transit destinations within walkable distance. Studies indicate that neighborhoods with transit destinations within walking distance of the households report higher average walking trips (Handy 1996). Increased walking to destinations like transit stations and using transit for both work and non-work related trips has other benefits with the obvious health benefit (CDC 1996, Francis 1997, and USDHHS 2000) through regular physical activity.

Built-Environment and Auto-Travel

Pedestrian neighborhoods report higher rates of travel by walking and transit (Fehr and Peers, 1992), and reduced travel by personal vehicles (Cervero and Gorham, 1995). Also, pedestrian neighborhoods with transit destination within walking distance of the households report higher average walking trips (Handy, 1996).

In a study conducted by Cevero and Radisch (1996) two communities: (i) suburban community oriented to mass transit and (ii) an automobile-oriented community in the metropolitan areas of San Francisco Bay Area and Los Angeles – Orange County were analyzed. Their study investigated the travel choices in pedestrian versus automobile communities in San Francisco Bay Area. The core reason for this investigation was to determine the role of the design principles of New Urbanism such as grid-like street patterns, mixed land uses, and pedestrian amenities on travel choices. They analyzed two communities: Rockridge, a neo-traditional neighborhood and Lafayette, a conventional suburban community. Rockridge reported higher percentage of trips by walk and transit compared to the conventional suburban community. For trips less than one-mile in distance, Rockridge reported 28% of trips by walk compared to Lafayette, which reported 8% of non-work related trips by walk. So, 20% higher share of trips by walking to BART stations was reported in Rockridge. Therefore, neo-traditional neighborhoods such as Rockridge with characteristics of pedestrian communities, with compact and mixed-use developments, report at least three times more trips by walk to various destinations compared to a suburban community. The Bay Area's transit-oriented neighborhoods, on average, generated around 70% more transit and 120% more pedestrian/bicycle trips than the auto-oriented neighborhoods. Their study concluded that neighborhood design affect the degree to which people walk or bicycle.

While the study by Cervero looked at the relation of type of neighborhood with trip mode, the Land Use-Transportation-Air Quality (LUTRAQ) study for Portland, Oregon (1000 Friends of Oregon, 1997) looked at the impact of specific built-environment variables on travel. The built-environment variables such as ease of street crossings, sidewalk continuity, local street characteristics, and topography were reported to be highly correlated with transit trips but did not show a significant impact on Vehicle Miles Traveled (VMT) in the neighborhood. On the contrary, a study by Holtzclaw (1994) reported reduction in VMT by 25% when the densities doubled and reduction in VMT by 8% when the transit service doubled. Henceforth, studies have investigated the correlates of built-environment that reduces use of private-auto for all kinds of trips. Last decade, studies have investigated the effect of built-environment on walking in general.

Built-Environment and Walking

Cervero (2002) analyzed the built-environment variables in 3-Dimensions (3D's) of design, density, and diversity to develop the mode-choice models for the Montgomery County, Maryland using the 1994 Household Travel Survey. Using the binomial logit model, he estimated the choice of driving-alone and the use of transit versus other modes of travel for all trip purposes. They looked particularly at the relative importance of land-use variables using two models: one was a basic binomial logit model without land-use variables and another expanded model with the land-use variables. Land-use diversity, density, and ratio of sidewalk miles to road miles worked against driving. Only ratio of sidewalk was statistically significant built-environment variable. In predicting the choice of transit, density and land-use diversity were significant. Density, land-use diversity, and ratio of sidewalk miles were positively associated with choosing transit as mode of travel. Point elasticity revealed that the probability of choosing transit increases with increase in density, land-use, and sidewalk ratio.

Similarly, Handy (1996) analyzed the urban-form of three types of communities: Traditional communities, Early-modern communities, and Late-modern communities in Austin, Texas for its influence on walking for strolling trips and for walking to destination. New urbanism concepts to encourage walking and interaction and discourage automobile usage were tested in these communities. Average walking trips to destinations such as retail stores was reported to be higher in the traditional versus the other two types of communities. Traditional communities reported 2 to 6 times more walking to store when compared to the late-modern communities. Handy, therefore, suggested that more walking was reported in traditional communities partially because of supporting urban-form such as higher household densities and better commercial areas with rectilinear grid street-patterns. Urban-form thus plays a greater role when it comes to walking to destination.

Built-Environment and Walking to Transit

Walking to destinations such as transit stations has been reviewed and reported in this section. A study by Loutzenheiser (1997) investigated the pedestrian access to Bay Area Rapid Transit (BART) stations. They used the data obtained from the BART survey conducted in 1992 to investigate the choice of trips by walk versus other modes of travel using binomial logit model. Distance was one of the most significant principal components to walk. Income was less important when walking was compared to transit users whereas mean income had similar relation with choosing to walk or choosing to use transit for any trip. He also reported that for every additional distance of 0.3 mile from the station, the probability to walk decreased by 50 percent. Car ownership and availability of parking at transit stations were inversely and significantly related to walking to the stations.

Another study by Cervero (1996) looked at the impact of land-use mix and commuting using the 1985 American Housing Survey. Binomial Discreet Choice Model was used to measure the probability of commuting by walking (or bicycling). Presence of retail stores such as grocery and drug stores between 300ft and 1mile and availability of private automobiles were negatively and significantly related to walking whereas availability of adequate transit services and commercial buildings are positively significant with walking to transit. Mixed land-use was a better predictor than residential densities of commute by transit, foot or bicycle. Both density and land-use reduce vehicle ownership rates and are associated with shorter commutes.

While these studies investigated walking in communities with destinations such as transit stations and compared the communities with respect to the mode of travel, two particular studies have analyzed the communities around transit stations, otherwise termed as Transit-Oriented Community (TOC) for its walkability. A study by Besser and Dannenberg (2005) investigated the 2001 National Household Travel Survey for transit-associated walking. They concluded that minorities, people with low-income, and people in high density urban areas were likely to walk to and from transit daily. Their study recommends increased access to public transit to maintain active lifestyles. The main limitation of their study was they did not include the built-environment aspect in their analysis which has shown to have significant effect on walking to transit.

Another study by Schlossberg and Brown (2004) compared the TOCs for walking. The effectiveness of TOC, commonly identified as Transit-Oriented Development TOD, depends on high density, land use mix, and roadway connectivity. Access to transit stop is an important component of TOCs. Their study analyzes the built-environment in communities at 0.25 and 0.5 mile distance equivalent of 10 min. and 20 min. of walking, around the station. Their paper focuses on connectivity of walking environment to transit stations. One major limitation of their study was they did not include dimensions of walkable environment related to density and land use mix. It is important to include these neighborhood variables because they significantly adds to the regression models of walking beyond socio-demographic variables (as done by Besser and Dannerburg) (Eg. Kockelman 1997; Frank and Pivo 1994; Kitamura, Mokhtarian, and Laidet 1997).

Therefore, few variables of built-environment have been empirically analyzed for its impact on walking in transit-oriented communities. Investigation of large number of built-environment variables that can influence walking to transit station still needs to be conducted and reported because based on the impact of the determinants of built-environment on walking, various interventions can be recommended. Therefore, this study reviewed twenty-one pedestrian indices (Allan, 2001; Bandara et al., 1994; Bradshaw, 1993; Dixon 1996; USDOT; Landis et al., 2001; City of Ft. Collins, 2002; Khisty, 1994; Moudon, 2001; Moudon et al., 2002; City of Portland, 1998; Wellar; Gallin, 2001; Portland Pedestrian Master Plan, 1998; Saelens at al., 2003b; Carreno, Willis, Stradling, 2002; Milazzo, 1999; and Dannenberg, 2004) that were developed during the last two decade to develop a comprehensive list of built-environment variables and identify those that could be measured using GIS.

Section - II

Review of Pedestrian Indices

One particular study that is germane to this review is the evaluation of environmental audit by Moudon and Lee (2003). Their study reviewed audit instruments and indices[1] for both walking and biking and guides the review of indices for this study.

Identifying the Indices

This study reviews the ‘pedestrian indices’ that evaluate walking in communities. The primary need for this review was to identify built-environment variables associated with walking (only) that can be objectively measured using GIS. Therefore, indices developed in the last two decades to quantify the pedestrian environment were selected from the existing literature. The indices were reviewed for the scale of measurement, type of data, source(s) of the data, and the list of specific variables used to develop the index (Table 1). The identified variables were classified into 11 constructs such as sidewalk, road, intersection, vehicle, pleasantness, and safety (Table 2). Doing so helped to identify the specific constructs of built-environment that were used to develop these indexes over the span of two decade.

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[1] Audits refer to measuring the environment for the quantity of a specific determinant of built-environment through either GIS, Site Survey or individual survey. Indices on the other hand uses the audited measured and aggregates them to evolve a number that could be used to compared walking or biking-oriented communities across the nation.

Table 1.
Review of existing pedestrian indices.

Author	Index	Unit of Analysis	Data Source	Data Measured
Allan	Walking Permeability Indices	Area	GIS	Objective
Bandara	Grade-Seperated Pedestrian Systems	Area	Unclear	Objective (?)
Bradshaw	Walkability Index	Area	Survey	Both
Dixon	Pedestrian Performance Measures	Segment	Audit	Objective
DOT	Walkability Checklist	Area	Survey	Subjective
FDOT	Florida Pedestrian Level of Service	Segment	Audit	Objective
Fort Collins	Pedestrian Level-of-service	Area	Audit	Both
Khisty	Qualitative level of service	Segment	Survey	Subjective
Moudon	Pedestrian Infrastructure Prioritization Decision System	Area	GIS	Objective
Moudon	Pedestrian Location Identifier 1	Area	GIS	Objective
Moudon	Pedestrian Location Identifier 2	Area	GIS	Objective
Portland	Pedestrian Deficiency Index	Segment	GIS	Objective
Portland	Pedestrian Environmental Factor	Area	Unclear	Objective
Portland	Pedestrian Potential Index	Segment	GIS & Survey	Objective
Gallin WA-LOS	Pedestrian Level of Service	Segment	Audit	Both
Wellar	Basic walking security Index	Intersection	Audit	Both
Dannenberg (Virginia)	Walkability Audit Tool	Segment or Area	Audit	Both
Highway Manual	Level of Service	Segment	Audit	Objective
Carreno et al (2002)	Pedestrian Quality of Service	Segment	Survey	Both
Saelens et al (2003)	Neighborhood Environment Walkability Scale	Area	Survey	Both
Frank et al	Walkability Index	Area	GIS	Objective

Table 2.
Factors used to develop the pedestrian indices.

Author	Distance	Sidewalk	Roads	Intersection	Vehicles	Pleasantness	Demographics	Safety	Destinations	Lateral Separation	Land-Use
Allan-WPI	X	-	-	-	-	-	-	-	-	-	-
Bandara-GSPS	X	-	X	-	-	X	-	-	-	-	X
Bradshaw-WI	-	X	-	-	X	X	X	X	X	-	-
Dixon-PPM	-	X	X	X	X	-	-	-	X	X	-
DOT	-	X	X	X	X	X	-	-	-	X	-
FDOT-LOS	-	X	X	-	X	-	-	-	-	X	-
Fort Collins-LOS	X	X	X	X	-	X	-	X	-	-	-
Khisty-QLOS	X	X	X	X	X	X	-	-	X	-	-
Moudon -PIPDS	-	-	-	-	-	-	X	-	-	-	X
Moudon-PLI1	-	-	-	-	-	-	X	-	-	-	X
Moudon-PLI2	-	-	-	-	-	-	X	-	-	-	X
Portland-PDI	-	X	X	-	X	-	-	-	-	-	-
Portland-PEF	-	X	X	X	-	-	-	-	-	-	-
Portland-PPI	X	-	-	-	-	-	-	-	X	-	X
Gallin WA-LOS	-	X	X	X	X	X	-	X	-	X	X
Wellar-BWSI	-	-	-	X	-	-	-	-	-	-	-
Dannenberg-WAT	-	X	-	X	X	X	-	-	-	X	-
Highway Manual-LOS	-	-	-	X	-	-	X	-	-	-	-
Carreno et al-PQS	-	X	-	X	-	X	-	X	X	-	-
Saelens et al-NEWS	-	-	X	-	-	X	X	X	X	-	X
Frank et al- WI	X	-	X	-	-	-	-	-	-	-	X
Total occurrence	6	11	11	10	8	9	6	5	6	5	8

Unit of Analysis

The scale of measurement of each index is identified by the quantification of pedestrian variables for an area, segment or location. For example, the index developed by Wellar quantified the suitability to walk based on the intersection features and thus the scale of measurement was the location (of intersection). Whereas the Khisty's Qualitative Level of Service quantified the pedestrian suitability for a road segment and thus the scale of measurement is the road segment. From the reviewed indices, eleven indices quantified the suitability for an area, eight quantified a segment, and one measured the suitability to walk at a location (intersection). The walkability audit tool developed by Dannerburg can evaluate the suitability to walk at the scale of both segment and area.

Sources

It was important to identify the sources of the data used to evaluate the suitability to walk because it helped in classifying the variables into objective or subjective variables. It has to be noted that either due to unavailability of diligent methods or technology, some variables used in certain indices were measured subjectively either through survey or site audit. With the current improvements both due to availability of data and the technology, these variables can be measured objectively in GIS. Only six indices used GIS measures to develop their index. Thirteen indices used either survey or site audits to develop the index. It was unclear from the literature if the Grade-Separated Pedestrian Systems by Bandara and the Pedestrian Environmental Principal component for Portland used a survey, GIS, or aerial imagery to evaluate each variable used to develop the respective index. The Portland Potential Index used both GIS based measures and measures obtained through survey to quantify the suitability to walk.

Type of Data

The pedestrian indices were reviewed to list the specific variables used to quantify a score of suitability to walk. Once these variables were identified, they were evaluated if the variables used for that index could be measured objectively using GIS. For example, Khisty's Level of Service was assessed using perception of the environment and therefore was subjective to the location and the observer, whereas the Dixon's Pedestrian Performance Measure uses variables that can be measured using GIS and were thus classified as objective variables. In the currently reviewed indices for this study, 12 indices used variables that can be objectively measures using GIS, two were purely based on perception and were thus subjective, and seven indices used both objective and subjective variables to quantify the suitability to walk.

Measure of Indices

The variables of each index were categorized into twelve different constructs of built-environment. The physical construct of road were the most commonly used constructs across various indices followed by the construct of sidewalk and intersection in eleven indices. Lateral separation was a construct least used across the 21 indices. Only five indexes of 21 used the variables of lateral separation such as sidewalk buffer and shoulder lane. In total, 73 variables were measured to develop the 21 indices (Table 3). Of the 73 variables, 49 were identified as objective variables and 24 were identified as non-objective variables. Variables identified as objective but were either proxy for

Table 3.
Classification of variables as objective and non-objective variables.

	OBJECTIVE - Used	OBJECTIVE - Not Used	NON-OBJECTIVE
Distance:		(1) Origin to destination (2) Actual Dis/ Min Dis (3) Distance to Schools	
Sidewalk:	(1) Availability (2) Connectivity	(4) Continuity (5) Width	(1) Visibility (2) Usage Density (3) Maintenance
Roads:	(3) Connectivity (4) Width (5) Median (6) Network	(6) No. of Lanes	***(a) Driveway*** (4) Frequency/Volume
Intersection:	(7) Density ***(b) signalization*** (8) Availability	(7) Curb-cuts (8) Safety (9) Size ***(a) crosswalk*** (10) Availability	(5) Comfort ***(a) Crosswalk*** (6) Visibility ***(b) Signalization*** (7) Visibility (8) Synchronization
Vehicles:	(9) Speed (10) Volume (11) Parking		(9) Not Cautious
Pleasantness:	(12) Lighting (13) Street Tree	(11) Benches/HH	(10) Attractiveness (11) Visibility (12) Local Architecture (13) Building Frontage (14) Supporting Facilities (15) Attractive Delight (16) Interest (17) People (18) Dogs (19) Street Furniture (20) Exploration
Demographics:	(14) Population Density (15) Housing Density (16) Employment Density (17) Ethnic Minority Density (18) Households with cars		
Safety:	(19) Traffic Security (20) Personal Security		(21) Clear Sight Lines (22) Sense of Security
Destinations:	(21) Recreational (22) Essential (23) Administrative		
Lateral Separation:	(24) Shoulder Lane	(12) Sidewalk Buffer	

Table 3. contd.

Others:	(25) Land Use Mix	(13) Other Development	(23) Odor, Ventilation
	(26) Parcel Size	(14) Pedestrian Classification	(24) Noise, Crowding, absence of concealed area
	(27) Topography	(15) Pedestrian Friendly Commercial Area	
	(28) Compactness	(16) Parkways	
	(29) Shade and Rain Cover	(17) Pedestrian Plaza	
	(30) Weather/Climate		
	(31) Green-ways		
	(32) Trails		

existing variable, or required spatial data currently not available, were not included in the study. Since this study investigates the communities at a distance of quarter and half-mile around the stations, the distance variables were not included. The non-objective data either required a detailed survey or audit of the communities and its individuals, which is not within the scope of this study. This study only uses the 32 variables that can be objectively measured using GIS that evolved from the review of 21 indices. Since this study analyzes communities around transit stations, availability of parking at stations is assumed to have a significant effect on people's choice of walking to light-rail stations. Therefore availability of parking spaces at transit stations is used in addition to the 32 variables.

Thus, this study investigates, in a broader sense, the existing gap of influence of built-environment on walking to transit. Specifically, this study looks at the role of density, urban form, safety, residential compactness, and availability of destinations on walking to transit. Therefore this study investigates the built-environment in the communities around transit stations for its impact on walking to transit stations. Identifying the specific built-environment constructs and investigating its impact on walking to transit will help propose design interventions to increase walking to transit stations.

