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Creating a Pedestrian Level-of-Service Index for Transit Stops: Evidence from Denver's Light Rail System

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Creating a Pedestrian Level-of-Service Index for Transit Stops:

Evidence from Denver's Light Rail System

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CHAPTER 1: INTRODUCTION

1.1 Background and Research Questions

Since the 1990s there have been increased efforts to promote public transportation in American cities. Growing awareness of the environmental and economic risks associated with the structural dependence on fossil fuels has generated discussion about the ways to reduce fossil fuel consumption. Fossil fuel consumption can be reduced in many ways by implementing either technological solutions (such as improving the fuel efficiency of vehicles) or behavior-changing solutions (such as incentivizing people to reduce vehicle miles traveled or VMT). Policy alternatives that fall into this latter category include providing public transportation, and co-locating housing, employment, and amenities in mixed-use developments to reduce the need to drive between highly-segregated land uses (TCRP, 1997; Ewing et al. 2008). Currently, 40 percent of urban trips are less than 2 miles. Of these trips, 90 percent are taken by car (USDOT, 2011). In the last two decades, over a dozen American cities including Denver, Phoenix, Dallas, Salt Lake City and Charlotte have installed commuter light rail systems in an attempt to reduce auto-dependence. In that same time period the number of annual light rail trips has more than doubled from 175 million to 457 million (APTA, 2011). Consensus is emerging that simply overlaying public transit onto the existing urban fabric does little to encourage transit ridership, and much depends on the quality of the pedestrian environment. Transportation and land use policy have served as catalysts for improving our pedestrian environments. Several planning paradigms such as smart growth, new urbanism and transit-oriented development have promoted land use policies that are conducive to walking and transit use. Similarly, since the passage of ISTEA in 1991, the federal government has increased the amount of funding for transit and pedestrian projects. The resurgence of public transit infrastructure projects requires new methods of measuring pedestrian accessibility to transit.

This thesis will create a comprehensive pedestrian level-of-service index for Denver's RTD Light Rail system that seeks to bridge the gap between spatial and amenity driven approaches for measuring accessibility. Scholars have offered several definitions for accessibility. However, two definitions that inform this work are the ease of getting from one location to another using a transportation network (Dalvi and Martin, 1976) and the potential for interaction (Hanson, 1959; Handy, 2002). Traditionally, accessibility is measured in terms of cost or travel time (which impacts the ease of movement). However, pedestrian accessibility is also dependent on destination and choice (influenced by land use and transportation patterns) (Handy, 2002). First, this thesis will introduce an improved method for creating pedestrian-scale transit service-areas. Transit service-areas typically show locations that are within walking distance to transit stops. Transit service-area analysis has evolved from simple Euclidean distance buffers to more complex network-based buffers. Current methods assume that the street network is representative of the pedestrian network. However, a growing body of literature suggests that informal paths also are also important components of the pedestrian network. Social paths are informal paths that emerge in grassy areas due to pedestrian traffic. By incorporating social paths into the analysis, this thesis will create transit service-areas that are more reflective of how pedestrians actually access transit. This thesis will next create an index that measures the overall pedestrian accessibility for transit stops. The index will include spatial variables (pedestrian catchment ratio and average route directness index) and amenity variables (density and diversity of land uses, number of parking spaces, and transit connectivity). A two part hierarchical cluster analysis will be used to determine a scoring for each variable as well as a classification of the total score for all nine variables. The index is flexible and allows planners and policy-makers to customize the index to fit a particular mode or transit system.

1.2 Structure of Thesis

This thesis is structured as follows. Chapter 2 summarizes literature on pedestrian accessibility. It first defines the concepts of walking distance and accessibility and later reviews spatial and amenity-based approaches of pedestrian accessibility. Chapter 2 also introduces literature on informal social paths. Chapter 3 builds a conceptual framework for the thesis. The conceptual framework spans several fields including sustainability, planning, urban design and public policy. Chapter 4 discusses the historical land use and transportation patterns in study area. Chapter 5 discusses data and methods. Both the data and methods sections are broken up into two subsections. The first subsection discusses data and methods used in the social path transit service-area analysis. The second subsection discusses data and methods used to build the pedestrian level of service index for transit stops. Chapter 6 examines the results of the pedestrian level of service index. In addition it will use the index to examine the pedestrian accessibility of a future station along the East corridor commuter rail, scheduled to open in 2016. The concluding chapter, Chapter 7, critiques this thesis and presents directions for future research.

CHAPTER 2: LITERATURE REVIEW

2.1 Introduction

The concept of pedestrian accessibility borrows important ideas from several academic disciplines including geography, urban planning and civil engineering. However, these fields each focus on different ways of examining and analyzing pedestrian accessibility. Geographers focus on spatial approaches such as transit service-area analysis. Urban planners emphasize the interactions between pedestrians and the built environment. Finally, civil engineering literature focuses on topics such as pedestrian connectivity, safety and level of service. The lack of comprehensive, cross-disciplinary research is one of the major weaknesses in existing pedestrian accessibility literature.

The first section of this chapter analyzes the concepts of accessibility and mobility. While these two concepts are often used together without clear distinction, it is important to separate the two (Handy, 2002). Accessibility focuses on the potential for interaction while mobility focuses on the facility of movement (Handy, 2002). These two concepts are discussed in greater detail in the first section. The next section examines literature on walking distance. Walking distance literature focuses on measuring both the optimal and maximum walking distances to transit stops. The next section discusses methods used to measure pedestrian accessibility. These methods are divided into two distinct bodies of literature: transit service-area approaches and amenity-based approaches. The first body of literature centers on calculating transit service-areas. Transit service-areas create ped-sheds around transit stops based on a particular walking distance. These ped-sheds can be used to calculate the number of households within walking distance to transit. With the aid of geographic information systems, transit service-areas have evolved from simple Euclidean distance buffers to more complex network-based approaches.

The second body of literature focuses amenity base approaches. Amenity-based approaches have focused on the quality of the pedestrian environment. Amenity-based can measure either pedestrian amenities (such as pedestrian safety, sidewalk width or land use density) or station area amenities (such as distance to restaurants, parks or entertainment). In order to distinguish between these two bodies of literature, each is given its own subsection. Level of service approaches, while falling into the category of amenity-based approaches, are discussed separately because their methodology will be used later in this thesis. Level of service approaches can be applied to individual pedestrian links or aggregated at to areal units. Finally, there is an emerging body of literature that deals with informal aspects of the pedestrian environment. Social paths, also known as desire paths, emerge in grassy areas due to footfall. Social paths can be found near transit stops, especially in environments with a disjointed street network. The final section will discuss literature on social paths, travel behavior in the informal pedestrian environment and its potential applications in measuring pedestrian accessibility.

2.2 Accessibility and Mobility

Accessibility is an important concept in the fields of geography and transportation planning. The Oxford English Dictionary defined accessibility as the quality of being accessible or of admitting approach (OED, 2002). In their evaluation of accessibility, Geurs and van Wee (2004) broke up definitions into four components: the land use component, the transportation component, the temporal component and the individual component. Handy (2002) determined that choice is a vital component of accessibility. More choices in both destinations and modes increase interaction and correspond with good accessibility. Geurs and van Wee (2003) also noted that there are four approaches to measuring accessibility: infrastructure-based measures, location-based measures, personal measures and utility measures. This thesis will use infrastructure and location-based measures. Infrastructure-based measures, which are typically used by transportation planners, analyze the performance or service level of transportation infrastructure (Geurs and van Wee, 2004). Location-based measures, which are well suited to geographic studies, analyze accessibility of spatially distributed phenomena (Geurs and van Wee, 2004). Location-based measures have been performed in a variety of spatial frameworks ranging from aggregate zonal-based frameworks to point-based frameworks (Kwan et al. 2003). The advent of GIS technology has led to several location-based methods to measure accessibility (O'Neil et al. 1992; Kwan et al. 2003; Upchurch et al. 2004, Biba et al. 2010). Transit service-area analysis is a common location-based measure that is used measure the pedestrian accessibility of transit stops and will be discussed in detail in subsequent sections.

While closely related to accessibility, the concept of mobility has a distinct definition. Mobility is defined as the potential for movement and the ability to get from one place to another (Handy, 2002). Mobility enhancing strategies focus on improving the performance of a transportation system to improve travel time or cost (Handy, 2002). A pedestrian friendly environment would produce both good mobility and good accessibility. As Handy (2002) noted, it is possible to have good mobility and bad accessibility and vise versa. A dense, mixed use environment with no sidewalks would have good accessibility but poor mobility. Similarly, a location with an ample sidewalk network but no diversity of land uses or transportation modes would have good mobility but poor accessibility.

2.3 Walking Distance

Walking distance is at the core of measuring pedestrian accessibility to transit stops. However, there is little consensus on what distance is considered walkable for pedestrians. The lack of consensus can be attributed to differences in individual travel behavior. One user may be willing to walk one-half mile to a transit stop while another user may only be willing to walk one-quarter mile. This divide has led to studies on both optimal walking distance and maximum walking distance. Optimal walking distance refers to a distance in which a majority of users are willing to walk. Maximum walking distance refers to the outer boundary of pedestrian accessibility. Optimal walking distance values tend to be significantly lower than maximum walking distance.

Numerous studies have attempted to calculate optimal walking distance. Optimal walking distance is not universal and depends on the context of a particular station. O'Sullivan and Morrall (1996) noted that median walking distance for stations ranges from 280 meters for central business district (CBD) stations to 540 meters for suburban stations. Barber (1995) came to a similar conclusion, with median walking distances ranging from 400 feet to 1200 feet. Several papers have noted variations in walking distance across populations. Untermann (1984) concluded that most pedestrians were willing to walk 500 feet, but that only 10 percent of pedestrians were willing to walk a half mile. A similar study found that transit use by the elderly dropped by 70 percent as walking distance increased from 200 meters to 400 meters (Nielson and Fowler, 1972). Optimal walking distance can also be influenced by pedestrian conditions and transit mode. A Canadian study found that 50% of pedestrians would walk more if pedestrian conditions were improved (Has-Klau et al. 1993). Two studies have determined that users are willing to walk further to light rail stations than they are to bus stops (O'Sullivan and Morrall 1996; Upchurch, 2012).

Other studies have tried to define the outer boundaries of pedestrian accessibility. Cervero (2007) concluded that users that lived within one-half mile of a transit stop were four times as likely to use transit as those living between one-half and three miles of a transit stop. In a second study, Cervero (1994) concluded that more than half of automobile users switched to transit after moving within one-half mile of a transit stop. One-half mile walking distance has been used in several transit accessibility studies (Upchurch et al. 2004; Kuby et al. 2004; Ditmar and Ohland, 2004). While one-half mile is the general consensus on maximum walking distance for a vast majority of users, studies have noted that some users are willing to walk up to two miles to a transit stop (O'Sullivan and Morrall, 1996; Canepa, 2007). Others have concluded that local terrain impacts the distance pedestrians are willing to walk (Cervero, 2003; Saelens et al., 2003).

2.4 Measuring Pedestrian Accessibility

TRANSIT SERVICE-AREAS

Transit service-areas fall under location based measures of accessibility as defined in Guers and van Wee (2003). While most frequently used to measure pedestrian accessibility, transit service-area analysis has also been used to examine vehicle catchments for terminal transit stops (Horner and Grubesic, 2001) and bus catchment areas (Cairns, 1997). Transit service-area analysis is used to measure pedestrian accessibility by creating ped-sheds around transit stops. Ped-sheds are spatial features that show areas within walking distance to a transit stop. Methods for calculating transit service-areas have evolved from simple Euclidean distance approaches to more complex, network-based approaches.

Initially, simple Euclidean distance buffers were used when conducting service-area and ped-shed analysis. The major drawback of this approach is that it assumes that walking distance for the transit user is simply a Euclidean distance that does not take into consideration the street pattern. As a result, service-areas are much larger and over-represent populations that are within walking distance to transit (O'Neil et al. 1992).