Section - III

Objective Measures of Built-Environment

Until recent, most studies that have objectively measured the built-environment did not use GIS. Most of these studies either used self-measured environmental correlates or conducted audits to objectively measure, store, and analyze the effect of built-environment on walking. Aggregated level of information was used by studies that used GIS for objective measure of built-environment. One of the primary reasons for this was unavailability of physical environment data at disaggregated level. With recent improvements in technology to create and store data at disaggregate level, studies have used GIS for objective measure of built-environment (Aultman-Hall et al 1997, Moudon et al 1997, Rodriguez and Joonwon 2004, Frank et al 2005, Lee and Moudon 2006a). Bauman et al encourage the use of GIS system because GIS-derived measures can help overcome some of the methodological problems of reliance on self-reported environmental factors. Studies have reported that self-reported measures have shown to have lesser reliability compared to objective measures derived using GIS.

Various theoretical and empirical studies report that environment affects walking within the communities. A huge inventory of variables that can measure the effect of built-environment on walking has been developed (reviewed in the earlier section of this chapter). Though some or large number of these variables are currently being investigated for its influence on walking, standard methods of measuring these (objective) variables has not been developed and used. Forsyth et al. (2006) reported that "measures developed in urban geography, planning, and transportation may not be relevant to research on physical activity, and public health researchers are not always aware of the problems with physical environment data." So no standard approaches exist to measure the objectively measurable data in GIS. The following section of literature will review some of the existing literature that has used objective measures of built-environment using GIS at community level in their analysis.

Aultman-Hall et al (1997) used GIS to analyze design-based approach to evaluate neighborhood pedestrian accessibility. They evaluate accessibility to various destinations by walk with an assumption that if neighborhood can be designed with destination within walking distances for its residents, a diversion to walking can be achieved. They thus targeted the land-use and connectivity of the environment in their alternate designs for the community. They proposed a redesigned plan as an alternative to the original development layout. The redesigned plan included increased housing density (26.5 to 35 units/ha) and introduced commercial destinations with decreased total area of development (19.3 to 15.6 ha). Using GIS they evaluated the average walking distances to schools, transit stops, and open spaces.

Evaluation of Distance in GIS

Distances were evaluated using network coverage using the centerline of the roads and pathways and connected to center (node) of lots or properties using a dummy link. GIS macro programs were used to calculate the shortest walking distance to various destinations in the original versus redesigned community. The current available version of network analyst extension in ArcGIS 9.2 can help perform this function readily and is easily transferable for all types of data. Nonetheless, this could be tedious process when the area under study has large number of parcels included in its analysis.

While the study by Aultman et al looked at measuring distances with varying land-use and connectivity communities, the study by Moudon et al (1997) analyzed 12 communities in Puget Sound area in Washington State. Their study analyzed the effects of site design on pedestrian travel by evaluating the pedestrian network connectivity and its effect on pedestrian activity. They conducted evaluation of the 12 neighborhood and compared its land-use mix, population density, Income, Auto-Ownership, and amount of retail services for four groups of urban and suburban setting. Using GIS, characteristics of street and pedestrian facilities, completeness and relative safety of pedestrian facilities and directness of pedestrian routes were analyzed with pedestrian-trip volume. Urban sites with higher population density (34.3 versus 31.5 in suburban) reported higher pedestrians/hour and better sidewalk completeness (42% more).

Evaluation of Neighborhoods in GIS

Socio-demographic data such as income, vehicles per household and population density data were derived from the census at block or block-group (income) level. An aerial photos analysis with field survey was used to evaluate the intensity, distribution, physical shape, form, and type of commercial land-uses (retail uses) in the 12 communities. Independent variables mentioned in the earlier sub-section were also obtained through analysis of aerial photos complemented by field work. Completeness of pedestrian facilities was measured by computing the ratio of total length of sidewalk to the total length of block or street). Route directness was measured by the ratio of actual route distance to a straight-line distance. Their study does not report the exact methodology used to evaluate distances but informs about the process of data gathering for neighborhood based analyses related to walking.

A study conducted by Rodriguez and Joonwon (2004) investigated the role of physical environment not just on walking, but all modes of non-motorized mode of travel within the university campus of University of North Carolina, Chapel Hill. Their study used GIS analysis to determine the density, travel time, presence of walking and biking paths, sidewalk availability, and local topography. Their study compared multimodal travel mode choice using one-level logit, nested logit, and a heteroscedastic extreme value model. Topography reported significant negative coefficient with people's probability to walk or bike. Existence of sidewalk increased the odds of walking or using transit. Residential density reported a negative coefficient with use of transit.

Evaluation of Physical Environment in GIS

Travel time used in the analysis of mode choice was computed by evaluating the fastest route to the campus. To do so, the vehicles were assumed to travel at the posted speed limits on the streets. Gross population density was calculated at the block group level from the 2000 US Census. Local physical environment such as walking and cycling paths and sidewalk availability were extracted from digital orthophotographic images at 1-m resolution and 1:1200 scale created in 1998. Slope was calculated using the topographic (contour) maps obtained from the images. The presence of sidewalk on only one side was treated the same as the presence of sidewalks on both sides.

A recent study by Frank et al (2005) rightly reported that to date, almost all studies that have analyzed built-environment have used perceived measure of built-environment. Objective measure on the other hand, can be more reliable and thus needs to investigate in its use for assessment of built-environment. They developed a walkability index that used objective measures in GIS of land-use mix, residential density, and street connectivity. He measured the urban-form of the neighborhoods using the walkability index and reported that neighborhoods with high walkability reported 2.4 times of more activity than those in the low walkability neighborhoods. Therefore, policy interventions that encourage the improvements of neighborhood urban-form can help increase activity such as walking and biking.

Walkability Index in GIS

The three measures used to develop the walkability index were the residential density, street connectivity, and land-use mix. Residential density was measured at the block-group level using the 2000 census data. The net residential area was calculated using the land cover data from the aerial images. Therefore, the residential density was measured as the ratio of number of households for the amount of land in residential use. Street connectivity was measured as the number of intersection per kilometer of road network. The street center-line file was used to evaluate the total kilometers of road network. Land-use mix was measured as "evenness of distribution of square footage of residential, commercial, and office development". Parcel-level data was used to evaluate the percent footage for each of the land-uses and the land-use mix calculated using the following formula:

Land-use Mix = $$-\left[\left(\sum_{1}^{n}(p_i)\ln(p_i)\right)/\ln(n)\right]$$

p- Proportional footage of each land-use

n- Number of land-uses

A recent study by Lee and Moudon (2006a) addressed the challenges faced by earlier studies in quantifying the relationship of non-motorized travel and transit use which is the difficulty to acquire precise data for non-motorized travel and micro-environment. A large number of micro-level attributes of land-use and urban form measured using a custom-made GIS tool were used in their analysis including density, street length, intersection density, volume and speed of vehicles, and groups of destinations. To deal with the multi-collinearity of this huge inventory of built-environment measures, factor analysis was used to identify the clustering of variables. Destination, density, distance and route are reported as simple and effective alternatives to capture land-use mix and street connectivity.

Grouping Destinations in GIS

The purpose to group the destinations together was to examine if the clustered destinations are more attractive than individual destinations. Individual parcel database was used to identify the destinations within the eleven study areas such as Mixed-use, church, sports facilities, museum, grocery store, restaurant, office, and parks. Neighborhood clusters that evolved varied from common usages like just grocery and retail stores to diverse uses such as office, fast food restaurant, and hospital. Their study concluded that the parcel-level data in GIS benefits the investigation on walkability in the environment.

Lessons Learnt

The review of studies that have used GIS to objectively measure the built-environment guides the developed of various measures identified from the review of pedestrian indices. Measures such as land-use mix, density, and urban form variables such as the pedestrian features (sidewalk) reviewed in this section were used to measure the built-environment variables for this study. The GIS data used for this analysis were extracted from aerial images replicating the method similar to the one used by Rodriguez (2004) in his study. Land-use mix formula used by Frank et al was used to measure the land-use mix for this study as well. Density was measured at block-group level, similar to one used of Aultman-Hall in their study. The destination were grouped as little different from the one used by Lee and Moudon. Their grouping was not based on any specific type of use of that destination. For example, the restaurants and offices were grouped together for one of their study area. These two destinations serve different purpose of walking. Therefore based on the purpose of walking to the destinations, this study groups the destinations into three (1) Recreational destinations, (2) Administrative destinations, and (3) Essential destination. A detailed description of what exact uses are categories under each of these subgroups will be discussed in the next chapter. Therefore to support community based interventions for promoting physical activity such as walking, it is essential to develop systems that are more responsive to data needs at the local level (ie., city, county, or neighborhood) (Brownson et al. 2001). Geographical Information Systems (GIS) can help develop such a system.

As indicated in the study by Lee and Moudon, large number of built-environment variables in a single analysis can result in the problem of multi-collinearity. Therefore, to avoid the problem of collinearity among the measures used this study, principal component analysis was performed to investigate the clustering of these variables. The next chapter describes the methodology used to investigate the objectives of this research.

CHAPTER III

METHODOLOGY

Introduction

The analysis for this dissertation is divided in two sections. The first section delineates the development of objective measures of built-environment variables in Geographic Information Systems (GIS) and the second to perform inferential statistical analysis using principal component analysis and regressing the objective measures with walking to transit stations to determine its relation with the built-environment.

GIS has been an effective tool for evaluating walking accessibilities in neighborhood designs (Aultman-Hall, et al., 1997) and lately has been used to evaluate the built-environment in recent studies (Pikora et al, 2002; Troped et al., 2001). This study builds on the existing built-environment measures in GIS and uses the spatial data developed by North Central Texas Council of Governments (NCTCOG). DART mobility analysis report (Regional Mobility Initiatives, 2003) aims to develop or improve walking to transit stations and has therefore created and stored an extensive spatial database, which were used to study the pedestrian built-environment around its light-rail transit stations.

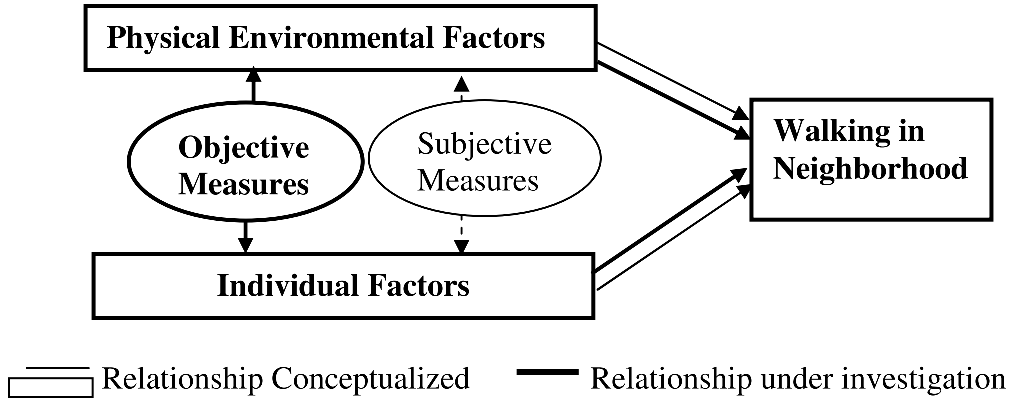
Conceptual Framework and Hypothesis

Pikora et al (2003) conceptualized the two main factors that influence walking in neighborhood. Their study identified physical environmental factors and individual factors as two main determinants of walking. This study adds to the conceptual model by including the objective measures of both physical environment and individual factors such as amount of sidewalk, road network, demographic of the study population and subjective measures of physical environment and individual factors such as perception of environment and preference of individual in the community (Figure 3).

This study investigates the objective measures of built-environment, which includes both the physical environment and individual characteristics. The objective measures that can be quantified in GIS needs to be conceptualized for three reasons: (1) measures developed in GIS can be cost and time effective, (2) GIS based measures can easily be standardized and replicated across studies, and (3) common measures comparable across studies can help make better policy based decisions (Figure 3).

Therefore conceptualizing the objective measures of the physical and individual measures in GIS reveals three distinct characteristics: (1) Locational Characteristics, (2) Segmental Characteristics, and (3) Areal Characteristics.

- Locational characteristics most commonly include point features in GIS such as intersection, pedestrian-vehicle accidents, street lights, etc.
- Segmental characteristics include sidewalk characteristics such as sidewalk length and width, greenway and trail, etc
- Areal characteristics include polygon based features such as land-use, demographics, etc.



Schema of type of physical environmental factors that may influence walking in neighborhood

Adapted and Modified from Pikora, Corti, et al., 2003. *Social Science & Medicine (56).*

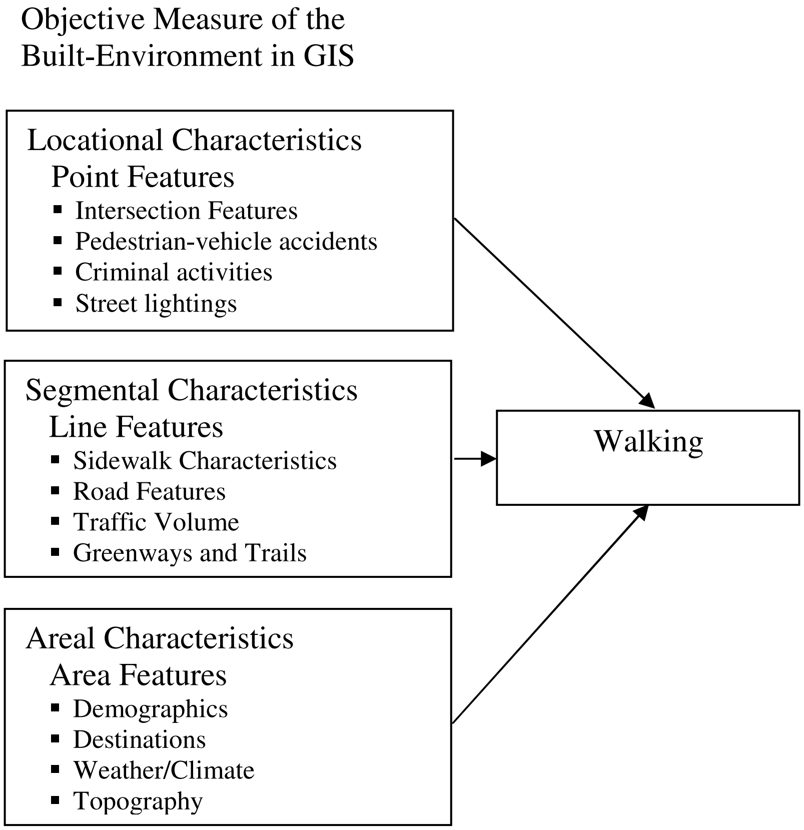


Figure 3. *Conceptual framework of walking using GIS measures*

These characteristic can be quantified to understand their influence on walking in general. This study develops these measures in GIS to investigate its influence on utilitarian trips, specifically, walking to transit. The central hypothesis will be tested and the objectives of this study achieved by pursuing the following specific aims:

- What built-environment characteristics in communities around transit stations function together as constructs of the physical environment?

  Hypothesis 1: The characteristics of built-environment function together to define constructs of physical environment that affect walking.
- Do constructs of the physical environment in communities around transit stations affect walking to transit?

  Hypothesis 2: The built-environment constructs positively affect the percentage of people walking to transit stations for all trips.

Research Design

Study Area

Dallas county is one of the 16 counties in the NCTCOG with a population of about 2.2 million (US Census, 2000) and a median income of around $43,000. Dallas County hosts the majority of 93 miles of light rail system and 35 miles of commuter rail system operated by DART. Currently, DART LRT serves 34 destinations with well connected bus service within the Dallas County and averaged 59,292 riders per weekday in 2005. DART has also encouraged various transit-oriented development around its LRT stations and has attracted extensive private investment to improve communities around stations.

The City of Dallas, NCTCOG, and DART has assessed the built-environment around transit stations to create an inventory of data that could increase accessibility to stations by walk and biking. For this research, spatial data from the NCTCOG were used to study the built-environment around the 20 DART transit stations that were already in operation in 2000.

Unit of Analysis

A study conducted by Lee and Moudon (2006b) determined that the 1km or 0.6 mile distance is walkable distance. Other studies by Moudon, et al (2002), Sullivan and Morrall (2002) identified close to 0.5 miles as a walking distance which is equal to 15-20 minutes of walking. Sullivan and Morrall looked at the walking distances to and from the calgary LRT stations. Transit-users who walked to and from the stations were asked to locate an approximate point of origin or destination. Distances measured from the maps indicated that the average walking distance to suburban stations is 649m and a CBD station is 326m. The walking distance guidelines used or proposed by most American cities with light-rail transit ranged from 457m (by Niagara Frontier Transportation Authority , Buffalo) to 804m (by New Jersey Transit, Newark). This study indicated that people walk farther to reach LRT stations when compared to walking to bus stop stations. Though various studies have identified various distances capable to walk, this study takes a conservative approach and analyzes communities within a distance of 0.5 miles. Also, Healthy People 2010 (USDHHS, 2000) hopes to increase trips by walking, by at least 50%, for trips made by adults that are less than 1 mile. Therefore, the unit of analysis is quarter and half mile around (n = 20) DART light rail stations.

Figure 4. *Unit of analysis: Quarter-mile and half-mile airline distance buffer from transit station*

However, the built-environment measures observed at the half-mile distance were inclusive of the built-environment within quarter-mile distance. As stated earlier in chapter I, this study was conducted with a premise to develop two indices that identifies appropriate intervention at community level. Since the perception of individuals walking from half-mile distance to the transit station would be influenced by the built-environment within the quarter-mile distance, this study measured the built-environment up to half-mile distance. However, using measures of built-environment at every quarter-mile and analyzing its impact on walking to transit could provide information regarding the role of each built-environment construct specific to each quarter-mile distance from station (Figure 4).

Study Design and Variables

Data Analysis

Existing indices that measure pedestrian environment were reviewed to develop an inventory of comprehensive pedestrian measures. The existing 21 pedestrian indices from the literature were reviewed to identify 73 variables in total (Appendix A). These included both objective and subjective measures obtained through survey, site analysis, spatial data analysis, and other existing database. This study aims to objectively measure built-environment using spatial data. Based on these criteria the total number of variables was narrowed down to 32 variables.

The 32 listed variables (spatial) are used to check the influence of built-environment on walking to transit. Each of these variables was measured for a quarter and half mile around each station. It is important to look at the relation or influence of the above listed variables on walking to transit. It is also important to determine directionality of each variable (positive or negative influence) on walking to transit. To do so principal component analysis and regression will be performed to look at the relation of specific variables on walking to transit.

Variable Measurement

Dependent Variable: Walking to Transit

Walking to transit is calculated as percentage of transit users who walk to the DART LRT stations. This information was gathered by DART and NCTCOG through Dallas Area Rapid Transit System On-board Customer Survey (Table 4). A total of 663 (of 1026) weekday surveys and 359 (of 470) weekend surveys were collected and analyzed. The response rate was factored to evaluate expanded population of transit users who walk to station. The boarding factor expands the completed interviews from sampled trips by stratum to represent total boarding by stratum. This was evaluated as product of response factor and vehicle factor. Response factor was calculated as ratio of questionnaires distributed by questionnaires completed and vehicle factor was calculated as ratio of number of vehicle trips in universe for stratum by number of vehicles sampled in stratum.

The spatial autocorrelation showed that the number of people walking to transit with respect to the stations was random. The Moran's I Index showed at value of -0.03 and standard deviation of 0.3 Z score using an inverse distance of spatial relationship. The Euclidean distance was used to evaluate the spatial correlation (Detailed description of Moran's I index is available for readers in Appendix C).

Table 4.
Characteristics of DART LRT station.

Station	Corridor	Opened	Parking	Walk Percentage
Mockingbird	NC	December 1996	725	8.9
Park Lane	NC	December 1996	532	14.4
Westmoreland	WOC	June 1996	668	22.8
Ledbetter	SOC	May 1998	400	22.9
West End	CBD	June 1996	0	26.5
Hampton	WOC	June 1996	467	31.9
Union Station	CBD	June 1996	0	33.5
Corinth	OC	June 1996	78	34.0
Illinois	SOC	June 1996	350	35.2
Tyler/Vernon	WOC	June 1996	0	37.3
Dallas Zoo	WOC	June 1996	0	39.4
Kiest	SOC	May 1997	465	40.1
Lovers Lane	NC	December 1996	0	40.5
Akard	CBD	June 1996	0	44.1
St. Paul	CBD	December 1996	0	46.0
Pearl	CBD	December 1996	0	53.4
Cedars	OC	June 1996	0	59.6
Morrell	SOC	June 1996	0	66.4
VA Hospital	SOC	May 1997	0	70.9
Conv. Center	CBD	June 1996	0	82.1

Independent Variables

The independent measures used the list of base layers listed above in the Table 5. The data layers listed in Table 5 were available or mapped into spatial data to develop the measures to be used for further analysis of this study. All the measures except those listed from 19 to 27 used the base layers obtained from various sources in Dallas County. The following subsection describes the geo-spatial process used to derive the measures listed from 19 to 27 in the table above.

Table 5.
Data layers used for the study.

	Base Spatial Data	Format	Sources	Measured by
	Data Layers Obtained			
1	Signalized Intersection	GIS	City of Dallas	-
2	Posted Speed Limit	Database	City of Dallas	Mapped to Streets
3	Vehicle Volume	Database	City of Dallas	Mapped to Major Streets
4	Tree Canopy	GIS	City of Dallas	-
5	Streetlight	GIS	City of Dallas	-
6	Road Feature	GIS	City of Dallas	-
7	Vehicle-Pedestrian Accidents	GIS	City of Dallas	-
8	Criminal Activities	GIS	City of Dallas	-
9	Curb-Cut	GIS	NCTCOG	-
10	Sidewalk Feature	GIS	NCTCOG	-
11	Off-Road Path	GIS	NCTCOG	-
12	Pedestrian Trail	GIS	NCTCOG	-
13	Parcel Information	GIS	Appraisal District	-
14	COOP Stations	GIS	NOAA	-
15	Topography	GIS	TNRIS	-
16	Block-groups 2000	GIS	ESRI	-
17	Parking Spaces	GIS	DART	-
18	Walking Percent	GIS	DART	-
	Data Layers Derived*			
19	Demographics	-	US Census 2000	Geocoded with Blockgroups
20	Intersection	-	Road Feature	ET GeoWizard
21	Network	-	Road Feature	Observed
22	Road with Parking	-	Road Feature	City of Dallas standards
23	Road with Shoulder	-	Road Feature	City of Dallas standards
24	Road with Median	-	Road Feature	City of Dallas standards
25	Land-use Mix	-	Parcel Data	-
26	Destinations	-	Parcel Data	-
27	Residential Compactness	-	Parcel Data	-

Demographics

The demographic measures such as population density, housing density, employment density, ethnic minority, vehicles per household and median income were measured at block-group level from the US Census 2000. Spatial block-group level data were joined with the census data and density per block-group was calculated. These block-groups were clipped for a quarter and half-mile distance from the stations. Area of the clipped block-groups was recalculated and multiplied by the density. This resulted in actual number of population, household, etc, which was factored by the quarter and half-mile area to calculate the respective density measures.

Intersection Density

Number of intersection within quarter and half-mile distance from the station was generated in GIS using the ET Geo wizard extension. Road networks excluding the highways, speedways, expressway, parkways, or freeways were clipped for quarter and half-mile distance. These high-speed roadways were excluded from the analysis because these road cross-sections generally do not have any walking facilities. The clipped road feature was processed in ET Geowizard to identify the three or four-way intersection and the cul-de-sacs within the quarter and half-mile distance (Figure 5). "Regular" nodes indicated the 3 or 4-way intersection whereas "Pseudo" nodes indicated the cul-de-sacs in the study area. The number of 3 or 4-way intersections was factored for unit length of roadway to evaluate the intersection density.

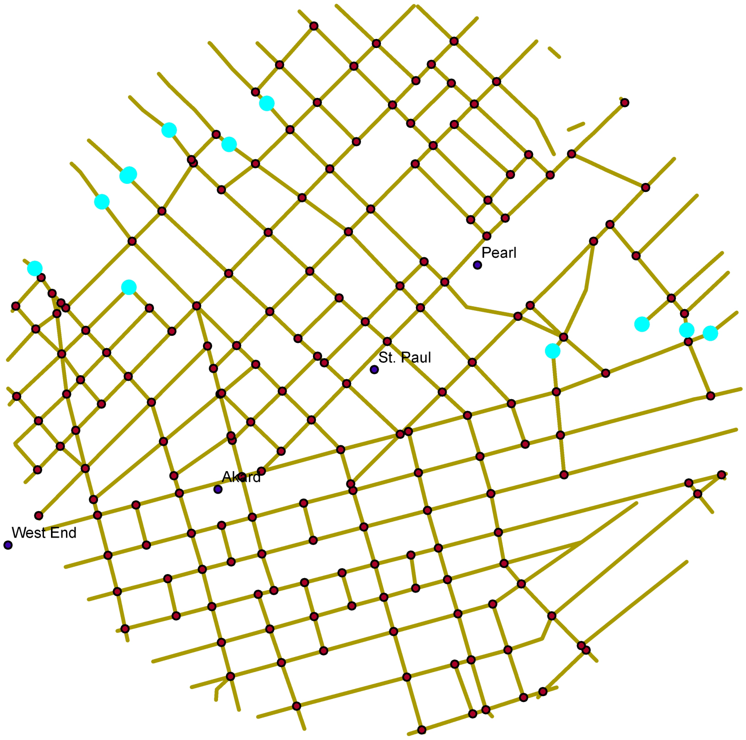
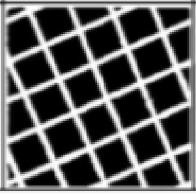
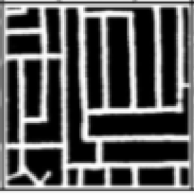
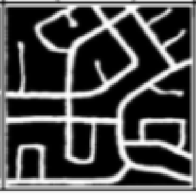
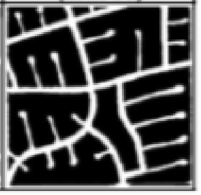


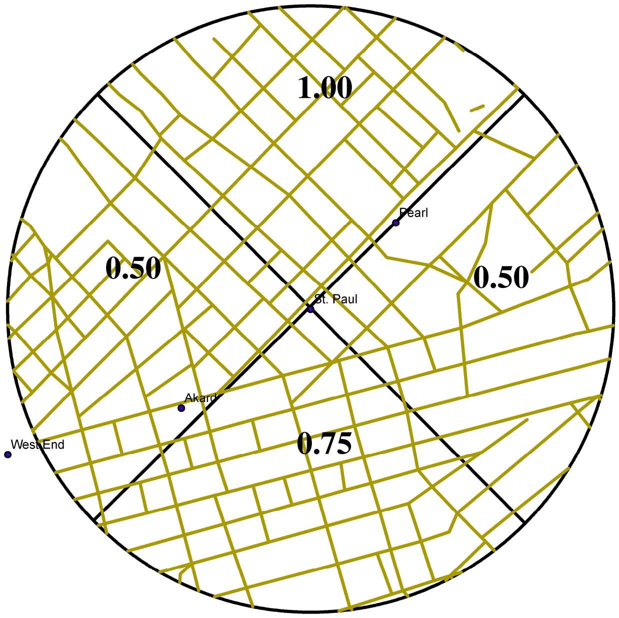
Figure 5. *Three and four-way intersection created using ET Geo-wizard*

Network

Street network was measured by using the network classification system shown by Southworth and Owen (1993). Each quarter and half-mile station area was divided into four quadrants and based on the type of the network were given values from 0 to 1 (Figure 6). Visual evaluation of each quadrant was performed and average was calculated to measure the road network within the study distances.

	Gridiron (c. 1900)	Fragmented Parallel (c. 1950)	Warped Parallel (c. 1960)	Loops and Lollipops (c. 1970)	Lollipops on a Stick (c. 1980)
Street Patterns					
Score	1.00	0.75	0.50	0.25	0.00

Source: Southworth & Owens (1993)



= 1 + 0.50 + 0.50 + 0.75

= 2.75

Figure 6. *Road network classification and scoring*

Road with Median

The characteristics of road features assessed by the City of Dallas Transportation Department were used to derive the measure of length of road with median. The transportation department measures the percentage of road with median. This database file was matched with the road names within the quarter and half-mile of the station.

Based on the percentages of road length with median, the total length of road with median within quarter and half-mile distance was evaluated.

Road with Parking and Road with Shoulder

The road section standards for the lane width used by the Department of Transportation in Dallas County were used to evaluate the length of road with either parking or with shoulder. The standards stipulate a width of 10ft for local roads and 11ft for thoroughfare. Width of the roads clipped within the quarter and half-mile were divided by the standard lane width. The number of lanes so evaluated was compared with the number of lanes observed in the database. For examples, if the road width observed by the transportation department for a local road was 24’, the standard of 10ft for local road was used to determine the number of lanes. The transportation department also provides the number of lanes on the same road (in this case two lanes). If the excess width observed was eight feet or over, that length of the road was classified as road with parking facility and anything less than eight feet was measured as road with shoulder. If any of these roads was already classified as road with median, they were removed from the total length of road with parking or shoulder.

Land-use Mix

Land-use mix was calculated using the similar method used by Frank et al. (2005) to calculate the land-use mix. The NCTCOG’s classification of specific land-use was used to determine the land-use mix for quarter and half-mile from each station. Nine specific classifications were identified as shown below:

$$\text{Land-use Mix} = -\left[\left(\sum_{1}^{n}(p_i)\ln(p_i)\right)/\ln(n)\right]$$

Where, *p* is proportional square footage of a land use *i*

n is total number of different land-uses

NCTCOG Land Use Classification:

1. Commercial: 11
2. Retail: 22
3. Office: 33
4. Residential: 44
5. Mixed-use: 55
6. Parking: 66
7. Institutional: 77
8. Utility: 88
9. Recreational: 99

Based on the number of land-uses at each station, land-use mix was evaluated for the proportional square footage of a particular land-use. This process was repeated at half-mile distanced to evaluate the land-use mix for all the stations.

Destinations

Destinations were primarily classified into three based on the type of services they provide: 1) Administrative which includes banks, post office, police station, etc., 2) Recreational which includes parks, restaurants, theaters, etc, and 3) Essential which includes community-based retail centers, medical centers, etc. Total number of destinations of each type was calculated based on the land-use type of the parcel classified by the ordinance of City of Dallas. Densities of these destinations were evaluated for the quarter and half-mile area around the stations.

Residential Compactness

Residential compactness is measured as amount of residential units for every other non-residential uses within quarter and half-mile distance from the station (Figure 7). Since

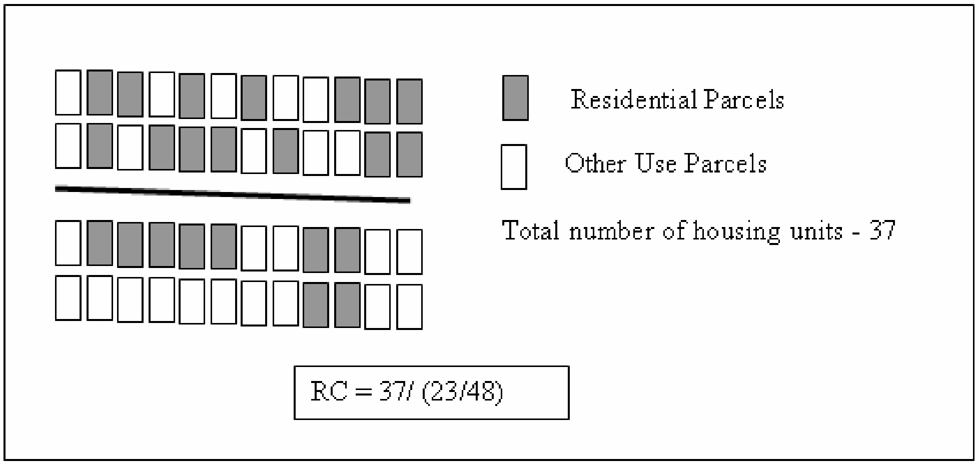


Figure 7. *Measure of residential compactness*

residential land-use is associated the most with walking, higher amount of residential compactness will encourage increased walking in the community.

Safety and Other Miscellaneous Measures

Safety was measured objectively in two ways: Safety from traffic and Safety from individuals. Safety from traffic was measured by average number of pedestrian-vehicular accidents in a month during the year 2000. This data was obtained from the City of Dallas Police Department. Safety from individuals was measured as average of sum of burglaries, assault (of all kinds), and thefts for a month in the year of 2000. Other spatial data such as the sidewalk, curb-cuts, tree canopy, greenways, and trail were obtained from the NCTCOG. Table 6 lists the measures used for each independent variable used in the analysis of this study.

Table 6.
Factors identified based on the variable grouping and measure of each variable.

VARIABLES	MEASURE
Sidewalk	
Density	Total length of sidewalk on one or both sides / total length of road network
Connectivity	No. of Intersections with 4 curb-cuts / total no. of intersections
Roads	
Connectivity	No. of Cul-de-Sac / Total length of the road network
Width	Average width of the road leading to transit
Median	Length of 2-way roads with median/total length of 2-way roads
Network	Gridiron = 1, Fragmented Parallel = 0.75, warped parallel = 0.5, loops & lollipops = 0.25, and lollipops on a stick = 0 (for 4 quadrants along rail line)
Intersection	
Density	No. of Intersections / total length of road
Signals	No. of signalized intersection / total no. of Intersection
Vehicle	
Speed	Avg. speed on roads leading to transit station
Volume	Avg. volume of vehicles on roads leading to transit station
Parking	Avg. length of parking available on roads leading to transit station
Pleasantness	
Street tree canopy	Area of tree canopy on roads leading to transit station
Lighting	Amount of street lights on roads leading to transit station
Demographics	
Population Density	Population / Sq. Mile
Housing Density	Housing Units / Sq. Mile
Employment Density	No. of Employment / Sq. Mile
Ethnic Minority	No. of Non-Caucasian population / Sq. Mile
Cars / HH	No. of Cars / HH
Income	Median Income
Safety	
From Traffic	No. of Vehicle-Pedestrian traffic per month
Personal	No. of reported assaults and burglary per month
Destinations	
Recreational	No. of parks and theaters/cinema/ fitness center parcels
Essential	No. of stores and shopping center parcels
Administrative	No. of school, post office, and bank parcels
Lateral Separation	
Shoulder lane	Avg. width of shoulder lane on roads leading to transit station
Land-Use	
Land-use Mix	$-\left[\left(\sum_{1}^{n}(p_i)\ln(p_i)\right)/\ln(n)\right]$ p-proportion of sq. ft of landuse i, n-no. of landuses
Parcel	Average parcel area
Residential Compactness	Number of Housing Units/Proportion of Residential Parcels
Other	
Shade and Rain Cover	Amount of sidewalk covered by tree canopy
Weather/Climate	Avg. temperature at COOP stations closest to study area
Green-ways	Avg. length of off-road path
Topography	Slope within 0.5 mile of the station
Trails	Avg. length of pedestrian trail
Station Infrastructure	
Available Parking	No. of parking spaces available at the station

Statistical Method

Bootstrapping – General Concept

The number of stations (n) in operation and used for analysis in this study is 20. These form the total observations available. Statistical inference cannot be validated with such a small sample. Nevertheless, the available sample can be treated as pseudo or virtual population from which random samples could be generated used the resampling method.

Several resampling methods such as jackknifing, cross-validation, randomization, and bootstrapping have been developed and used. Bootstrapping has shown to have clear advantage over other methods because it allows drawing many more sub-samples than any other method and the resampling is done with replacement. This allows, all the observations (in this case stations) to be used for random resampling with some observations being used one or more time for each sub-sampling.

As explained by Higgins (2005), bootstrapping involves four steps:

1. Draws a sample with replacement into the mega-sample (Psuedo-population)
2. Calculates and stores the result of the sub-sample
3. Repeat the resampling process desired number of times
4. Results are averaged, SE calculated, CI for the averages are computed and interpreted.