Several studies have shown how street connectivity influences pedestrian behavior (Ewing, 1996; Frank et al., 2004; Leslie et al., 2005). Suburban street design, which is characterized by fractured and indirect routes, is not conducive to pedestrian activity, while gridded urban neighborhoods tend to promote walking (Hess et al. 1999). Several network-based approaches have taken into consideration the impact of street design on walking to improve the accuracy of transit service-area analysis. Upchurch et al. (2004) created pedestrian transit service-areas for light rail stations that provided more accurate results than the built-in service-area tools included in GIS software. Their raster-based method, called the 'linked on-off network' (LOON) method, offered improvements over previous methods in that it gave equal weights to both on and off network cells. It also created mutually exclusive transit service-areas. While the latest ArcGIS software allows mutually exclusive service-areas to be created it does not have equal weights for on and off network locations. Biba et al. (2010) also took a network-based approach, albeit at the parcel level. Parcel centroids were linked to the street network before computing walking distance (Biba et al. 2010). The advantage of this method is that it can accurately determine the number of parcels and households that are within walking distance to a transit stop. Pedestrian catchment areas are also based on network distance. Pedestrian catchment areas compute a ratio that examines the difference between Euclidean distance buffers and network distance buffers. A network distance buffer located in an area with excellent pedestrian connectivity (which would produce a buffer closer in size to the Euclidean distance buffer) would produce a pedestrian catchment ratio closer to 1. Generally, a ratio of 0.50 to 0.60 characterizes an adequate pedestrian environment while a ratio of 0.30 or less characterizes service-areas that are inhospitable for pedestrians (Schlossberg & Brown, 2004; Schlossberg 2006). The biggest weakness of network-based transit service-area approaches is that they assume that the street network is representative of how pedestrians access transit. Using street networks in analysis can grossly underestimate pedestrian connectivity. In addition to streets, pedestrian networks also include walkways, multi-use trails, bike paths and informal trails. Chin et al. (2007) found that using pedestrian networks instead of street networks increased overall connectivity by up to 120 percent.

AMENITY-BASED APPROACHES

Amenity-based approaches have focused on the quality of the pedestrian environment and the needs of pedestrians in the built environment (San Francisco Department of Public Health, 2008). Amenity-based approaches have analyzed variables such as the density and diversity of land use, presence of park and ride facilities and transit connectivity. All of these components affect pedestrian behavior and may either improve or detract from a pedestrian's ability or willingness to walk.

Several studies have determined that the density and diversity of land uses is an important component of pedestrian accessibility. Dunphy and Fisher (1996) identified three impacts of population density on travel behavior. The first is that the travel behavior of residents in high density communities may be a reflection of their population characteristics (for example, a lower income urban family will take fewer trips than a high income suburban family). A second conclusion is that higher density offers a wider variety of choices for meeting daily transportation needs (such as having shopping located within walking distance). A final conclusion is that higher densities make driving less attractive because of the lack of cheap parking. Frank and Pivo (1994) identified a negative relationship between population density, employment density and single-occupancy vehicle uses. They found that transit use and walking dramatically increase as a mode share once employment density exceeds 75 employees per acre. Residential density is more strongly related to mode choice than employment density, with a threshold of 13 people for acre for the affect to be detected (Frank and Pivo, 1994). The Denver RTD suggested that residential density near stations should reach 10 to 20 dwelling units per acre and commercial densities should be in excess of 20 jobs per acre (RTD Transit Access Committee, 2009). The diversity of land uses also impacts travel behavior. This is best exemplified by mixed use developments. According to Cervero (in Frank and Pivo, 1994), mixed use developments "are those with a variety of offices, shops, restaurants, banks, and other activities intermingled amongst one another." In her analysis of Austin neighborhoods, Handy (1996) found that retail land uses decreased the number of auto trips in mixed use neighborhoods and that a greater variety of land uses led to even greater reductions in driving.

While park and ride stations may help boost ridership of light rail systems, they often create hindrances to pedestrians. Park and ride stations are often seen as an essential part of maintaining balance in a transit system, especially in areas with poor pedestrian accessibility (Bolger et al., 1992). Merriman (1998) found that each additional parking space resulted in an additional 0.6 to 2.2 passenger boardings while Kuby et al. (2004) found a ratio of 1 to 1. While suburban park and rides may promote transit use, limiting downtown parking may also promote transit use (Morrall, 1996; Voith, 1998). While park and rides may lead to increased ridership for certain stations, they come with several costs. The first is that they compete with non-motorized modes such as walking and biking. The number of parking spaces has an inverse relationship with the number of walk trips when controlling for land use density and diversity (Ewing and Cervero, 2001). Park and rides also generate overflow parking near the station and cause higher traffic volumes on local roads. Higher traffic volume and vehicle speeds further discourage walking and biking (Bolger et al., 1992). A second cost is that park and rides tend to generate peak usage (RTD Transit Access Committee, 2009) while improved pedestrian connections and transit-oriented developments tend to promote transit use throughout the day. A final cost of park and rides is that they may actually increase trip-generation. Parkhurst (1996) found that 2 to 11 percent of weekday park and ride users would not have made their trip without the park and ride.

Indexes are a popular method used to measure pedestrian accessibility. The WalkScore © method is an algorithm-based method that rates the pedestrian environment on distance to amenities such as parks, grocery stores, shopping and restaurants (WalkScore, 2010). The WalkScore © method is based on studies that have calculated the variables that are most important to facilitating walking, including the presence of sidewalks, clusters of retail and entertainment and smaller block size (Lee and Moudon, 2006; Moudon et al. 2006; Iacono et al. 2010). The main weaknesses of WalkScore © are that it does not use network distance when calculating distance to amenities and it does not incorporate residential land uses or density into its calculation. The pedestrian environmental quality index (PEQI) is a second index-based approach that quantifies the quality of the pedestrian environment based on intersection safety, traffic, street design, perceived safety and land use (San Francisco Department of Public Health, 2008). The PEQI is more focused on pedestrian safety as opposed to pedestrian accessibility. Other studies have focused on the qualitative and perceptual qualities of pedestrian environments (Sarkar, 1993; 2003). The greatest strength of amenity-based approaches is that they allow researchers and policy makers to examine the factors that influence the behavior of pedestrians within the environment.