For example, in the current study, the number of observations for a variable, say sidewalk density is 20 (stations). These 20 observations are copied an enormous number of times. Doing so, results in a pseudo-population with large number of observations of sidewalk density. Samples of exact size 20 (sub-sample) are then selected randomly from the pseudo-population and desired statistics calculated. Similar sub-sample of 20 random observations is drawn and statistics calculated for each sub-sample. This process is repeated for desired number of times. The distribution of the statistics obtained for the sub-samples can be treated as if it were a distribution constructed from real samples.

Random resampling with replacement in bootstrapping allows to develop an empirical distribution for a given sample statistics (Efron and Tibshirani, 1993). This avoids the requirement of large sample to determine sampling distribution for significance testing in the classical test theory. Also, as indicated by Efron and Tibshirani (1993, pg 51) the bootstrap estimate of standard error usually have relatively little bias. Efron showed that as the number of replications increases to infinity, the coefficient of variation replicates the original sample (pg 53). Hoyle (1999, pg.100) suggested that larger the number of repetitions, more accurate the numerical evaluation of the bootstrap sampling distribution. He suggests using atleast 2000 repetitions for hypothetical testing and interval construction so as to accurately evaluate the bootstrap sampling distribution.

Bootstrapping can be used for both random and non-random data (Edgington, 1995). Since the observations for this study have not been collected through random sampling, the resampling using the non-random data cannot be used to determine inferential conclusions. Lunneborg (2000) suggested that use of non-random data in resampling can tell more about the local description of data and stability of result. Also, studies have shown that the bootstrap can work reasonably well even with n = 20 (Eg. Boos and Brownie, 1989; Stine, 1985; Zhang, Pantula, Boos, 1991).

Bootstrapping – Principal Component Analysis

Bootstrap principal component analysis can be useful for "(a) determining the number of principal components to retain, or (b) the replicability of pattern/structure coefficients (Lorenzo-Seva and Ferrando, 2003; Thompson, 1988; Thompson, 2004) or both", as reported by Zientek and Thompson (2007). Using the exploratory principal component analysis, minimum principal components were determined. The principal components so obtained were regressed along with median income and ethnic minority as independent variables and percentage of transit users who walk to transit stations as dependent variable. Bootstrap principal component analysis program developed by Dr. Linda Zientek and Dr. Bruce Thompson (2007) was used for this analysis. This program developed in SPSS was used to perform the bootstrap principal component analysis to determine the built-environment factors that affect walking to transit.

Bootstrapping – Multiple Regression

The factor scores obtained through exploratory principal component analysis were used to perform the inferential analysis by bootstrap multiple regression to determine the relation of the built-environment principal components on walking to transit. Two methods for bootstrapping the regression model have been suggested: (1) Resampling with random regressors and (2) Resampling with fixed regressors (Fox, 2002; Stine 1990). This study involves predictors obtained as in a designed experiment. The bootstrap resampling is required to preserve the structure of the design matrix. Random resampling would likely not possess the needed structure (Stine 1990). Regression models in which the predictor variables have non-random or fixed design, regression residuals are used to obtain the required design matrix. This change is incorporated in the first step of bootstrapping the regressors. Though not a straightforward method, it is considered computationally efficient.

Procedure (Stine 1990)

1. Compute the bootstrap samples by adding resampled residuals onto the least square regression fit, holding the regression design fixed:

   i. $\mathbf{Y}*^{(b)} = \mathbf{X}\,\hat{}\beta + \mathbf{e}*^{(b)}$

   where the vector $\mathbf{e}*^{(b)} = (\mathbf{e}_1*^{(b)}, \mathbf{e}_2*^{(b)}, \ldots\ldots, \mathbf{e}_n*^{(b)})$, and each $\mathbf{e}_i*^{(b)}$ is a random draw from the set of n regression residuals.

2. Obtain least square estimates from the bootstrap sample:

   $\beta*(b) = \mathbf{X'Y}*^{(b)} / \mathbf{X'X}$

   $= \beta + \mathbf{X'e}*^{(b)} / \mathbf{X'X}$

3. Repeat (1) and (2) for repetitions (3000) and use the resulting bootstrap estimates $\beta*^{(1)}, \beta*^{(2)}, \ldots., \beta*^{(3000)}$ to estimate confidence intervals.

In contrast to the random regressor model, this resampling approach generates Y* by adding samples of the residuals to the fitted equation X β rather than by resampling from the actual data.

Constructing Confidence Interval (CI)

Various methods have been putforth by Efron and Tibshirani (1986) to calculate Confidence Interval of estimate. Percentile and Bias-Corrected methods are the two most commonly used methods. Bias-Corrected (BC) method for constructing the bootstrapped samples has shown an improved approach over the percentile method. This study therefore computed the BC CIs for the bootstrapped sampled statistics since it encompasses the impact of bias when percentile method is used to construct the CIs (see Fox 2002 for the procedure). STATA was used to perform the bootstrap regression.

CHAPTER IV

DATA ANALYSIS AND RESULTS

Introduction

The built-environment variables analyzed in this study were identified from the inventory developed after reviewing the 21 pedestrian indices. The objective variables that can be measured using GIS measured as described in the previous chapter.

In this study, variables such as weather/climate, green-ways, topography, and trails were measured but dropped from the final analysis. Weather is usually measured with reference to temperature and rainfall of an area. These characteristics are measured by first-order stations that are located predominantly at the airports and second-order stations such as Cooperative rain gage stations (COOP) that are spread across the nation. Therefore, the location of COOP stations close to the 20 stations was identified. Only one COOP station was located in proximity to all the 20 stations. This would result in the same measure of average temperature across the twenty-stations, leading to no variance and was therefore dropped. The slope of terrain within quarter and half-mile distances from the stations did not vary across the stations and thus the topography measure was dropped from the analysis. The greenways were observed only at the Hampton station within a half-mile distance from the stations. No greenway was observed within a quarter-mile of the station. Similarly the off-street facility was present only within a half-mile of the Mockingbird station for a length of 442.00 ft.

Therefore, a final list of 30 variables were measured and analyzed further for this study. The following sections will discuss the descriptive and inferential analyses that were performed to address the objectives of this study. Tests for Skewness and Kurtosis were conducted to identify the distribution of measured variables. Inter-correlation test of independent variables and bootstrap principal component analysis were performed to identify the constructs of built-environment within the quarter and half-mile distances. Bootstrap regression was conducted as part of the inferential analysis and the results were compared between quarter and half-mile distance from the DART stations.

Descriptive Analysis

Descriptive analysis was performed for quarter and half-mile distances from the DART stations. Mean and Standard Deviation (SD) were calculated for the 30 independent variables and the difference in means for quarter-mile versus half-mile radii were observed (Table 7). The average sidewalk density at quarter-mile distance is 1.34 with SD of 0.35 whereas the sidewalk density at half-mile distance is 1.08 (SD: 0.31). Connectivity of sidewalk when compared to the road was reported to be 20% and 30% higher at quarter mile and half-mile distances respectively from the stations. Built-environment measures such as average road width, length of road with median, road network, road with parking, and land-use mix were the same across the two distances. Intersection density, signalized intersection density, average speed limit, traffic volume, tree canopy, amount of criminal activities, destination density, and residential compactness were higher in the quarter-mile distance of the stations. Density

Table 7.
Descriptive statistics of measured variables.

Variables	Quarter Mile		Half Mile		Mean Difference
	Mean	Std. Dev	Mean	Std. Dev	HMile - QMile
Sidewalk					
Sidewalk Density	1.34	0.35	1.08	0.31	-0.26
Sidewalk Connectivity	0.32	0.20	0.26	0.15	-0.06
Roads					
Road Connectivity	0.20	0.08	0.15	0.02	-0.05
Avg. Road Width	22.91	2.90	22.91	2.90	0.00
Road with Median	0.17	0.10	0.18	0.07	0.01
Road Network	2.26	0.72	2.26	0.72	0.00
Intersection					
Intersection Density	205.86	92.18	185.73	69.56	-20.13
Signalized Intersection	0.21	0.21	0.18	0.18	-0.03
Vehicle					
Road Speed	28.39	1.90	27.74	1.74	-0.64
Traffic Volume	14956.08	7541.13	14189.82	6690.50	-766.25
Pleasantness					
Tree Canopy	4.88	3.83	2.97	1.96	-1.91
Number of Street Lights	50.10	19.11	227.82	63.68	177.72
Sidewalk Cover	2.81	3.04	5.65	4.54	2.84
Density					
Population Density	3898.32	2788.84	4291.44	3106.36	393.12
Housing Density	1583.17	1311.13	1698.35	1395.80	115.17
Employment Density	3125.61	2193.82	3422.49	2359.51	296.88
Ethnic Density	2079.48	1608.39	2285.91	1755.24	206.43
Vehicles per HH	1.30	0.35	1.39	0.22	0.09
Median Income	17563.53	18798.29	38216.35	13394.33	20652.82
Safety					
Vehicular Safety	2.90	3.89	7.60	9.25	4.70
Personal Safety	687.13	590.75	561.94	393.57	-125.19
Destination Density					
Recreation	27.52	26.32	24.06	23.84	-3.46
Essential	57.83	62.61	44.56	28.51	-13.27
Administration	36.69	27.50	33.98	23.74	-2.71
Lateral Separation					
Road with Shoulder	0.36	0.21	0.41	0.12	0.05
Road with Parking	0.02	0.04	0.02	0.02	0.00
Land-Use					
Land-use Mix	0.37	0.26	0.37	0.22	0.00
Average Parcel Area	23281.65	17940.81	40834.68	21005.90	17553.04
Residential Compactness	27.57	89.69	12.25	13.86	-15.32
Station Infrastructure					
Parking at Station	184.25	261.45	184.25	261.45	0.00
Walk Percent to Station	40.50	18.64	40.50	18.64	0.00

(population, employment, housing, and ethnic), vehicles per household, median income, and average parcel area were higher at half-mile distance compared to the quarter-mile distance. The characteristics observed at the transit stations such as amount of parking at the stations and the percentages of transit users walking to transit station are the same for both the distances of quarter and half-mile from the station.

Test for Skewness and Kurtosis

The distributions of the independent variables were observed for both quarter and half-mile distances from the station. The tests for skewness and kurtosis were performed on all 30 independent variables. Appropriate transformations were done to the variables that were skewed or did not have a normal distribution (Table 8). The threshold value for both skewness and kurtosis were set at 4.0. Any variable whose distribution reported a statistics (either skewness or kurtosis) above 4.0 was transformed to represent a normal distribution with minimum skewness. Variables transformed when analyzed at quarter-mile distance were road connectivity (transformation: Inverse), residential compactness (transformation: Log), and sidewalk cover (transformation: Square-root). Similarly, population density (transformation: Log) and residential compactness (transformation: Square-root) were transformed for the half-mile distance analyses.

Table 8.
Abbreviation of measured variables for quarter and half-mile distance.

	Variable	Quarter-Mile	Half-Mile
1	Sidewalk Density	SW_DEN	SW_DEN
2	Sidewalk Connectivity	SW_CON	SW_CON
3	Road Connectivity	I_RDCON	RD_CON
4	Avg. Road Width	RD_WITH	RD_WITH
5	Road with Median	RD_MEDN	RD_MEDN
6	Road Network	RD_NET	RD_NET
7	Road with Parking	RD_PARK	RD_PARK
8	Intersection Density	INT_DEN	INT_DEN
9	Signalized Intersection	SIG_INT	SIG_INT
10	Road Speed	RD_SPD	RD_SPD
11	Traffic Volume	TRF_VOL	TRF_VOL
12	Tree Canopy	CANPY_PER	CANPY_PER
13	Number of Street Lights	ST_LGHT	ST_LGHT
14	Sidewalk Cover	SQT_SWCVR	SW_CVR
15	Population Density	POP_DEN	LOG_POPDEN
16	Housing Density	HOU_DEN	HOU_DEN
17	Employment Density	EMP_DEN	EMP_DEN
18	Vehicles per HH	VEH_P_H	VEH_P_H
19	Vehicular Safety	PED_VEH	PED_VEH
20	Personal Safety	CRM_DEN	CRM_DEN
21	Recreation	RECR	RECR
22	Essential	ESSEN	ESSEN
23	Administration	ADMIN	ADMIN
24	Road with Shoulder	RD_SHLD	RD_SHLD
25	Land-use Mix	LU_MIX	LU_MIX
26	Average Parcel Area	AVG_PAR	AVG_PAR
27	Residential Compactness	LOG_RESCOM	SQT_RESCOM
28	Parking at Station	ST_PARK	ST_PARK
29	Median Income*	MED_INC	MED_INC
30	Ethnic Density*	ETH_DEN	ETH_DEN

Test for Correlation

Bi-variate correlation was performed to look at the correlation of independent variables. In the quarter-mile analysis, high correlation was observed among the density variables. Population density reported a correlation coefficient of 0.980 and 0.919 with employment density and housing density respectively. High correlation was also observed between the pedestrian-vehicle accidents and the crime density (0.943). Similarly, the half-mile analysis had a high correlation of signalized intersections with recreational destinations (0.932), pedestrian-vehicle accidents (0.926) and the crime density (0.918). Also, street lights were highly correlated with intersection density. The density variables reported high correlation coefficient for the half-mile analysis as well. The employment density (Correlation coefficient: 0.986) and housing density (correlation coefficient: 0.938) had high correlation with population density.

Hypothesis I

The characteristics of built-environment function together to define the constructs of physical environment that affect walking. This section discusses the analysis performed to test the first hypothesis. The chapter III of this study proposed and discussed the use of Bootstrap Factor Analysis (BFA) to identify the constructs of physical environment. Exploratory principal component analysis using principal components analysis with varimax rotation was performed. Principal components that make sense theoretically and conceptually were identified for further analysis. Based on the number of principal components that evolved using the principal component matrix method, BFA was performed with 1000 repetitions using the SPSS syntax written by Zientek and Thompson (2007). Results of the principal components analysis and bootstrap factor analysis are discussed in the section that follows.

Principal Component Analysis

Exploratory principal component analysis performed for both quarter and half-mile distances revealed six and five principal components respectively. Since the grouping of variables did not explain the principal components theoretically, a principal component analysis with restricted principal components was performed to determine the final set of principal components at each quarter and half-mile distance. The quarter-mile and the half-mile analysis were finally restricted to four principal components (Vehicle-Oriented Design, Density, Diversity, and Walking-Oriented Design). The variables that defined the density and design principal components (Vehicle-Oriented and Walking-Oriented) varied for the quarter and half-mile distance. Diversity principal component was defined by the same set of variables for both the distances.

Principal Component Analysis for Quarter-Mile Distance

Exploratory principal component analysis was performed to understand the pattern of clustering of the 28 variables identified from Table 8. Principal components analysis with Varimax Rotation and Kaiser Normalization revealed six principal components. The clustering of these variables did not form a definitive principal component that could be explained theoretically. Further analysis was performed by restricting the number of principal components. Even with restricted principal components, two variables (1) Essential Destinations and (2) Road Parking did not produce a reliable principal component or did not report a factor coefficient over 0.5. Therefore, these two variables were dropped from the final analysis. The final pattern of variable grouping revealed four principal components: (1) Vehicle-Oriented Design, (2) Density, (3) Diversity, and (4) Walking-Oriented Design as shown in the Table 9. The reliability for each of these principal components was established by calculating the internal consistency using Cronbach's alpha based on standardized items (or Spearman-Brown-

Table 9.
Quarter-mile principal component analysis.

	Vehicle-Oriented Design	Density	Diversity	Walk-Oriented Design
PED_VEH	**0.927**	0.034	0.032	-0.209
CRM_DEN	**0.920**	0.053	0.009	-0.255
SW_CON	**0.892**	0.054	0.171	0.156
SIG_INT	**0.889**	-0.071	0.157	-0.047
VEH_P_H	**-0.852**	0.182	-0.119	0.005
ADMIN	**0.816**	-0.178	0.440	0.063
RECR	**0.725**	0.012	0.143	-0.399
RD_SPD	**0.631**	-0.158	-0.147	-0.401
ST_LGHT	**0.628**	-0.389	**0.513**	0.166
TRF_VOL	-0.257	**0.899**	0.157	0.030
HOU_DEN	0.127	**0.843**	-0.348	-0.092
EMP_DEN	0.156	**0.788**	-0.436	0.033
ST_PARK	-0.237	**0.752**	-0.163	0.071
POP_DEN	0.041	**0.751**	-0.496	0.130
LOG_RESCOM	-0.269	**0.702**	-0.094	0.464
SW_DEN	0.250	**0.670**	**0.553**	0.099
INT_DEN	0.424	-0.493	0.451	-0.476
RD_WITH	-0.100	-0.224	**0.808**	-0.003
RD_NET	0.346	-0.014	**0.775**	-0.095
LU_MIX	-0.260	0.203	**-0.583**	0.020
RD_MEDN	-0.194	0.465	**-0.552**	0.033
I_RDCON	-0.030	0.151	-0.132	**0.829**
CANPY_PER	-0.464	-0.132	-0.272	**0.752**
RD_SHLD	0.133	0.337	0.231	**0.734**
AVG_PAR	-0.012	0.082	-0.379	**-0.693**
SQT_SWCVR	-0.342	0.004	-0.296	**0.688**

Coefficients over | 0.5 | are reported in bold

Extraction Method: Principal Component Analysis. Rotation: Varimax with Kaiser Normalization.

Reliability Coeff.	0.947	0.903	0.804	0.817
Variance Explained	37.6%	23.6%	14.3%	9.1%

Corrected reliability). The Cronbach's alpha based on standardized items is an appropriate measure of internal reliability for this study because of the variance in scale of built-environment measure. For example, the road network was classified into five different categories and was measured as interval data whereas the sidewalk density was measured as continues data. Santos (1999) recommended the use of Spearman-Brown-Corrected reliability for mixture of scales of variables with relatively heterogeneous variance.

The Vehicle-Oriented design reported a reliability of 0.947. Lowest reliability (0.804) was reported for diversity of the environment. The other two principal components (Density and Walking-Oriented Design) reported reliability of 0.903 and 0.817 respectively. In all, at a threshold of 0.8 (Landis & Koch, 1977; Nunnally, 1978; Shrout, 1998) for reliability coefficient, all the principal components reported a high reliability. Almost 85 percent of total variance was explained by these principal components at a quarter-mile distance.

Principal Component Analysis for Half-Mile Distance

Built-environment variables were analyzed for their grouping at the half-mile distance. Exploratory principal component analysis revealed five principal components using the Varimax Rotation and Kaiser Normalization. When the number of principal components was restricted to four, essential destinations, road shoulder, and road median combined to form a principal component whose reliability coefficient was less than 0.75 (0.603). The same principal component was formed when the number of principal components was restricted to three. Therefore, due to the low internal consistency values, these variables were not included in further analysis. After restricting the analysis to four principal components, the same principal components, (1) Walking-Oriented Design, (2) Diversity, (3) Density, and (4) Vehicle- Oriented Design were obtained (Table 10). However the variables that formed these principal components were different from those

Table 10.
Half-mile principal component analysis.

	Walk-Oriented Design	Diversity	Density	Vehicle-Oriented Design
SQT_RESCOM	**-0.885**	0.170	0.372	-0.086
SW_CVR	**-0.875**	0.304	0.224	-0.037
CANPY_PER	**-0.865**	0.080	0.390	0.035
SIG_INT	**0.848**	0.241	-0.102	0.363
CRM_DEN	**0.846**	0.100	0.072	0.310
PED_VEH	**0.809**	0.285	0.115	0.369
RECR	**0.781**	0.335	-0.157	0.303
SW_CON	**0.770**	0.351	0.278	-0.191
ADMIN	**0.753**	0.302	0.031	0.304
RD_SPD	**0.689**	0.293	0.008	0.240
VEH_P_H	**-0.549**	0.389	-0.071	**-0.547**
SW_DEN	**0.506**	0.281	0.483	-0.360
RD_WITH	0.053	**0.856**	-0.297	0.029
LU_MIX	0.055	**-0.823**	0.250	-0.161
AVG_PAR	-0.286	**-0.763**	0.080	-0.213
RD_NET	**0.557**	**0.695**	-0.094	-0.133
LOG_HOUDEN	-0.037	-0.215	**0.941**	-0.160
LOG_EMPDEN	-0.109	-0.198	**0.912**	-0.183
LOG_POPDEN	-0.260	-0.224	**0.881**	-0.193
RD_PARK	-0.041	**0.519**	**-0.617**	0.226
TRF_VOL	-0.048	-0.015	0.435	**-0.838**
INT_DEN	**0.567**	0.383	-0.144	**0.668**
RD_CON	**0.533**	0.200	-0.268	**0.642**
ST_PARK	-0.176	-0.188	0.317	**-0.630**
ST_LGHT	0.480	**0.554**	-0.098	**0.564**
Coefficients over | 0.5 | are reported in bold				
Extraction Method: Principal Component Analysis. Rotation Method: Varimax with Kaiser Normalization.				
Reliability Coefficients	0.952	0.888	0.940	0.903
Variance Explained	9.2%	10.6%	23.3%	44.8%

in the quarter-mile analysis. These four principal components together explained a variance of almost 88%. Reliability coefficients for each of the principal components were quite high with the Cronbach's alpha for standardized item values of 0.952, 0.888, 0.940, and 0.903 respectively

Theoretical Explanation of Principal components

Cervero and Kockelman (1997) segregated the built-environment into three main components with a rationale that

> New urbanists, neotraditionalists, and other reform-minded designers argue for changing three dimensions, or the 3Ds, of the built environment density, diversity, and design-to achieve these objectives.

The role of density has been long investigated for its impact on travel pattern (Handy, et al., 1992; Cervero, 1996). Increase in densities such as population and employment have shown to reduce the use of auto (Holtzclaw, 1994). But the role of density, specifically for walking to transit, has not been investigated so far. The density dimension in the present study were captured by demographic variables such as population and employment density, and by other built-environment such as intersection density, sidewalk density, and vehicular density such as traffic volume, amount of parking on roads and at the station. The diversity dimension conceptualized by Cervero and Kockelman (1997) used various measures of land-uses to define the diversity of built-environment. However, in the present study, the diversity dimension was defined by the land-use mix with types of road network, average parcel area, average road width, and road length with median (quarter-mile only). In a sense, these variables define the variety or diversity of roads and site specific characteristics within quarter and half-mile distance from the station. Design dimension of the built-environment are characteristics of streetscape and site that affect the use of streets and sidewalks. Unlike the design dimension conceived by Cervero and Kockelman, this analysis evolved two distinct design factors that affect the use of streets and sidewalk. Characteristics of street that affect the use of vehicles were identified as vehicle-oriented design principal component, whereas, the characteristics that affect walking were categories as walking-oriented design principal component. Since there are features of streets that influence walking as much as use of auto, there is bound to be an overlap of physical features that influence walking and use of auto on the streets. Therefore, some design features such as administrative and recreational destinations, personal and vehicular safety, signalized intersection, and vehicles per household constitute the vehicle-oriented design principal component at quarter-mile distance, and as walking-oriented design at half-mile distance.

Bootstrap Principal Component Analysis

Exploratory principal component analysis using the principal component method with Varimax Rotation indicated the principal components that evolved from the quarter and half-mile analyses. Once the principal components were identified, bootstrap principal component analysis was performed individually for both the distances. Thousand repetitions of the principal component analysis were performed using the scripts in SPSS. Factor coefficients that evolved from the repetitions were averaged to obtain the bootstrap factor coefficients. Because the clustering of variables in the bootstrap principal component analysis was identical to the principal component analysis, the factor scores obtained from the principal component analysis were used for bootstrap regression analysis for both the quarter and half-mile principal component analysis.

Bootstrap Principal Component Analysis for Quarter-Mile Distance

The bootstrap principal component analysis resulting from the averaged repetitions reported factor coefficients similar in direction and clustering to the principal components that resulted from the principal component analysis (Table 11). The bootstrap principal component analysis was performed for 1000 repetitions and the factor coefficients were averaged.

The Vehicle-Oriented Design principal component consisted of the signalized intersection, pedestrian-vehicle accidents, crime density, administrative destinations, vehicles per household, recreational destinations, road speed, street light, and sidewalk connectivity. Though sidewalk connectivity is not a supportive principal component of vehicular-environment, the grouping indicates that a well connected sidewalk is available in environment supportive of use of auto. Average parcel size, road connectivity, availability of shoulder on the road, amount of tree canopy, and amount of shade from trees on sidewalk constituted the walking-oriented design principal component. The density principal component included the amount of traffic, amount of parking at stations, residential compactness, sidewalk density, intersection density, housing density, employment density, and population density whereas the diversity principal component was defined by the width of the road, the road network, length of road with median, and land-use mix. Since these principal components were identical to the principal components from principal components analysis, the factor scores obtained from the principal components analysis were used for the bootstrap regression analysis for the second hypothesis.

Table 11.
Quarter-mile bootstrap principal component analysis.

	Vehicle-Oriented Design	Density	Diversity	Walk-Oriented Design
SIG_INT	**0.94** (0.08)	-0.06 (0.15)	0.10 (0.21)	-0.05 (0.16)
PED_VEH	**0.93** (0.08)	0.02 (0.16)	0.04 (0.22)	-0.22 (0.13)
SW_CON	**0.93** (0.06)	0.09 (0.16)	0.14 (0.15)	0.14 (0.19)
CRM_DEN	**0.92** (0.07)	0.05 (0.16)	0.04 (0.21)	-0.26 (0.12)
VEH_P_H	**-0.90** (0.09)	0.21 (0.18)	-0.05 (0.23)	0.00 (0.24)
ADMIN	**0.87** (0.09)	-0.19 (0.12)	0.34 (0.18)	0.07 (0.15)
RECR	**0.80** (0.18)	0.00 (0.16)	0.17 (0.18)	-0.46 (0.20)
RD_SPD	**0.73** (0.17)	-0.20 (0.23)	-0.15 (0.33)	-0.41 (0.24)
ST_LGHT	**0.65** (0.20)	-0.39 (0.16)	0.47 (0.24)	0.18 (0.22)
TRF_VOL	-0.20 (0.15)	**0.90** (0.09)	0.02 (0.25)	-0.01 (0.23)
HOU_DEN	0.04 (0.16)	**0.85** (0.11)	-0.23 (0.30)	-0.15 (0.27)
EMP_DEN	0.03 (0.18)	**0.84** (0.11)	-0.26 (0.33)	-0.04 (0.26)
ST_PARK	-0.25 (0.16)	**0.82** (0.16)	-0.26 (0.27)	0.05 (0.26)
POP_DEN	-0.10 (0.21)	**0.82** (0.10)	-0.31 (0.33)	0.05 (0.26)
LOG_RESCOM	-0.32 (0.15)	**0.81** (0.10)	-0.08 (0.21)	0.38 (0.13)
SW_DEN	0.38 (0.23)	**0.65** (0.21)	0.40 (0.29)	0.09 (0.28)
INT_DEN	0.48 (0.15)	**-0.57** (0.13)	0.42 (0.18)	-0.42 (0.14)
RD_WITH	0.04 (0.25)	-0.28 (0.28)	**0.82** (0.18)	0.04 (0.28)
RD_NET	**0.50** (0.24)	-0.04 (0.26)	**0.71** (0.25)	-0.10 (0.23)
RD_MEDN	-0.25 (0.23)	**0.56** (0.20)	**-0.59** (0.32)	-0.04 (0.28)
LU_MIX	-0.43 (0.26)	0.26 (0.32)	**-0.55** (0.38)	-0.05 (0.36)
I_RDCON	-0.06 (0.14)	0.29 (0.24)	-0.15 (0.24)	**0.85** (0.17)
RD_SHLD	0.13 (0.24)	0.44 (0.21)	0.22 (0.24)	**0.75** (0.13)
CANPY_PER	**-0.54** (0.15)	-0.03 (0.25)	-0.20 (0.21)	**0.72** (0.14)
SQT_SWCVR	**-0.50** (0.20)	0.13 (0.26)	-0.20 (0.25)	**0.70** (0.19)
AVG_PAR	0.02 (0.23)	0.05 (0.33)	-0.35 (0.46)	**-0.65** (0.29)

Values in parenthesis reports the standard deviation for the bootstrapped factor coefficients

Coefficients over | 0.5 | are reported in bold

Reliability Coeff.	0.939	0.838	0.797	0.817

Bootstrap Principal Component Analysis for Half-Mile Distance

The half-mile bootstrap principal component analysis was performed after the principal component analysis with varimax rotation revealed four principal components. The average coefficients for the bootstrap principal component analysis with 1000 repetitions revealed the same four principal components with identical grouping of variables (Table 12).

Table 12.
Half-mile bootstrap principal component analysis.

	Walk-Oriented Design	Diversity	Density	Vehicle-Oriented Design
CRM_DEN	**0.90** (0.06)	0.06 (0.25)	0.04 (0.16)	0.25 (0.18)
SIG_INT	**0.89** (0.04)	0.17 (0.11)	-0.14 (0.11)	0.35 (0.11)
SW_CVR	**-0.89** (0.05)	0.30 (0.13)	0.18 (0.20)	-0.05 (0.16)
PED_VEH	**0.88** (0.06)	0.21 (0.14)	0.06 (0.14)	0.33 (0.13)
SQT_RESCOM	**-0.88** (0.07)	0.17 (0.13)	0.33 (0.18)	-0.13 (0.12)
CANPY_PER	**-0.87** (0.08)	0.06 (0.19)	0.36 (0.20)	-0.01 (0.14)
RECR	**0.85** (0.06)	0.26 (0.15)	-0.21 (0.15)	0.32 (0.16)
ADMIN	**0.84** (0.10)	0.28 (0.15)	-0.01 (0.20)	0.35 (0.16)
RD_SPD	**0.83** (0.10)	0.26 (0.21)	-0.04 (0.26)	0.27 (0.22)
SW_CON	**0.80** (0.12)	0.40 (0.16)	0.25 (0.17)	-0.16 (0.22)
VEH_P_H	**-0.59** (0.23)	0.45 (0.22)	-0.08 (0.25)	-0.47 (0.25)
SW_DEN	**0.52** (0.20)	0.35 (0.29)	0.48 (0.26)	-0.28 (0.33)
RD_WITH	0.08 (0.19)	**0.86** (0.09)	-0.34 (0.16)	0.20 (0.17)
LU_MIX	0.02 (0.21)	**-0.80** (0.15)	0.33 (0.23)	-0.26 (0.25)
AVG_PAR	-0.35 (0.16)	**-0.79** (0.13)	0.12 (0.17)	-0.35 (0.21)
RD_NET	**0.59** (0.15)	**0.71** (0.15)	-0.11 (0.21)	0.01 (0.20)
LOG_HOUDEN	-0.02 (0.12)	-0.14 (0.14)	**0.91** (0.07)	-0.31 (0.13)
LOG_EMPDEN	-0.10 (0.16)	-0.12 (0.19)	**0.88** (0.08)	-0.34 (0.15)
LOG_POPDEN	-0.25 (0.16)	-0.15 (0.17)	**0.84** (0.09)	-0.35 (0.13)
RD_PARK	-0.02 (0.25)	0.49 (0.19)	**-0.63** (0.25)	0.38 (0.25)
TRF_VOL	-0.08 (0.17)	0.11 (0.15)	0.41 (0.12)	**-0.86** (0.08)
ST_PARK	-0.26 (0.21)	-0.11 (0.26)	0.35 (0.24)	**-0.75** (0.25)
INT_DEN	**0.60** (0.12)	0.26 (0.09)	-0.17 (0.12)	**0.70** (0.11)
RD_CON	**0.59** (0.11)	0.10 (0.14)	-0.29 (0.11)	**0.70** (0.11)
ST_LGHT	**0.53** (0.17)	0.46 (0.12)	-0.14 (0.15)	**0.63** (0.15)

Values in parenthesis reports the standard deviation for the bootstrapped factor coefficients

Coefficients over | 0.5 | are reported in bold

Reliability Coeff.	0.955	0.873	0.940	0.893

The walking-oriented design principal component constituted of twelve variables including signalized intersection, pedestrian-vehicle accidents, administrative destinations, vehicles per household, recreational destinations, road speed, and sidewalk connectivity along with the amount of tree canopy, and the amount of shade from trees on sidewalk. Diversity principal component at half-mile distance was defined by the width of the road, the road network, the average parcel area, and the land-use mix, whereas density principal component was characterized by the amount of parking on the road, housing, employment, and population densities. Vehicle-oriented design principal component included traffic volume, amount of parking at the stations, intersection density, road connectivity, and street lights. Factor scores that evolved from the principal component analysis were used to perform the bootstrap regression for the half-mile analysis of Hypothesis 2.

Hypothesis II

Bootstrap Regression

The second hypothesis of the present study investigated the relationship between the constructs of built-environment, identified through principal component analysis, and percent of transit users that walk to transit stations. Bootstrap regression with 1000 repetitions was performed to analyze this hypothesis. Two regressions were performed at quarter and half-mile distance from the stations. Income (measured as median income) and ethnic density were included in the equation as control variables as identified by Besser and Dannenberg (2005).

Walking to Transit (Y) = c (Constant) + β1 *(Vehicle-Oriented Design) +

β2 *(Walking-Oriented Design) + β3*(Density) +

β4 *(Diversity) + β5 *(Median Income) + β6 *(Ethnic Density)

Since the grouping of variables that defined the bootstrap principal components were similar to the grouping observed in the principal component analysis, the factor scores obtained from the principal component analysis were used to perform the bootstrap regression. The factor scores for each principal component at every station were obtained by the formula described in Thompson (2004):

$$F_{N \times F} = Z_{N \times V} \, R_{V x V}^{-1} \, P_{V \times F}$$

Where, $F_{N \times F}$ is the factor score of each principal component (N – No. of stations; F – No. of factors); $Z_{N \times V}$ is the Z-value of the variable V at station N; $R_{V x V}^{-1}$ is inverted correlation matrix of variables V; and $P_{V \times F}$ is varimax-rotated pattern/structure coefficients of each variable under each factor.

These factor scores were available for further analysis from the principal component analysis performed in the SPSS. Therefore, the factor scores of all the four principal components and the two measured control variables were used as the predictor variables and walking percent to transit was used as the criterion or the dependent variable in the bootstrap regression.

<u>Bootstrap Regression for Quarter-Mile Distance</u>

The quarter mile analysis included the four principal component and the two control variables as independent variables that were regressed on the percentages of walking to transit at each station. The overall model was moderately explained with r-square of

54%, but was not a statistically significant model (*p*=0.47). Though not significant, the effect size of the quarter-mile regression analysis is moderate at a value of 0.328. Also, the bootstrap r-square value is statistically significant at *p*<0.001 level. Therefore, the regression coefficients will be discussed to report the influence of the variables on walking to transit.

The results of bootstrap regression analysis indicate that at quarter-mile distance, density matters the most as shown in Table 13. Density (β = -0.767) was the only principal component that significantly (*p*<0.05) explained walking to transit station at quarter-mile distance from the station. Both the structure coefficient (-0.776) and the standardized coefficient indicate that density has maximum influence on the outcome (walking to transit). Other principal components, though not statistically significant, indicated interesting relationship to walking to transit. Diversity of land-use and road features reported a positive relationship with walking to transit (β = -0.593). The structure coefficient indicates that diversity of the built-environment is the second most influential variable on walking to transit. As expected, vehicle-oriented design that supports the use of auto reported a negative influence (β = -0.098; r_s = -0.203) on walking to transit. Surprisingly, walking-oriented design reported a negative relationship (β = -0.349) with walking to transit. However, the structure coefficient indicates that the walking-oriented design principal component is a suppressor variable whose inclusion indirectly effected walking to transit. Thompson (2006, 243) suggested that when predictors have nonzero β weight but have a close to zero structure coefficient they are

Table 13.
Quarter-mile bootstrap regression.