PEDESTRIAN LEVEL OF SERVICE

Level-of- service measures fall under the category of infrastructure-based measures as classified in Geurs and van Wee (2004). Level-of-service is a common method used in traffic engineering to describe highway links and intersections based on factors such as delay, vehicle queuing and vehicle speeds (Drew and Keese, 1965; FHWA, 1997). Handy (2002) noted that level-of-service is used to measure mobility (i.e travel time) as opposed to accessibility. Level-of-service is a relatively simple tool to understand since it produces A-F letter grades for a unit based on an aggregate of scores. A is considered the best level-of-service while F is considered the worst. One of the benefits of level-of-service analysis is that it can be used to predict the success of transportation improvement projects. Pedestrian level-of-service measures have been implemented on two scales. The first scale measures the level-of-service for individual pedestrian links. The second measure produces level-of-service scores for areal units.

Several studies have introduced pedestrian level-of-service indexes for individual pedestrian links. Similar to road level-of-service indexes which focus on roadway characteristics, pedestrian indexes focus on characteristics of the pedestrian network. Pedestrian level-of-service analysis goes back to 1971 when Fruin created a six level classification of pedestrian facilities based on both quantitative and qualitative factors. Landis et al. (2001) expanded on Fruin's idea by incorporating additional variables such as the presence of a sidewalk, width of the sidewalk and speeds of vehicles on adjacent roadways. Dixon (1996) included presence of facilities, pedestrian conflicts and pedestrian amenities. Both articles note the importance of pedestrian level-of-service analysis for transportation improvement projects.

Several studies have created level of service indexes at the areal scale. These indexes focused on both transit (metropolitan scale) accessibility as well as pedestrian (neighborhood scale) accessibility. The transit friendliness factor is one method that used an areal scale (Evans et al. 1997). This method produced a transit friendliness score for the pedestrian environment based on four factors; sidewalks, street crossings, transit amenities and proximity to destinations. This approach applied scores to all zones in a metropolitan area. The major weakness of this approach is that it assumes that all zones have some pedestrian access to transit. In reality, pedestrian access to transit is limited by constraints in walking distance (Kuby et al. 2004). The Public Transport Accessibility Level (PTAL) is an index used by transportation planners in Greater London (Transport for London, 2010). The PTAL index measures accessibility to transit stops based on walking time, reliability of service mode, the number of services within the catchment area and average waiting time (Transport for London, 2010; Abley and Williams, 2008). This index essentially measures the density of the public transportation network at any location in Greater London. Several studies have introduced transit accessibility indexes that focus on both the spatial and temporal components of accessibility (Polzin et al. 2004; Bhat et al. 2006; Sha al Mamum and Lownes, 2011). Others have incorporated pedestrian routes into their analyses (Ryus et al 2000; Fu and Xin, 2007). These indexes, which have been done at regional scales, are focused on the accessibility of transit systems as a whole rather than individual transit stations.

2.5 Social Paths and the Informal Pedestrian Environment

A growing body of literature has studied pedestrian travel and behavior in informal environments. Pedestrians have been shown avoid walking indirect routes. In addition, pedestrians have been shown to have self-organizing tendencies in which pedestrians tend to follow in the footsteps of others (Helbing et al. 2001; Helbing et al. 1997; Helbing et al. 1997-2). Indirect walking routes plague pedestrians in suburban environments and lead to the formation of social paths. An example of a social path can be seen in the upper central portion of Figure 2:1

Figure 2:1 A Social Path Viewed from the Air

Source: Bing Maps

Despite being formed to overcome pedestrian barriers, social paths do not always follow the shortest path between two points. Helbing et al. (2001) concluded that social paths can deviate from the shortest path by up to 25 percent. Researchers have put forth several ways to model pedestrian behavior in informal pedestrian environments. The social forces model examines how pedestrians influence the behavior of others. Collective patterns of motion and self organization are two social forces that can lead to the formation of social paths (Helbing and Molnar, 1995). Agent-based models have also been used to model pedestrian behavior. The active walker model simulated the formation of trails in the informal pedestrian environment. This model looks at how the physical environment effects the decision making process of pedestrians (Helbing et al. 1997-2). The active walker model concluded that trail formation has a bundling effect (trails going to different destinations have some concurrency) and self reinforcing tendencies (pedestrians are apt to follow existing paths as opposed to creating new paths) (Helbing et al. 1997-2). The active walker model has been expanded to include how pedestrian decisions are influenced by steep terrain (Gilks and Hague, 2009) and dynamic urban landscapes (Batty, 2005). The STREETS model used a combination of vector, raster and network data to identify and model pedestrian behavior. This model allowed pedestrians to walk on all unbuilt spaces albeit giving preference to formal paths (Haklay et al. 2001).

Because social paths show where there is a high demand for improved pedestrian facilities, they have been used in several pedestrian improvement programs. One of the more famous examples of involves the restoration of Central Park in the 1980s. The reconstruction of walking paths was based partially on turning the locations of heavily used social paths into permanent paved paths (Barlow-Rogers, 1987). Numerous municipal planning documents also make mention of converting social paths into new paved pedestrian or biking paths (City of Boulder, 2008; City of Flagstaff, 2011)

2.6 Conclusions

Pedestrian accessibility is a well studied topic that has come to the forefront of transportation planning. Good pedestrian accessibility is vital to the success of public transit systems. Despite this important connection, there has been little work done focusing on pedestrian accessibility to transit. Two distinct bodies of literature focused on measuring pedestrian accessibility have emerged. The first body of literature deals with transit service-areas. Transit service-area methods are the most frequently used method for calculating ped-sheds. Transit service-area methods have evolved from simple Euclidean distance service-areas to more complex network-based service-areas. However, network-based approaches assume that the street network is representative of how pedestrians access transit. Emerging literature on informal social paths suggests that more needs to be done to incorporate elements of the informal pedestrian environment into transit service-area approaches. A second body of literature focuses on amenity-based approaches. These approaches have measured characteristics are conducive or hindering to pedestrians. Land use diversity, density, level of transit service and the number of parking spaces are all factors that impact pedestrian behavior. A major weakness of amenity-based approaches is that they have yet to be applied to a transit service-area spatial framework. Therefore, existing methods have only skimmed the surface for measuring pedestrian accessibility to transit stops.