Number of obs = 20
Replications = 1000
Wald chi2(6) = 5.59
Prob > chi2 = 0.4706
R-squared = 0.5399
Adj R-squared = 0.3276
Root MSE = 15.2876
Std. Err. = 0.1532
z = 3.52
p < 0.001

		OLS Regression							
Walk_Per	Observed Coef.	Unstdized Coef	Stdized Coef.	Structure Coef.	Bootstrap Std. Err.	z	P>|z|	Normal-based [95% Conf. Interval]	
Veh_O_Design	-1.832876	-1.833	-0.098	-0.203	6.524826	-0.28	0.779	-14.6213	10.95555
Density	-14.29932	-14.299	-0.767	-0.776	6.216529	-2.30	0.021	-26.4835	-2.115151
Diversity	11.04621	11.046	0.593	0.390	7.006564	1.58	0.115	-2.686408	24.77882
Walk_O_Design	-6.501731	-6.502	-0.349	-0.088	8.124639	-0.80	0.424	-22.42573	9.42227
Med_Inc	.0001336	0.000	0.135	0.229	.0003907	0.34	0.732	-.0006322	.0008993
Ethn_Den	.0074195	0.007	0.640	-0.270	.0056945	1.30	0.193	-.0037415	.0185804
_cons	22.72072	22.721	-	-	16.44726	1.38	0.167	-9.515312	54.95675

Table 14.
Half-mile bootstrap regression.

Number of obs = 20
Replications = 1000
Wald chi2(6) = 4.05
Prob > chi2 = 0.6699
R-squared = 0.3470
Adj R-squared = 0.0456
Root MSE = 18.2133
Std. Err. = 0.1667
z = 2.08
p < 0.05

		OLS Regression							
	Observed	Unstdized	Stdized	Structure	Bootstrap			Normal-based	
Walk_Per	Coef.	Coef	Coef.	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
Veh_O_Design	2.464269	2.464	0.132	0.377	5.61992	0.44	0.661	-8.550573	13.47911
Density	-6.62353	-6.624	-0.355	-0.719	9.506362	-0.70	0.486	-25.25566	12.0086
Diversity	7.977038	7.977	0.428	0.332	7.501883	1.06	0.288	-6.726381	22.68046
Walk_O_Design	6.074842	6.075	0.326	0.010	8.979588	0.68	0.499	-11.52483	23.67451
Med_Inc	-.0008089	-0.001	-0.581	-0.153	.001078	-0.75	0.453	-.0029218	.001304
Ethn_Den	-.0013667	-0.001	-0.129	-0.385	.0085996	-0.16	0.874	-.0182215	.0154881
_cons	74.53185	74.532	-	-	55.75171	1.34	0.181	-34.73949	183.8032

classified as suppressor variable whose inclusion improves the overall model fit indirectly.

At quarter-mile distance, unlike in previous studies (eg., Besser and Dannenberg, 2005), increase in median income indicated an increase in walking (β = 0.135; r_s = 0.229). On the contrary, ethnic density reported a positive influence (β = 0.640) on walking to transit stations just as reported by Besser and Dannenberg (2005). However, the structure coefficient indicates that ethnic density has negative influence the $\hat{Y}$. Density reported maximum effect on walking to transit, followed by diversity and walking-oriented design.

Bootstrap Regression for Half-Mile Distance

The results of the bootstrap regression of built-environment variables at half-mile distance as shown in Table 14, did not report any significant relation to walking to transit. The overall explanatory power of the model was low at only 35%, which was again not a significant model (*p*=0.67). The half-mile regression analysis reported a very low effect size of value 0.046. However, the bootstrap r-square value is statistically significant at $p<0.05$ level.

In the half-mile analysis, similar pattern of structure coefficients of predictor variables was observed as in the quarter-mile analysis. However, both vehicle-oriented (β = 0.132) and walking-oriented (β = 0.326) design principal component reported a positive influence on walking to transit. Walking-oriented design again reported as a suppressor variable with a β of 0.326 and r_s of 0.010. Additionally, diversity reported a positive relation to walking to transit station (β = 0.428). For half-mile distance from the transit station, density reported a negative relation to walking to station (β = -0.355). Also, at half-mile distance from the station, median income reported a negative influence on walking to transit (r_s = -0.153).

Mediating Effect on Walking to Transit

The role of density on walking to transit was investigated to check if there was any mediatory effect that accounted for the unexpected negative coefficient at quarter and half-mile distance. Logically thinking, the reason a place with high density reports a low walking percentage could be because individuals of that community use other mode of transportation to get to the transit station. Since driving is one of the major modes of transportation, measuring the mediating effect of driving on walking to transit could explain the role of density as reported by the bootstrap regression analysis. However, since the percent of transit users who drive to transit station was not used for this analysis, the amount of parking at station could be used as a proxy to measure the driving amount to the station. Also, the amount of parking at stations reported a significant negative correlation with walking to transit. Therefore, the mediating effect of amount of parking at the station on walking to transit was empirically tested using the procedure suggested by Barron and Kenny (1986). The outcome variable (percent walking to transit) was regressed with the initial variable (population density) and the mediating variable (amount of parking at station). The significant regression coefficient of population density (β = -0.517 significant at $p<0.05$) on walking to transit, when regressed again along with the mediating variable reported a regression coefficient (β = -

0.231) that was not significant (Figure 8). This indicated that the amount of parking had a partial

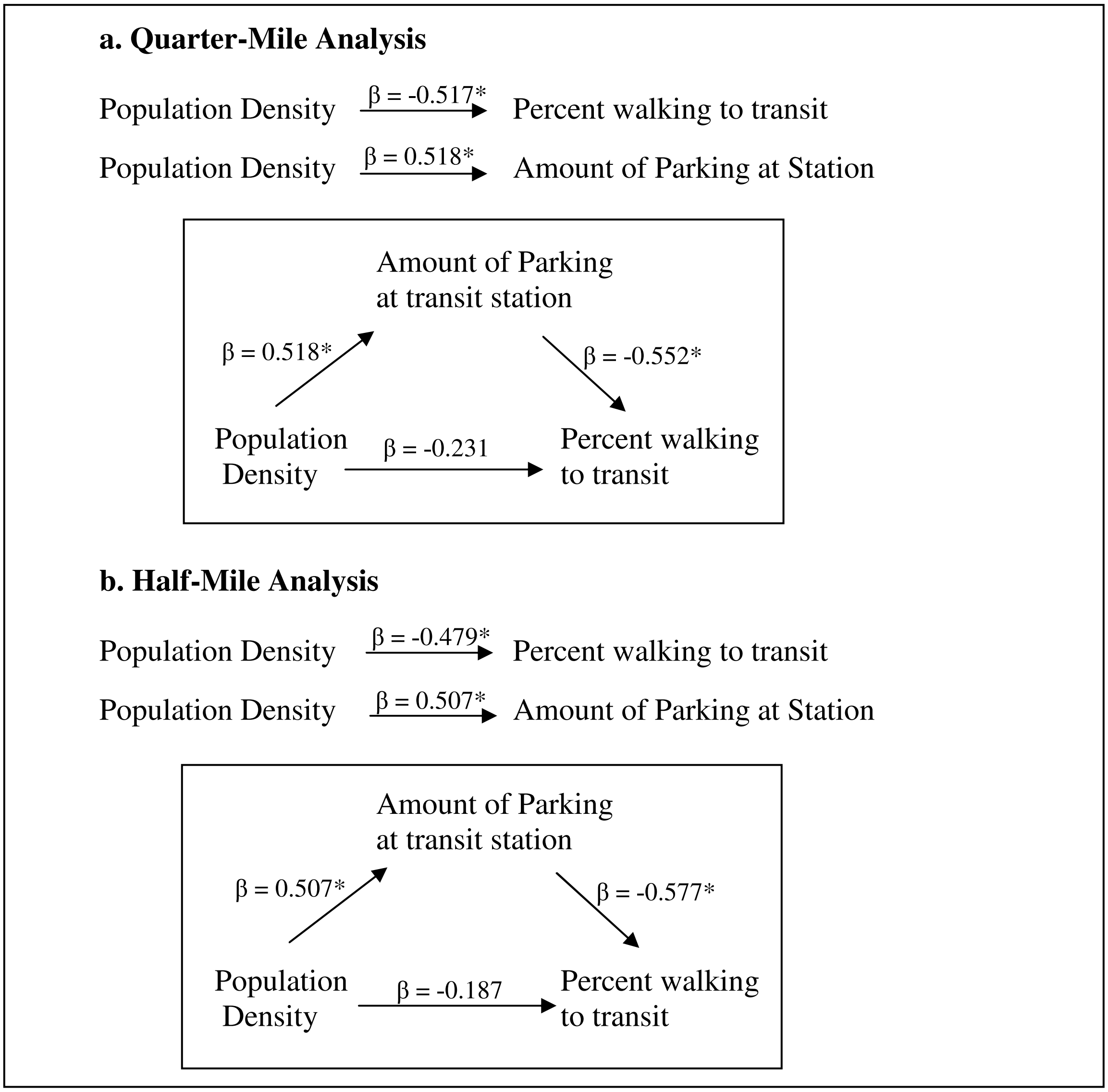


Figure 8. *Mediating effect of amount of parking on walking to transit at (a) quarter and (b) half-mile distance*

mediating effect on walking to transit. At the quarter-mile analysis, the amount of mediation or indirect effect was -0.286 and the half-mile analysis the indirect effect was reported to be -0.292.

Comparing Models

The following section compares the results from bootstrap principal component analysis and bootstrap regression between the quarter and half-mile distances. Comparison of these analyses across the varying distances can help identify environmental interventions that can promote walking to transit at a certain distance from the transit station. This can help identify the interventions that can be effective at certain distances versus other distance. The constructs that were extracted from the quarter and half-mile analysis are compared in the following section. The next section compares the regression coefficients from both the models.

Density

The density principal component at the half-mile distance from the transit station was constituted by the demographic variables (i.e., population density, housing density, and employment density) and the number (amount) of parking availability on the roads. Conversely, at the quarter-mile distance, other built-environment characteristics such as sidewalk density, intersection density, number of parking at the stations, amount of traffic, and residential compactness along with the demographic variables constituted the density principal component. Therefore, to greater extent built-environment characteristics at the quarter-mile distance, characterizes the density principal component.

Diversity

The diversity principal component at both quarter and half-mile distances constituted of land-use mix, road network, and road width. Other built-environment variables that constituted the diversity principal component were road median at quarter-mile distance and average parcel area at half-mile distance. This meant that the diversity principal component at both the distances of quarter and half-mile, reported similar characteristics.

Vehicle-Oriented Design

Road characteristics that are particularly supportive of auto use characterize the vehicle-oriented design principal component at half-mile distance. Road features such as connectivity of road, intersections, amount of parking on the road, amount of traffic on the road, and street lights defined the vehicle-oriented design principal component at half-mile distance. Conversely, at quarter-mile distance from the station, street light with other built-environment variables such as signalized intersections, vehicular speed on the road, destinations (administrative and recreational) within quarter-mile, safety (both vehicular and personal), and vehicles per household formed the vehicle-oriented design principal component. Surprisingly, sidewalk connectivity also defined the vehicle-oriented design principal component at quarter-mile distance.

Walking-Oriented Design

Built-environment characteristics, particularly supportive of walking defined the walking-oriented design principal component at quarter-mile distance from the station. Availability of shoulder on the road, percentage of canopy within the quarter-mile of the station, amount of sidewalk in shade, parcel size, and road connectivity defined the walking-oriented design principal component at quarter-mile distance. At half-mile distance the same principal component was defined by sidewalk in shade, percentage of canopy within half-mile distance with other destinations, sidewalk density and connectivity, safety, designated road speed, signalized intersection, residential compactness, and availability of vehicles per household. Therefore, walking-oriented design principal component was more clearly defined at quarter-mile distance from the station compared to half-mile distance.

Bootstrap Regression

The bootstrap regression at both quarter and half-mile distance reported a bootstrap r-square significant at $p<0.001$ and $p<0.05$ level respectively. However, the OLS regression did not report a significant r-square value. This was so because the bootstrap regression reports a standard error which is different from the standard error reported in the OLS regression. Since the bootstrap regression takes care of the assumptions of normal distribution of the observation values with resampling method, the standard error reported is better and thus report a significant r-square at both the analysis.

Only the density principal component at quarter-mile distance reported a statistically significance impact on walking to transit station, although, both quarter and half-mile distance analysis reported a negative coefficient for density when regressed on walking to transit. Diversity reported a positive relationship with walking to transit at both the distances, though they were not statistically significant in both the analysis. The structure coefficients of both the model were similar in magnitude in explaining the walking to transit station. The coefficient reported that density had the maximum influence on the Y explained. Also, in the both the models, since walking-oriented design principal component reported a non-zero beta coefficient but a structure coefficient close to value of zero, this analysis indicates that the walking-oriented design principal component is a suppressor variable in this analysis.

The vehicle-oriented design, walking-oriented design, ethnic density, and median income reported contrasting results at varying distances. Vehicle-oriented design and walking-oriented design reported a negative coefficient with walking to transit at quarter-mile distance whereas at half-mile distance, these principal components reported a positive relation with walking to transit, though not statistically significant at both the distances. Conversely, ethnic density and median income reported a positive coefficient at quarter-mile distance and negative coefficients at half-mile distance. Neither of these variables was significant at both the distances.

CHAPTER V

DISCUSSION AND CONCLUSIONS

Discussion

Travel demand management studies have reported that built-environment have moderate influence on the travel mode (Holtzclaw 1994; Handy 1996; Cervero 1996; Cervero and Radisch 1996; Kockleman 1997; Cervero 2002). Large number of these studies in the last decade targeted individual based interventions. Identifying the factors of built-environment at a larger scale such as community level, and investigating its impact on non-motorized mode of travel such as walking can help intervene the changes that "could effect entire community population on a relatively permanent basis as compared to individual oriented behavior change interventions" (Dishman and Buckworth 1996). This study captured the built-environment variables into specific constructs that influence walking at neighborhood level. Cervero and Kockelman (1997) conceptualized the grouping of environmental correlates of travel into three constructs or as they termed it 3Ds: Density, Diversity, and Design. Lee and Moudon (2006a) succinctly reported that

> "To date, .., the identification of specific variables and measurements that can reliably capture the Three Ds is lacking"

With a similar conceptual framework, Lee and Moudon identified four constructs of built-environment: 3D+R (Density, Diversity, Design and Route). This study investigated the grouping of environmental correlates using principal component analysis. This analysis revealed four principal components: Density, Diversity, Vehicle-

Oriented Design, and Walking-Oriented Design. The design principal component conceptualized by Cervero and Kockelman included road network, number of intersections, road connectivity, sidewalk density, signalized intersection, street lights, parking on the road, and other destination within the study area. Principal component analysis for this study segregated these variables that formed the design principal component into vehicle-oriented and walking-oriented. Built-environment variables used in this study, that are related to the street corridor that supports the use of auto grouped to define the vehicle-oriented design principal component. Meanwhile, the walking-oriented design principal component primarily consisted of built-environment variables that defined the walking corridor along the road network. Since both these corridors are part of a general streetscape, some built-environment variables such as signalized intersection, destinations within walking distance, crime density, pedestrian-vehicle accidents, and designated vehicle speed on the road can be part of both vehicle-oriented and walking-oriented design principal component. This might have been the reason for Cervero to conceptualize both the design principal components into one dimension. Segregating these design variables into vehicle-oriented and walking-oriented can help prioritize and manage the specific interventions that can support use of non-motorized mode of travel.

However, the vehicle-oriented design principal component in the quarter-mile analysis consisted of sidewalk connectivity variable. Though the connectivity of sidewalk is not a support environment for driving, the possible explanation for its grouping with other vehicle supportive environment is that generally, a well connected sidewalk exists on road network that is well connected and supportive of driving. For example, the new-urbanist communities have grid-iron network of streets that supports ease of driving. These environments also have sidewalks that are well connected and supportive of walking. Also, the walking-oriented design principal component included road connectivity, which can again be justified with the fact that well connected roads have well connected sidewalk. Conversely, in the half-mile analysis the vehicle per household measure was grouped along with the walking-oriented design principal component. Availability of private cars discourage non-motorized mode of travel such as walking and biking. Therefore, availability of cars was grouped along with other walking-supportive variables.

Density dimension or principal component as conceptualized by Cervero consisted of demographic variables and accessibility index. However, the density principal component at quarter-mile distance reported grouping of demographic variables such as population, employment, and housing with other measures of built-environment such as intersection density, sidewalk density, amount of traffic on roads, parking at stations, and amount of residential compactness. Meanwhile, the density principal component at half-mile distance consisted of demographic variables and amount of parking on roads. This indicated that at any distance from the station, density is primarily defined by the demographic variables. Diversity of built-environment is defined primarily in the present study by land use mix, type of road network, and width of road at both quarter and half-mile distance. Changing road characteristics with and without median was another variable that grouped with the variables mentioned above to define the diversity principal component at quarter-mile distance.

The four principal components (i) Density, (ii) Diversity, (iii) Vehicle-Oriented Design, and (iv) Walking-Oriented Design that evolved from principal component analysis were regressed with percentage of transit users walking to station. Contrary to previous studies that reported positive influence of density on walking (Handy 1996; Besser and Dannenberg 2005), in the current analysis, density principal component at quarter-mile distance reported statistically significant negative coefficient with walking to transit. Bi-variate correlation revealed that population, housing, employment density, and traffic volume reported positive significant correlation with parking at the station. This indicates that at locations with high density, both demographic and traffic, the availability of parking at stations is high. This results in more transit users probably driving and parking at stations, rather than walking to station. Therefore, the increase in density results in increased use of cars and not increased walking to transit station. Density reported a negative coefficient with walking to transit at half-mile distance as well, though statistically not significant.

Diversity reported a positive coefficient with walking to transit at both quarter-mile and half-mile distance. Though not statistically significant, diversity principal component showed similar relation to walking as reported in previous studies (Cervero and Kockelman 1997; Lee and Moudon 2006a). Mixed land-use has shown to have positive impact on non-motorized mode of travel such as walking and biking (Frank et al. 2005; and Moudon 2006b). In the present study, the regression coefficient of diversity indicate that increased mixed land-use and improving of road features such as road network, road with median, and road width increases the possibility of people walking to transit.