CHAPTER 3: CONCEPTUAL FRAMEWORK

3.1 Introduction

After decades of auto-oriented planning, suburbanization and sprawl, planners and policy makers have begun to look at alternatives that will prompt Americans to drive less and walk, bike and ride transit more (Cervero and Kockelman, 1997; Cervero, 2006). Pedestrian accessibility is an important component of sustainable transportation. The first section of this chapter examines definitions of sustainable transportation. It also examines the relationship between pedestrian accessibility and the goals of sustainable transportation. Consensus is emerging that simply overlaying public transit onto the existing urban fabric does little to encourage transit ridership, and much depends on the quality of the pedestrian environment. The transportation – land use relationship has been traditionally used to examine the relationship between transportation systems and the built environment. However, traditional models do not adequately explain the neighborhood scale factors that influence pedestrian accessibility. The second section of this chapter examines the weaknesses of traditional transportation – land use models and draws upon a more recent model that better incorporates pedestrian accessibility. Next, this chapter examines the relationship between pedestrian activity and land use policy. Several planning paradigms such as smart growth, new urbanism, and transit-oriented development (TOD) have focused on improving pedestrian accessibility by changing land use policy (Greenwald and Boarnet, 2001; Cervero and Kockelman, 1997). Finally, this chapter examines the role that transportation policy plays in pedestrian accessibility and public transit. In the last few decades there have been greater funding opportunities for public transit and pedestrian projects.

3.2 Sustainable Transportation

Pedestrian accessibility and transit use are integral to the concept of sustainable transportation. Therefore it is important to define the concept sustainable transportation and examine the role that pedestrians and transit play in achieving its goals. Definitions of sustainable transportation are rooted in the definition of sustainability itself. A simple definition of sustainable transportation modifies the Brundtland Commission's definition of sustainable development stating that "sustainable transportation allows current users to meet their transportation needs without compromising future generation's abilities to meet their transportation needs" (Black, 1996; Richardson, 2005, p. 30). More complex definitions of sustainable transportation recognize that the three domains that comprise sustainability: economic, environmental and social domains (Richardson, 2005). The economic viewpoint states that sustainable transportation forces beneficiaries pay their full social costs including those that would be paid by future generations (Schipper, 2003). The environmental viewpoint defines sustainable transportation systems as systems that do not endanger public health or ecosystems and use renewable resources below their regeneration capacity (Goodland, 1995). Finally, socially sustainable transport should give everyone, regardless of income or ability to drive access to jobs, education and social services (Schipper, 2003). Because of the importance of all three characteristics, comprehensive definitions of sustainable transportation are most commonly used. Many agencies prefer to use the Canadian Centre for Sustainable Transport's (2005) because of its comprehensive nature (Zheng, 2010). Using their definition, a sustainable transportation system:

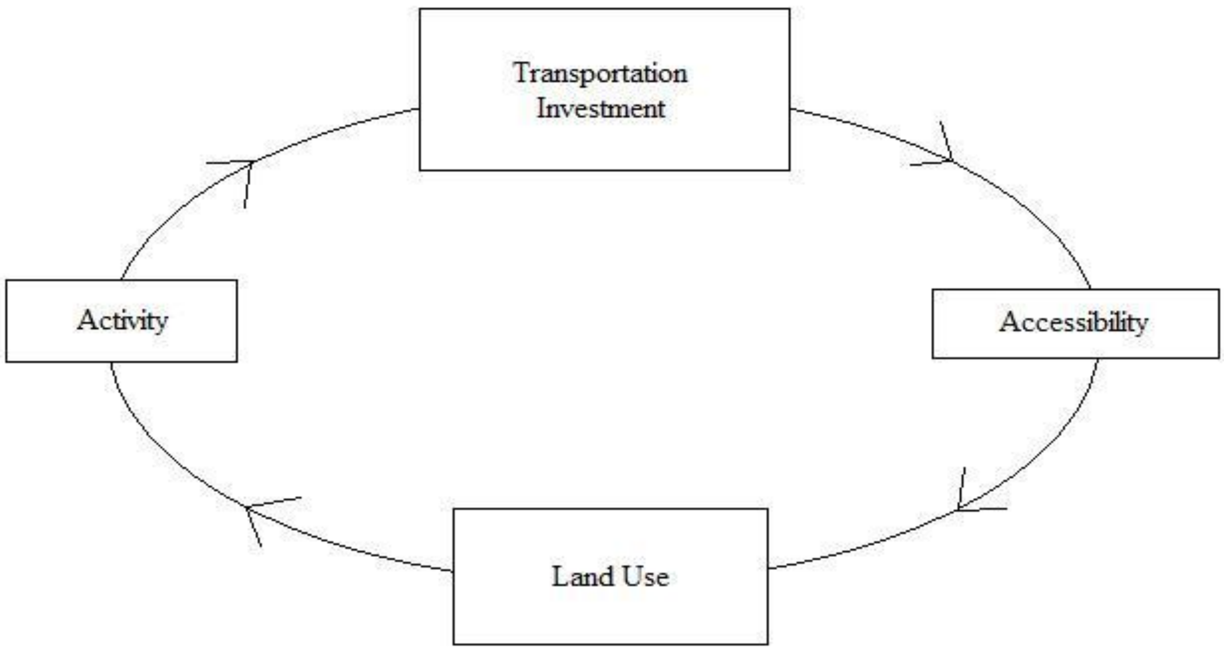
- Allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations.
- Is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy.
- Limits emissions and waste within the planet's ability to absorb them, minimizes consumption of non-renewable resources, limits consumption of renewable resources to the sustainable yield level, reuses and recycles its components, and minimizes the use of land and the production of noise.

Walking satisfies all three of the domains of sustainable transport. Benefits of walking include the conservation of energy, reduction of greenhouse gas emissions (Litman, 2011), the diversification of transport systems, improved public health (Litman, 2011; Evenson et al. 2011) and cost-effectiveness (Schipper, 2003). Walking will not achieve the goals of sustainable transportation by its self. The disabled and elderly may be unable to walk. Therefore, sustainable transportation requires a range of transportation choices for all users.

3.3 The Transportation – Land Use Relationship

The transportation – land use relationship is a vital component of pedestrian accessibility. Transportation and land use are intricately related. A simple model of the transportation – land use relationship, as seen in Figure 3:1, uses a feedback loop comprised of transportation, accessibility, land use, and activity patterns (Hanson and Giuliano, 2004). The accessibility of a location influences that location's land use patterns. Land use patterns, in conjunction with the transportation system produce specific activity patterns. Activity patterns then go on to influence the transportation system and the cycle continues (Hanson and Giuliano, 2004). While this model

Figure 3:1 The Transportation-Land Use Relationship

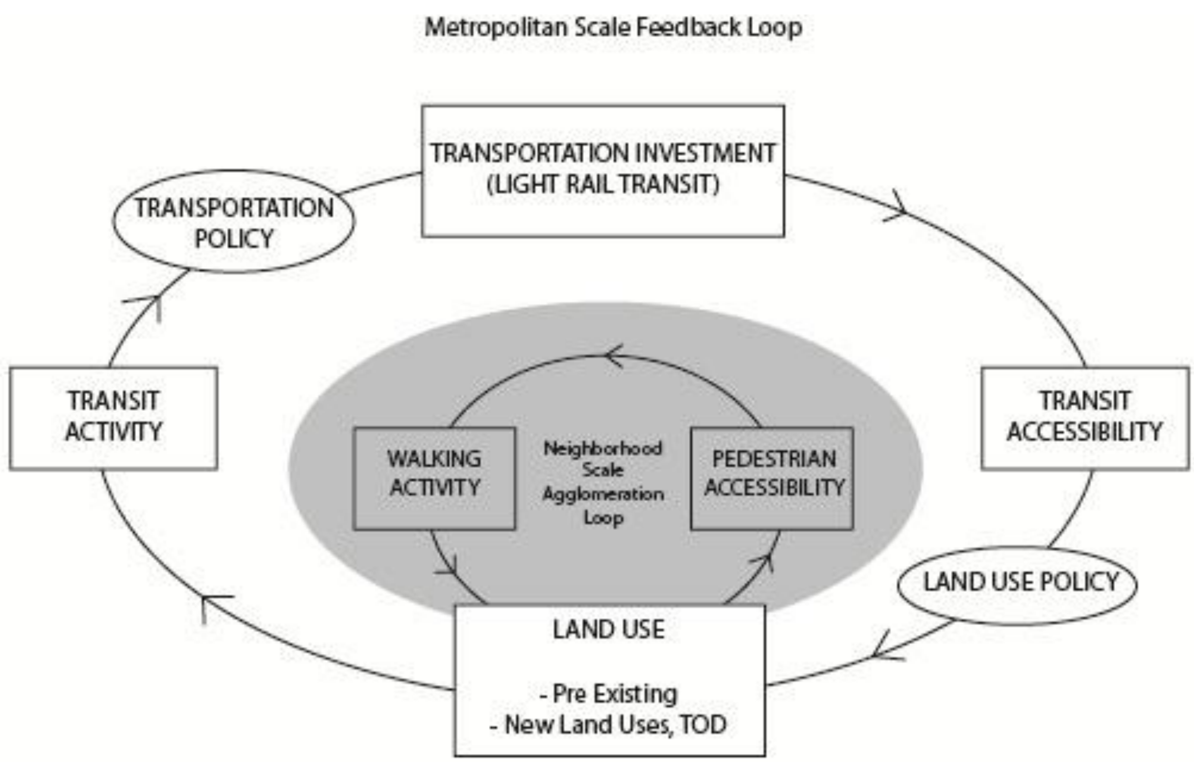


Source: Hanson and Giuliano (2004)

helps conceptualize the transportation – land use connection, it does not fully explain the relationship between pedestrians, the built environment and transit use. For example, accessibility metrics have been traditionally defined in terms of travel cost and travel time and been conceptualized with the automobile in mind rather than pedestrians. Pedestrian accessibility is also determined by factors such as the density and diversity of land use, design, destination accessibility and distance to transit (Cervero, 1997; Cervero and Kockelman, 1997). In addition this model exhibits a problem with scale in that it does not fully incorporate all of the factors at play when considering the neighborhood scale.

Atkinson-Palombo (2007) created a more in depth model applied specifically to light rail transit and TOD. This model better explains the relationship between pedestrians, land use and transit use. Atkinson-Palombo made several changes to Hanson and Giuliano's (2004) model (Figure 3:2). To better incorporate the driving forces at play at various scales, Atkinson-Palombo used two interconnected loops; an outer loop at the metropolitan scale and an inner loop at the neighborhood scale. These changes allowed transit accessibility and pedestrian accessibility to be

Figure 3:2 The Transportation-Land Use Relationship for Pedestrian Accessibility



Source: Atkinson-Palombo (2007)

examined separately. In addition, it incorporated transportation and land use policy, two components vital to pedestrian accessibility and transit use. In this thesis, I have slightly modified Atkinson-Palombo's model to better fit pedestrian accessibility (Figure 3:2). Transit accessibility is a metropolitan scale process (outer loop) that can be simply defined as the ease at which a user can get from one location to another using transit. Pedestrian accessibility is a neighborhood scale process (inner loop) that is influenced by both land use patterns and the transit system.