Design principal components, both vehicle-oriented and walking-oriented, reported negative coefficients at quarter-mile and positive coefficients at half-mile distance from the station. Negative relationship of vehicle-oriented design principal component with walking to transit indicated that as the environment supportive of vehicle reduces, the possibility of individuals walking to transit station increased. However, at half-mile distance the vehicle-oriented design principal component reported positive coefficient with walking to transit. This indicates that at half-mile distance from the transit station, even vehicle-oriented design principal components such as road connectivity and intersection density have positive influence on walking. Meanwhile, the walking-oriented design principal components reported a negative influence on walking to transit at quarter-mile distance. As a suppressor variable, the inclusion of walking-oriented design in the model improved the overall model, at least at the quarter-mile distance analysis. This means that walking-oriented design principal component by itself does not influence walking to transit, but affects the impact of other variables on walking to transit and thus justifies its inclusion in future studies.

Increase in median income at quarter-mile distance from the station reported a positive coefficient with walking to transit. Though the magnitude of the coefficient is low, this relationship indicates that as the median income of the individuals increases, they are more likely to walk to transit. However, at half-mile distance, increase in median income reported a negative and high coefficient with walking to transit, indicating that as the median income of individuals increases, they are less likely to walk to transit. Contrary to previous studies, this result indicates that even individuals with higher income walk to transit if they are at closer proximity to the station. Conversely, ethnic density reported a positive relation to walking to transit at quarter-mile distance and negative coefficient at half-mile distance. This result indicates that as the people of minority or other ethnic background than white, tend to walk to transit at closer proximity to station, but at half-mile distance, as minorities increases the possibility of them walking to transit decreases. This result is complimentary to a prior study conducted by Besser and Dannenberg (2005). However, their study did not check for influence of change in distance on minorities walking to transit.

Implications of This Study

This study provides several lessons, both methodological and inferential, that can help guide future studies. Firstly, the existing need of the physical activity research is to use spatial data to measure the built-environment that can be replicated efficiently. As pointed out by Heath et al. (2006), the knowledge of how existing spatial data can be used to improve the measure of built-environment needs to be derived for future studies. This study uses detailed environmental data to the scale of parcel-level information to understand its influence on walking to transit. This is important because walking is influenced by detailed fine-grain data. Lee and Moudon (2006a) reported that

> ..these data may not be sufficient to examine all important details of environments relevant to walking or other transportation behaviors. However, they serve to investigate a large number of variables efficiently and systematically, and therefore help circumvent cost-prohibitive field data collection or streamline field work to focus on those elements that are likely correlates of walking.

This study adapted or modified existing measures such as road length with median, road length with parking and shoulder, which were in tabular format into spatial format and identified ways to spatial measure the built-environment such as road network and safety using classification system from the existing literature. The ease of converting this information into spatial format allows these fine-grained data to be measures objectively in GIS and used for further analysis.

Secondly, the use of principal component analysis to group the variables helped narrow the list of observed variables to a reduced number of latent variables. Density principal component grouped the demographic and built-environment density measures such as intersection density, sidewalk density, population and employment density, and housing density. Diversity principal component, as in earlier studies, measured the changes in land-use, parcel area, road network. This measure builds on the diversity measure conceptualized by Cervero and Kockelman (1997) since it measures more than the just the diversity of land-uses. Built-environment includes diversity of not just land-use but diversity of urban form such as road network and parcel area, as well. However, the built-environment variables that identify the vehicle-oriented and walking-oriented design principal component were group together just as the design dimension conceptualized by Cervero. This analysis identified two distinct principal components of design variables that support the motorized and the non-motorized mode of travel, separately, in the existing streetscape. This is important because though the individuals driving and walking or biking use the same environment (street corridor), their experience of the environment differs. Also, since both the mode of travel (motorized and non-motorized) follow the same corridor, in most cases, they directly or indirectly influence each other to certain extent. This can be seen from the grouping of design variables at quarter-mile versus half-mile distance. Certain variables such as safety, destinations within walking distance, and signalized intersections form a part of vehicle-oriented design principal component at quarter-mile distance, whereas at half-mile distance, the same variables constitute the walking-oriented design principal component. This indicates that at the quarter-mile distance, these variables influence the vehicle-oriented environment whereas at half-mile distance, they influence the walking-oriented environment. Therefore, the interventions that can promote or influence walking at half-mile distance do not necessarily help do the same at quarter-mile distance. This is an important finding because generally investigation of built-environment reveals walking oriented interventions that are universally adopted at all distances. As the analysis of this study reveals, this is not the case. Environmental interventions need to be identified based on the distance and not be adopted universally for all distances.

Methodologically, this study introduces the use of bootstrapping for walking oriented research. Small sample data can still to be used to provide the local description of data and help improve the stability of result (Lunneborg 2000). The apparent lack of funds to observe large number of subjects can be compensated by use of modern statistical methods such as bootstrapping. However, it should be noted that using these techniques does not make the existing data magically representative of the population. These techniques only provide stability to the data analysis and helps report the results with more confidence. Though this study uses bootstrapping to overcome the small sample issue, it still uses the existing 20 observations for resampling. Availability of more observations can help make more valid and reliable decisions and probably help develop statistically significant model to test the influence of built-environment on walking to transit.

Finally, the reverse relation of density on walking to transit indicates that increasing density does not necessarily increase walking. Increase in crime and decrease in personal safety, and availability of environment and supporting facilities for motorized mode of travel such as highways, freeways, abundant parking, etc can facilitate use of private auto and discourage walking or biking. As the present study reveals, availability of parking at stations had a significant positive correlation with population and employment density. This explains the influence of parking at station on walking to transit. As density increased parking at stations increased, which led to decrease in transit users walking to transit station. Therefore, mere increase of density should not be taken as a proxy of increase in walking. Environmental interventions that can promote walking should be identified even at locations with high density. Though most of the other principal component remained insignificant, the coefficients indicate a relationship that is worth further investigation and clarification. As Rosnow and Rosenthal (1989) and Cohen (1988) reported that statistical significance is more often a function of number of observations. Therefore, the direction and magnitude of these coefficients cannot be dismissed as mere lack of sufficient observations. Advanced statistical models and methods can be used to further test the relationship of these variables on walking to transit.

Recommendations for Future Research

This study was developed with a premise to develop two indices that can help identify the specific environmental and/or policy interventions that can increase walking to transit stations. The use of factor analysis to test the role of latent variables of built-environment indicates that several constructs that have been indicated to be theoretically and conceptually important to support walking were reported to be not significant in this study. The availability of only twenty observations could be one of the reasons for these results. Using advanced statistical techniques such as Hierarchical Linear Modeling (HLM) or Structural Equation Modeling (SEM) to test the relationship of both the factors and the individual variables that define the factor can give a clearer understanding of this relationship. Another limitation of this study is the exclusion of ease and frequency of availability of transit service, which plays an important role in the travel choice decision. Also, this analysis does not include the objective measure of walking. It relies on self-reported data obtained from the NCTCOG survey. Use of digital counters to collect objective measure of transit users walking to transit can capture more reliable walking behavior. Also, certain variables that can be objectively measures were not included in this study for lack of appropriate method to spatially evaluate the information. Advances in GIS and data collection method can help identify methods to incorporate that information in a spatial format and use them for further analysis.

Conclusion

This study investigated the relationship of built-environment principal components on walking to transit using the objective measures of built-environment. Twenty-nine objective measures, developed in GIS, were grouped using principal component analysis to determine the built-environment principal components. This analysis performed for the quarter-mile and half-mile distance from the transit station evolved four built-environment principal components namely, Density, Diversity, Vehicle-Oriented Design, and Walking-Oriented Design. Bootstrap regression was performed to test the role of these principal components on walking to transit. Density was the only principal component at quarter-mile distance that significantly influenced walking to transit. Unlike previous studies, density was negatively related to walking to transit. Control variables, median income and ethnic density, reported a positive relation with walking to transit at quarter-mile distance, whereas at half-mile distance, these variables reported a negative relation with walking to transit.

The results of the present study suggest that increasing density does not necessarily increase walking to transit. Improving other supporting environment that encourages walking and discourages use of auto can justify the increase in density for increasing walking to destinations such as transit station. Also, both individual and grouped latent variable’s influence on walking to transit needs to investigated to identify specific environmental interventions that can increase walking to transit. Finally, more research is needed to identify effective environmental interventions that can increase walkability to transit stations and use transit for their everyday travel instead of private cars that is known to cause congestion and environmental pollution.

REFERENCES

1000 Friends of Oregon. 1997 *Making the Connections: A Summary of LUTRAQ Projects*. Prepared by Parsons Brickerhoff Quade and Douglas, Inc., with Cambridge Systematics, Inc. and Calthorpe Associates.

1000 Friends of Oregon. 1993. *Making the Land Use Transportation Air Quality Connection: The Pedestrian Environment*, Volume 4A. Prepared by Parsons Brickerhoff Quade and Douglas, Inc., with Cambridge Systematics, Inc. and Calthorpe Associates.

Allan, A. 2001. Walking as a local transport model choice in Adelaide. *World Transport Policy Practice* 7(2):44–51.

Aultman-Hall, L., Roorda, M., and Baetz, B.W. 1997. Using GIS for evaluation of neighborhood pedestrian accessibility. *Journal of Urban Planning and Development* 123(1):10-17.

Ball, K., Bauman, A., Leslie, E., Owen N. 2001. Perceived environmental aesthetics and convenience, and company are associated with walking for exercise among Australian adults. *Preventive Medicine* 33:434-40

Bandara, S., Wirasinghe, S.C., Gurofsky, D., and Chan, P. 1994. Grade-separated pedestrian circulation systems. *Transportation Research Record* 1438:59–66.

Baron, R.M., and Kenny, D.A. 1986. The moderator-mediator variable distinction in social psychological research: conceptual, strategic, and statistical considerations. *Journal of Personality and Social Psychology* 51(6): 1173-1182

Bauman, A., Sallis, J.F., and Owen, N. Environmental and policy measurement in physical activity research *In Physical Activity Assessment for Health-Related Research*. Eds: Welk G, Dale D. Champaign IL: Human Kinetics.

Besser, L.M., and Dannenberg, A.L. 2005. Walking to public transit: steps to help meet physical activity recommendations. *American Journal of Preventive Medicine* 29(4):273-280

Boos, D.D., and Brownie, C. 1989. Bootstrap methods for testing homogeneity of variances. *Technometrics* 31(1):69-82

Booth, M., Owen, N., Bauman, A., Clavisi, O., and Leslie, E. (2000). Social-cognitive and perceived environment influences associated with physical activity in older Australians. *Preventive Medicine* 31:15-22

Bradshaw, C. 1993. Creating and Using a Rating System for Neighborhood Walkability: Towards an Agenda for ‘‘Local Heroes.’’ Paper presented at the 14th International Pedestrian Conference; Boulder, CO.

Brownson, R.C., Baker, E.A., Housemann, R.A., Brennan, L.K., and Bacak, S.J. 2001. Environmental and policy determinants of physical activity in the United States. *American Journal of Public Health* 91:1995-2003.

Carreno, M., Willis, A., and Stradling, S. 2002. *Quality of Service Experienced by Pedestrians in Edinburgh*. Transport Research Institute, Napier University.

CDC (Center for Disease Control and Prevention). 1996. *Physical activity and health: A report of the Surgeon General.* Atlanta, GA: U.S. Department of Health and Human Services.

CDC (Center for Disease Control and Prevention). 1999. Neighborhood safety and the prevalence of physical activity – selected states. *MMWR* 48:143-146

CDC (Center for Disease Control and Prevention). 2001. *Increasing Physical Activity. Morbidity and Mortality Weekly Report*. Washington, DC: US Department of Health and Human Services.

Cervero R. 1996. Mixed land-uses and commuting: Evidence from the American Housing Survey. *Transportation Research A* 30:361-77

Cervero, R. 2002. Built environments and mode choice: Towards a normative framework. *Transportation Research D* 265-84

Cervero, R., and Gorham, R. 1995. Commuting in transit versus automobile neighborhoods. *Journal of American Planning Association* 61: 210-25

Cervero, R., and Radisch, C. 1996. Travel choices in pedestrian versus automobile oriented neighborhoods. *Transport Policy* 3(3):127-141.

Cervero, R., and Kockelman, K. 1997. Travel demand and the 3Ds: Density, diversity, and design. *Transportation Research D* 2(3). 199-219

City of Fort Collins. 2002. *Pedestrian Level-of-Service.* Fort Collins, CO: City of Fort Collins

City of Portland. 1998. *Portland Pedestrian Master Plan.* Portland, OR: City of Portland;

Cohen, J. 1988. *Statistical power analysis for the behavioral sciences.* (Rev. Ed.). New York: Academic Press.

Dannenberg, A. 2004. Assessing the walkability of the workplace: A new audit presented at the 4th National Congress of Pedestrian Advocates, America Walks. Silver Spring: MD

Dishman, R.K., and Buckworth, J. 1996. Increasing physical activity: a quantitative synthesis. *Med. Sci. Sports Exercise* 28:706-19

Dixon, L. 1996. Bicycle and pedestrian level of service performance measures and standards for congestion management systems. *Transportation Research Record* 1538:1–9.

Edgington, E.S. 1995. *Randomization tests*. M. Dekker: New York.

Efron, B., and Tibshirani, R.J. 1986. Bootstrap methods for standard errors, confidence intervals, and other measures of statistical accuracy. *Statistical Science* 1(1):54-75

Efron, B., and Tibshirani, R.J. 1993. *An introduction to the bootstrap*. Chapman & Hall Publishers: New York.

Ewing, R., Haliyur, P., and Page, G. (1994) Getting around a traditional city, a suburban PUD, and everything in-between. *Transportation Research Record* 1466: 53-62

Fehr and Peers Associates. 1992. Metropolitan Transportation Commission Bay Area Trip Rate Survey Analysis, Metropolitan Transportation Commission, Oakland.

Forsyth, A., Schmitz, K.H., Oakes, M., Zimmerman, J., and Koepp, J. 2006. Standard for environmental measurement using GIS: Toward a protocol for protocols. *Journal of Physical Activity and Health* 3(S1):S241-57

Fox, J. 2002. Bootstrapping Regression Models: An Appendix to An R and S-Plus Companion to Applied Regression. Available at: http://cran.rproject.org/doc/contrib/Fox-Companion/appendix-bootstrapping.pdf (accessed on August 2005)

Francis, K. 1997. The burden of physical inactivity and cardiovascular heart disease. *Comprehensive Therapy* 24(2): 87-92.

Frank, L.D., and Pivo, G. 1994. Impacts of mixed use and density on utilization of three modes of travel: Single-occupant vehicle, transit, and walking. *Transportation Research Record* 1466: 44-52.

Frank, L.D., Schmid, T.L., Sallis, J.F., Chapman, J., and Saelens, B.E. 2005. Linking objectively measured physical activity with objectively measured urban form: Findings from SMARTRAQ. *American Journal of Preventive Medicine* 28(2S2):117-125

Gallin, N. 2001. Quantifying pedestrian friendliness—guidelines for assessing pedestrian level of service. Paper presented at Walking the 21st Century: Perth, Western Australia.

Giles-Corti, B., and Donovan, R.J. 2002a. Socioeconomic status differences in recreational physical activity levels and real and perceived access to a supportive physical environment. *Preventive Medicine* 35:601-611.

Giles-Corti, B., and Donovan, R.J. 2002b. The relative influence of individual, social and physical environmental determinants of physical activity. *Soc Sci Med.* 54(12):1793-1812.

Greenwald, M., and Boarnet, M. G. 2002. The built environment as a determinant of walking behavior: Analyzing non-work pedestrian travel in Portland, Oregon. *Transportation Research Record* 1780: 33-42

Handy, S. 1992. Regional versus local accessibility: Neo-traditional development and its implications for non-work travel. *Built Environment* 18(4): 253-67

Handy, S. 1996. Urban form and pedestrian choice: study of Austin neighborhoods. *Transportation Research Record* 1552:135-44

Handy, L.S., Boarnet, M.G., Ewing, R., Killingsworth, R.E. 2002. How the built environment affects physical activity. Views from Urban Planning. *American Journal of Preventive Medicine* 23(2S): 64-73

Heath G.W., Brownson R.C., Kruger J., Miles R., Powell K.E., Ramsey L.T., & the Task Force on Community Preventive Services. 2006. The effectiveness of urban design and land use and transport policies and practices to increase physical activity: A systematic review. *Journal of Physical Activity and Health* 3(S1): S55-S76.

Higgins, G.E. 2005. Statistical significance testing: The bootstrapping method and an application to self-control theory. *The Southwest Journal of Criminal Justice* 2(1):54-76

Holtzclaw, J. 1994. *Residential patterns and transit, auto dependence, and costs*. San Francisco: Natural Resources Defense Council.

Hoyle, R.H. 1999. *Statistical strategies for small sample research*. Thousand Oaks, CA: Sage Publications.

Khisty, C. J. 1994. Evaluation of pedestrian facilities: Beyond the level of service concept. *Transportation Research Record* 1438:45–50.

Kitamura, R., Mokhtarian, P.L., and Laidet, L. 1997. A micro-analysis of land use and travel in five neighborhoods in the San Francisco Bay area. *Transportation* 24: 125-58

Kockelman, K. M. 1997. Travel behavior as function of accessibility, land use mixing, and land use balance: Evidence from San Francisco Bay area. *Transportation Research Record* 1607: 105-115

Landis, J.R., and Koch, G.G. 1977. The measurement of observer agreement for categorical data. *Biometrics* 33: 159-174.

Landis, B.W., Vattikuti, V.R., Ottenberg, R.M., McLeod, D.S., and Guttenplan, M. Modeling the roadside walking environment: a pedestrian level of service. *Transportation Research Record.* TRB No. 01-0511.