LAND USE POLICY

Several studies (TCRP, 2002; Atkinson-Palombo, 2007) have noted that supportive land use policies are needed in order for light rail transit to begin to impact land use patterns. Three closely related planning paradigms, smart growth, new urbanism, and transit-oriented development (TOD) have sought to improve pedestrian accessibility and increase transit use by changing our land use patterns. All three encourage policies that promote dense, mixed use urban centers built at the pedestrian scale with good access to public transit. While some correspondence exists between the end goals of all three movements are the same, they tend to employ different policy tools. Smart growth advocates policy at the metropolitan scale (which produces neighborhood scale pedestrian activity) while new urbanism and TOD advocate neighborhood scale policies. Despite the difference in scale, smart growth, new urbanism and TOD are not mutually exclusive.

Smart growth is a metropolitan scale anti-sprawl policy that seeks to concentrate growth into compact, walkable, urban centers with existing infrastructure (Handy, 2002; Ewing et al., 2008). Several tools have been used to achieve smart growth's goals including financial incentives (Gray, 2007), changing infill zoning requirements (Glitz, 2007) or through the establishment of urban growth boundaries (Marshall, 2003). Smart growth supporters suggest that the approach has a wide range of environmental, economic and social benefits. By concentrating growth into areas of existing infrastructure smart growth reduces government spending on new infrastructure while simultaneously preserving open space and reducing vehicle miles traveled (Danielson et al. 1999). In addition, smart growth encourages social equity by steering investment towards existing neighborhoods (Ewing et al., 2008). A meta-analysis of several smart growth studies revealed that residents living in dense, mixed use, accessible neighborhoods with an interconnected street pattern drove about 33 percent less than residents living in low density sprawl (Ewing et al., 2008). While smart growth has reduced per capita automobile use, urban densification often leads to increases in traffic congestion and associated environmental problems. This has led to suggestions that smart growth policies need to do more to discourage automobile use (Melia et al., 2011).

Neighborhood scale land use policy also impacts pedestrian accessibility. One of the most influential design movements of the last two decades has been new urbanism. The Congress for New Urbanism states four main goals for new urbanist design as:
1.) Livable streets arranged in compact, walkable blocks; 2.) A range of housing choices to serve people of diverse ages and income levels 3.) Schools, stores and other nearby destinations reachable by walking, bicycling or transit service 4.) An affirming, human-scaled public realm where appropriately designed buildings define and enliven streets and other public spaces.
New urbanist communities have improved walkability at the neighborhood scale and have encouraged the desegregation of land uses (Marshall, 2003). While new urbanist communities

have been successful at promoting pedestrian activity at the neighborhood scale, they do not always facilitate transit use. New urbanist communities such as Celebration, Florida have been built in isolation from the larger metropolitan context in which they are situated and do nothing to change metropolitan scale transportation patterns (Marshall, 2003). Other criticisms of new urbanism include their struggle to maintain a mix of incomes and land uses (Talen, 2000; Marhsall, 2003).

Like new urbanism, TOD encourages neighborhood scale policies that advocate dense, pedestrian friendly, mixed use developments within walking distance to transit (TCRP, 1997, 2002, 2004). The California Department of Transportation (2002, p. 18) defines TOD as

> "moderate to higher-density development, located within an easy walk of a major transit stop, generally with a mix of residential, employment and shopping opportunities designed for pedestrians without excluding the auto. TOD can be new construction or redevelopment of one or more buildings whose design and orientation facilitate transit use."

TOD has been influenced by demand-side factors such as increasing traffic congestion and demographic changes (Hanson and Giuliano, 2004) as well as supply-side policies such as giving preferential loan treatment to households near transit (Cervero et al., 2002) and the creation of overlay zoning (Atkinson-Palombo and Kuby, 2011). TOD promotes both metropolitan scale (transit) and neighborhood scale (pedestrian) accessibility. Several studies have noted that TODs have only produced limited results (Belzer and Autler, 2002; Cervero et al, 2002). However, existing literature suggests that TODs take years or even decades to unfold (Belzer et al., 2004; Boarnet and Crane, 1998; Hess and Lombardi, 2004). Reevaluations of TODs after a few decades of existence are likely to produce more pronounced results (Cervero, 1995). Cities such as Phoenix have adopted advance TOD policies in an attempt to accelerate the land use change process (Atkinson-Palombo and Kuby, 2011).

Atkinson-Palombo (2007) theorized that increased walking activity leads to a self-generating cycle of TOD (corresponding to the inner loop in Figure 3:2). The self-generating cycle of TOD is further encouraged by agglomeration effects and changes in local zoning (Atkinson-Palombo, 2007). Land use patterns and pedestrian accessibility can also increase the number of transit users. Several studies have concluded that high residential densities surrounding transit stops have led to increases in transit ridership (Dill, 2008; Lund et al., 2004; Cervero, 2006) as well as reductions in the number of trips per dwelling unit (Cervero and Arrington, 2008; TCRP, 2008).

TRANSPORTATION POLICY

As stated earlier, pedestrian accessibility only impacts land use and transportation at the neighborhood scale. Transportation policy helps promote changes at the metropolitan scale. As seen in Figure 3:2, transportation policy drives transportation infrastructure projects (such as light rail transit and pedestrian infrastructure). Federal funding for transit and pedestrian projects has increased since the passage of ISTEA in 1991 and the two subsequent federal transportation bills, TEA-21 and SAFETEA-LU. ISTEA gave much of the decision making power to metropolitan planning organizations and took a more comprehensive approach to transportation planning by incorporating non-transportation considerations (Plous Jr., 1993). The HUD-DOT-EPA partnership is another example of the comprehensive transportation planning approach the federal government has taken in the last few years (EPA, 2010). TEA-21 expanded pedestrian projects by allowing states to divert highway funding for pedestrian walkways and pedestrian safety and educational programs (FHWA, 2008). The most recent federal transportation bill, SAFETEA-LU, expanded funding for transit investment projects through the New Starts program. To date 8.8 billion dollars have been spent on over 330 transit projects (FTA, 2010). These projects have served as catalysts for both metropolitan and neighborhood scale land use change.