Lee, C., and Moudon, A.V. 2006a. The 3Ds + R: Quantifying land use and urban form correlates of walking. *Transportation Research D* 11: 204-215

Lee, C., and Moudon, A.V. 2006b. Correlated of walking for transportation or recreation purposes. *Journal of Physical Activity and Health* 3[S1]:S77-S98

Lorenzo-Seva, U., and Ferrando, P. J. 2003. An unrestricted factor-analysis-based program for assessing measurement invariance. *Behavior Research Methods, Instruments, & Computers* 35:318-321

Loutzenheiser, D. R. 1997. Pedestrian access to transit: Model of walk trips and their design and urban form determinants around bay area rapid transit stations. *Transportation Research Record* 1604:40-49

Lunneborg, C. E. 2000. *Data analysis by resampling: Concepts and applications*. Pacific Grove, CA: Duxbury

Milazzo, J., N. Rouphail, J. Hummer and P. Allen. 1999. Quality of Service for Uninterrupted Pedestrian Facilities in the 2000 Highway Capacity Manual, *Transportation Research 1678*, TRB, Washington, D.C., pp. 18-24.

Moudon, A.V., Hess, P.M., Snyder, M.C., and Stanilov, K. 1997. Effects of site design on pedestrian travel in mixed-use, medium-density environments. *Transportation Research Record* 1578: 48-55

Moudon, A. V. 2001. *Targeting pedestrian infrastructure improvements: A methodology to assist providers in identifying suburban locations with potential increases in pedestrian travel.* Olympia, WA: Washington State Dept of Transportation; WA-RD 519.1.

Moudon, A.V., Hess, P.M., Matlick, J.M., and Pergakes, N. 2002. Pedestrian location identification tools: Identifying suburban areas with potentially high latent demand for pedestrian travel. *Transportation Research Record* 1818:94–101.

Moudon, A.V., and Lee, C. 2003. Walking and bicycling: An evaluation of environmental audit instruments. *American Journal of Health Promotion* 18(1); 21-37

Nunnally, J. C. 1978. *Psychometric theory.* (2nd ed.). New York: McGraw-Hill.

Pikora, T. J., Bull, F.C.L., Jamrozik, K., Knuiman, M., Giles-Corti, B., Donovan, R. J. 2002. Developing a reliable audit instrument to measure the physical environment for physical activity. *American Journal of Preventive Medicine* 23(3):187-194.

Pikora, T., Giles-Corti, B., Bull, F., Jamrozik, K., and Donovan, R. 2003. Developing a framework for assessment of the environmental determinants of walking and cycling. *Social Science and Medicine* 56(8):1693-1703.

Portland Pedestrian Master Plan Technical Appendix D. 1998. Printed from website: http://www.trans.ci.portland.or.us/Plans/PedestrianMasterPlan/default.htm (accessed on April 2006)

Regional Mobility Initiatives. 2003. A report by the North Central Texas Council of Governments and the Regional Transportation Council, Dallas-Forth Worth Metropolitan Area 7(1).

Rodriguez, D.A., and Joo, J. 2004. The relationship between non-motorized mode choice and the local physical environment. *Transportation Research D* 9:151-73

Rosnow, R.L., and Rosenthal, R. 1989. Statistical procedures and the justification of knowledge in psychological science. *American Psychologist* 44: 1276-1284

Saelens, B.E., Sallis, J.F., Frank, L.D. 2003a. Environmental correlates of walking and cycling: Findings from the transportation, urban design, and planning literatures. *Annual Behavior Medicine* 25(2):80-91.

Saelens, B.E., Sallis, J.F., Black, J.B., and Chen, D. 2003b. Neighborhood-based differences in physical activity: An environment scale evaluation. *American Journal of Public Health* 93(9):1552-58

Sallis, J.F., Johnson, M.F., Calfas, K.J., Caparosa, S., and Nicholas, J.F. 1997. Assessing perceived physical environmental variables that may influence physical activity. *Res Q Exercise Sport* 68:345-351.

Sallis, J.F., Prochaska, J.J., and Taylor, W.C. 1999. A review of correlates of physical activity of children and adolescent. *Medicine and Science in Sports and Exercise* 963-975.

Santos, J.R.A. 1999. Cronbach's Alpha: A tool for assessing the reliability of scales. *Journal of Extension* 37(2):1-5

Schlossberg, M., and Brown, N. 2004. Comparing transit-oriented development sites by walkability indicators. *Transportation Research Record* 1887: 34-42

Shrout, P.E. 1998. Measurement reliability and agreement in psychiatry. *Statistical Methods in Medical Research*. 7:301-307.

Southworth, M., and Owens, P.M. 1993. The evolution metropolis: Studies of community, neighborhood, and street form at the urban edge. *Journal of the American Planning Association* 59(3):271-87

Stine, R. A. 1985. Bootstrap prediction intervals for regression. *Journal of American Statistical Association* 80:1072-78

Stine, R. A. 1990. An introduction to bootstrap methods: Examples and ideas. *Sociological Methods and Research* 18(2&3):243-291

Sullivan, O.S., and Morrall, J. 1996. Walking distances to and from light-rail transit stations. *Transportation Research Record* 1538: 19-26

Thompson, B. 1988. Program FACSTRAP: A program that computes bootstrap estimates of factor structure. *Educational and Psychological Measurement* 48:681-686

Thompson, B. 2004. *Exploratory and confirmatory factor analysis: Understanding concepts and applications.* Washington DC: American Psychological Association

Thompson, B. 2006. *Foundations of behavioral statistics: An insight-based approach*. New York: The Guilford Press.

Troped, P.J., Saunders, R.P., Pate, R.R., Reininger, B., Ureda, J.R., and Thompson, S.J. 2001. Association between self-reported and objective physical environmental factors and use of a community rail-trail. *Preventive Medicine* 32:191-200.

USDOT (United States Department of Transportation). *Walkability checklist*. Available at: http://www.nhtsa.dot.gov/ people/outreach/safesobr/OPlanner/ncpsw/walk.1.html or http://www.nsc.org/walk/wkcheck. htm (accessed on August 13, 2005)

USDHHS (United States Department of Health and Human Services). 2000. *Healthy People 2010*. Washington, DC.

United States Census accessed at http://census.gov (accessed on August 13, 2005 and June 7, 2006)

Wellar, B. Basic walking security index. Available at: http://aix1.uottawa.ca/;wellarb/ BWSIpsummary.htm (accessed on August 13, 2005)

Zhang, J., Pantula, G.S., and Boos, D.D. 1991. Robust methods for testing the pattern of a single covariance matrix. *Biometrika* 78(4):787-95

Zientek, L. and Thompson, B. 2007. Applying the bootstrap to the multivariate case: Bootstrap factor analysis. *Behavior Research Method*s 39(2):318-25

APPENDIX A

Author	Index	Distance	Sidewalk	Roads	Intersection	Vehicles	Pleasantness
Allan	**Walking Permeability Indices**	**Distance:** Origin to Destination	X	X	X	X	X
Bandara	**Grade-Separated Pedestrian Systems**	**Distance:** Origin to Destination	X	**Roads:** Connectivity	X	X	**Pleasantness:** Attractiveness
Bradshaw	**Walkability Index**	**X**	**Sidewalk:** Continuity Availability Width	**X**	**X**	**Vehicles:** Parking	**Pleasantness:** Benches/HH, People
Dixon	**Pedestrian Performance Measures**	**X**	**Sidewalk:** Continuity Availability Width Maintenance	**Roads:** Width Medians **Driveways**	**Intersection:** **(a) Signals** Synchronization **(b) Crosswalk** Visibility	**Vehicles:** Speed Volume	**X**
DOT	**Walkability Checklist**	**X**	**Sidewalk:** Continuity Maintenance Availability	**Roads:** Width	**Intersection:** **(a) Signals** Synchronization Availability **(b) Crosswalk** Visibility	**Vehicles:** Not cautious Speed Volume Parking	**Pleasantness:** Dogs, People, visibility
FDOT	**Florida Pedestrian Level of Service**	**X**	**Sidewalk:** Availability Width	**Roads:** Width of outside travel lane **Driveway** Frequency Volume	**X**	**Vehicles:** Parking Volume Speed	**X**

APPENDIX A CONTINUED

Demographics	Safety	Destinations	Lateral Separation	Others
X	X	X	X	X
X	X	X	X	**Others:** Land-uses
Demographics: Population Density	**Safety:** Child Women	**Destinations:** Transit Parks Others	X	X
X	X	**Destinations:** Transit	**Lateral Separation:** Sidewalk Buffer Benches or Ped-Scale Lighting Trees	**Others:** Green-ways, Parkways, Trails, Pedestrian Plaza
X	X	X	**Lateral Separation:** Trees/Plants	X
X	X	X	**Lateral Separation:** Sidewalk Buffer Shoulder Lane	X

APPENDIX A CONTINUED

Fort Collins	**Pedestrian Level-of-service**	Actual/Min. Distance	Continuity Width	No. of lanes	**(a) Signals** Availability Visibility Synchronization **(b) Crosswalk** Visibility Curb Ramp	**X**	Local Architecture, lighting, building frontage, street tree & Furniture
Khisty	**Qualitative level of service**	**Distance:** Origin to Destination	**Sidewalk:** Maintenance Visibility Connectivity Continuity Width	**Roads:** Connectivity	**Intersection:** **(a) Signals** Synchronization **(C) Density**	**Vehicles:**	**Pleasantness:** Attractive Delight Interest Exploration Benches
Moudon	**Pedestrian Infrastructure Prioritization Decision System**	**X**	**X**	**X**	**X**	**X**	**X**
Moudon	**Pedestrian Location Identifier 1**	**X**	**X**	**X**	**X**	**X**	**X**
Moudon	**Pedestrian Location Identifier 2**	**X**	**X**	**X**	**X**	**X**	**X**
Portland	**Pedestrian Deficiency Index**	**X**	**Sidewalk:** Availability	**Roads:** Width Network	**X**	**Vehicles:** Speed Volume	**X**

APPENDIX A CONTINUED

X	sense of security, clear sight lines	X	X	Roadway Character Lighting
X	X	**Destinations:** Transit	X	**Others:** Weather/Climate Odor, Ventilation, Noise, Crowding, absence of concealed area
Population Density, No. of residents or employees within walkable area, ethnic minorities, households with few cars, etc	X	X	X	Land-uses Compactness Topography
Population Density Housing Type & Density	X	X	X	Land-uses Compactness Other Development
Housing Density	X	X	X	Land-uses Compactness/ Proximity
X	X	X	X	**Others:** Auto-Ped Crash

APPENDIX A CONTINUED

Portland	**Pedestrian Environmental Factor**	**X**	**Sidewalk:** Continuity	**Roads:** Network	**Intersection:** **(b)** **Crosswalk:**	**X**	**X**
Portland	**Pedestrian Potential Index (1)**	Distance to Schools	**X**	**X**	**X**	**X**	**X**
Gallin WA-LOS	**Pedestrian Level of Service**	**X**	**Sidewalk:** Width Maintenance Use (B/W)	**Roads:** Connectivity	**Intersections:** **(b) Crosswalk** Availability **(C) Density**	**Vehicles:** Volume	**Pleasantness:** Support Facilities
Wellar	**Basic walking security Index**	**X**	**X**	**X**	**Intersections:** Safety Comfort	**X**	**X**
Dannenberg (Virginia)	**Walkability Audit Tool**	**X**	**Sidewalk:** Availability Maintenance Width	**X**	**Intersections:** Size **Crosswalk:** Availability Visibility Curb-cuts **Signals:** Synchronization	**Vehicles:** Speed Volume	Attractive Facilities
Portland	**Pedestrian Potential Index (2)**	**X**	**X**	**X**	**Intersections:** Density	**X**	**X**
Highway Capacity Manual	**Level of Service**	**X**	**X**	**X**	**Intersection:** Density Signalization	**X**	**X**

APPENDIX A CONTINUED

X	**X**	**X**	**X**	**Others:** Slope of Terrain
		Transit Stops (Frequency) Parks		Pedestrian Classification
X	**X**		**X**	Pedestrian Friendly Commercial Area
X	**Safety:** Personal	**X**	**Lateral Separation:** Buffer from Traffic	**Others:** Other Pedestrians
X	**X**	**X**	**X**	**X**
			Sidewalk Buffer	Shade and Rain Cover
X	**X**	**X**		
Employment Density	**X**	**X**	**X**	Land-use Mix Parcel Size Topography
X	**X**	**X**	**X**	**X**

APPENDIX A CONTINUED

Carreno, Willis & Stradling (2002)	**Pedestrian Quality of Service**	**X**	Sidewalk: Maintenance Usage density	**X**	Crosswalk: Availability	**X**	Attractive Bldg Supporting Facilities
Saelens, Sallis, Black & Chen (2003)	**Neighborhood Environment Walkability Scale**	**X**	**X**	Connectivity	**X**	**X**	Pleasantness
		Distance: (1) Origin to destination (2) Actual Dis/ Min Dis (3) Distance to Schools	**Sidewalk:** (1) Continuity (2) Availability (3) Width (4)Maintainance (5) Visibility (6) Connectivity (7) Usage Density	**Roads:** (1) Connectivity (2) Width (3) Median (4) No. of Lanes (5) Network **(A) Driveway** (1) Frequency (2) Volume	**Intersection:** (1) Safety (2) Comfort (3) Size (4) Density **(A) Crosswalk:** (1) Visibility (2) Availabilty (3) Curb-cuts **(B)signalization** (1)syncronization (2) Visibility (3) Availability	**Vehicles:** (1) Speed (2) Volume (3) Parking (4) Not cautious	**Pleasantness:** (1) Attractiveness (2) Benches/HH (3) People (4) Dogs (5) Visibility (6) Local Architecture (7) lighting (8) building frontage (9) street tree (10) Street Furniture (11) Supporting Facilities (12)Attractive Delight Interest Exploration

APPENDIX A CONTINUED

	Personal	Transit Facility		
X			**X**	**X**
Residential Density	Traffic Crime	Facilities (Recreational, Essential, administrative)	**X**	Land Use Mix-diversity, Land Use Mix- Access
Demographics: (1) Population Density (2) Housing type & Density (3) Employment Density (4) Residential Density (5) Ethnic Minority (6) Households with cars	**Safety:** (1) Traffic (2) Crime on Personal *(a) Child* *(b) Women* (3) sense of security (4) clear sight lines	**Destinations:** (1) Recreational (2) Essential (3) Administrative	**Lateral Separation:** (1) Sidewalk Buffer (2) Shoulder Lane	**Others:** (1) Land Use Mix (2) Parcel Size (3) Topography (4) Compactness (5) Other Development (6) Shade and Rain Cover (7) Weather/Climate Odor, Ventilation, Noise, Crowding, absence of concealed area (8) Green-ways, Parkways, Trails, Pedestrian Plaza (9) Auto-Ped Crash (10) Pedestrian Classification Pedestrian Friendly Commercial Area

APPENDIX B

Sidewalk Connectivity

Connectivity of sidewalk is measured as ease of walking on sidewalk from one block to another. Therefore the availability of curb-cut for every intersection was calculated.

$$\text{Sidewalk Connectivity} = \frac{\text{Number of Intersection with 4 curb-cuts}}{\text{Total number of Intersections}}$$

Number of Intersection with 4 curb-cuts was available from the NCTCOG, whereas total numbers of intersections were calculated as described in the intersection density of chapter III.

Road Connectivity

Road network with lesser cul-de-sacs report better accessibility. Therefore, road connectivity is actually measured as barrier to better road network, which is number of cul-de-sacs for every length of road network, or

$$\text{Road Network} = \frac{\text{Number of Cul-de-Sac}}{\text{Total number of intersections}}$$

Number of cul-de-sacs and the total number of intersections were observed using the methodology described in the intersection density of chapter III.

Signalized Intersection

The location of signalized intersection was available from the City of Dallas. These intersections were measured as ratio with total number of intersections, therefore accounting for the existing intersections within the study area (quarter and half-mile distance).

$$\text{Signalized Intersection} = \frac{\text{Intersections with signals}}{\text{Total number of intersections}}$$

Road Speed

The designated speed on the road was factored with the length of that respective road. The sum of all the factored speed length was then divided by the total length of the road network. This helped to account for large road lengths with higher speed, which would otherwise be averaged with other designated speeds on the road.

$$\text{Road Speed} = \sum \frac{\text{Designated speed x respective road length}}{\text{Total length of road network}}$$

Designated speeds were available in the database of streets.

Traffic Volume

City of Dallas measures the traffic volume for arterial roads within the city limit. The average traffic volume was measured as average volume of all arterial roads within the study area.

$$\text{Average Traffic Volume} = \frac{\text{Traffic Volume on the arterial roads}}{\text{Number of arterial roads}}$$

Tree Canopy

The amount of tree canopy within the quarter and half-mile distance was divided by the area of quarter-mile and half-mile. The amount of tree canopy was obtained from the City of Dallas, who used aerial images to digitize the tree canopy.

$$\text{Tree Canopy} = \frac{\text{Area of tree canopy within quarter or half-mile}}{\text{Quarter or Half-mile area}}$$

Street Lights

The standard distance used by the City of Dallas to locate street lights is 400 mtrs. Based on the length of street network in a study area, the total number of streetlights was evaluated as

$$\text{Street Lights} = \frac{\text{Total length of street network in study area}}{400}$$

Average Parcel Area

The total area of parcels in the study area was divided by total number of parcels in the study area.

$$\text{Average Parcel Area} = \frac{\text{Total area of parcels in study area}}{\text{Total number of parcels}}$$

APPENDIX C

Moran’s I Calculation

The correlation of a variable(s) measured based the location of the observation is called spatial autocorrelation. This correlation is measured based on the feature location and feature value together and ranges between a Moran’s I value of +1.0 and -1.0. The +1.0 value indicates clustering and -1.0 indicates dispersion. The Z score reports the significance of Moran’s I value. The spatial autocorrelation of amount of walking across the transit stations indicated a Moran’s I value of -0.03 significant at 0.05 level. This meant that the amount of walking was randomly observed across the stations, which is appropriate to conduct the regression analysis for the second hypothesis.

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