State and local policies have also helped promote pedestrian accessibility and transit use. Complete streets policies, which have been passed in 25 states, Washington D.C. and Puerto Rico, seek to change the notion that streets are meant to serve the automobile above all other modes. Complete streets policies try and ensure that transportation systems are safe for all ages, modes and abilities (Farber and Shinkle, 2011). These policies are far from uniform. Some states policies focus solely on pedestrians and bicyclists while others may include transit, automobiles and freight transport (Farber and Shinkle, 2011). Portland's urban growth boundary is one of the more unique local policies to change transportation patterns. While initially created to preserve forest and agricultural land, the increased density within the boundary has led to greater transit use and a more pedestrian friendly environment (Marshall, 2003).

3.4 Conclusion

Pedestrian accessibility (a neighborhood scale process) is closely intertwined with public transit accessibility (a metropolitan scale process). Public transit projects rely on pedestrian accessibility to promote neighborhood scale land use change and vice-versa. Land use policies such as new urbanism, smart growth and TOD, which focus on creating dense, mixed use, pedestrian scale developments with good access to public transportation, help bring the two together. The pedestrian activity created by these land uses promotes transit ridership and further land use change. Transportation policy is the driver of transportation infrastructure projects. In the last few decades there has been increased federal, state and local funding for transit and pedestrian improvement projects. Finally, pedestrian accessibility and transit fulfill the goals of sustainable transportation and can help alleviate the negative impacts of the automobile.

CHAPTER 4: STUDY AREA

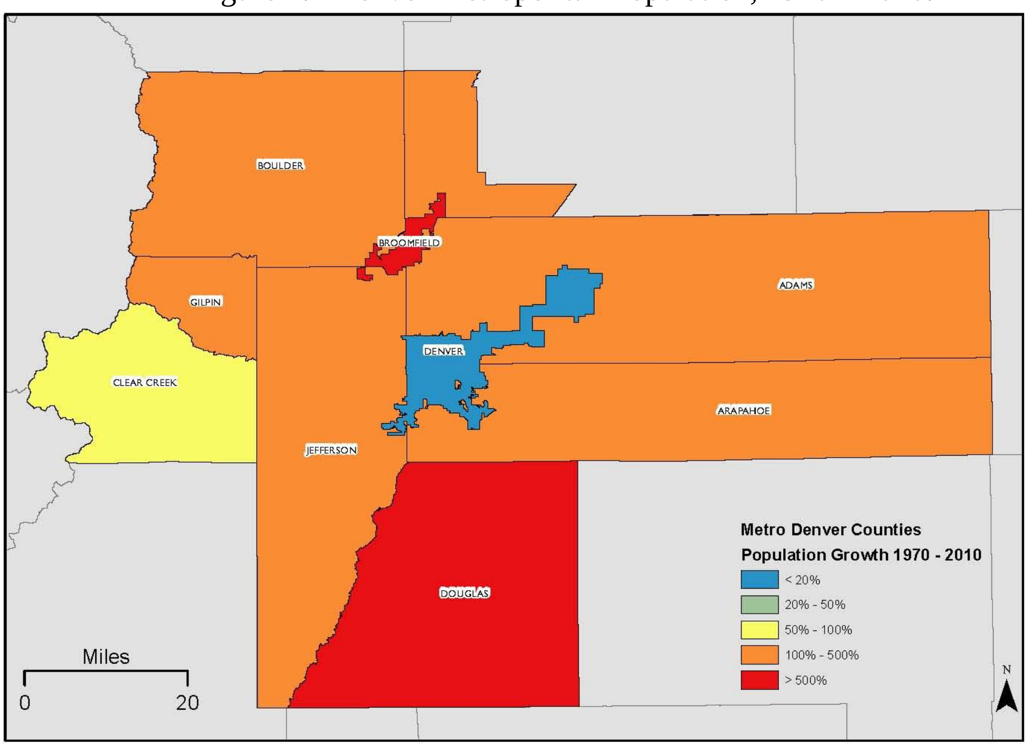
4.1 Introduction

This study examined transit stops on Denver's RTD light rail system. Denver was chosen as the study area for this thesis because its stations were built in a myriad of different settings. Downtown Denver and inner-city neighborhoods were built before the widespread adoption of the automobile and were reliant on public transit such as streetcars. Explosive population growth since the 1950s has generated concern about the myriad of problems associated with automobile-oriented suburban expansion. Denver's RTD light rail system, which opened in 1994, was an attempt to introduce an alternative to the automobile. The start segment was so successful that it has attracted widespread support for expansion. T-Rex, completed in 2006 was the first major expansion of the system. In addition, Denver is in the midst of building the FasTracks system, one of the most ambitious transit projects in the United States (RTD, 2012). This chapter examines some of the forces that have shaped Denver's land use patterns and transportation system over the last 150 years and gives a detailed look at the current RTD light rail system.

4.2 Streetcars, Buses and Auto-Dependence

The City of Denver has undergone significant changes in transportation and urban morphology over the last 150 years. Initially founded as a gold and silver mining settlement, the city's growth in the late 19th century was attributed to the railroads (Fisher, 2009). Denver's role as a regional railroad center ushered in an era dominated by manufacturing, finance, agriculture and food processing. The streetcar was Denver's first urban mass transit system. While horse drawn omnibuses had existed since the early 19th century, they were too expensive to carry the typical working class laborer (Warner 1962). Electrified streetcars emerged in the 1890s and greatly increased the range and speed of transportation, subsequently opening up the hinterlands to members of the middle and working classes. Denver's streetcar system began with the private Denver Tramway Company in 1886 (Fisher, 2009). At its peak, Denver, Colorado had one of the most extensive streetcar systems in the United States (Reps, 1979). By 1910 Denver's population was just over 200,000 and its streetcar system was seeing 120,000 boardings per day (Fisher, 2009). Like many other American cities, Denver began replacing its streetcar lines with buses in the 1930s, a process which ended in 1950 with the demise of the Denver streetcar system (Slater, 1997; Fisher, 2009). This decline of rail transit led to decades of auto-dependence, suburbanization and sprawl. Since 1970, Metro Denver's population has increased from 1.3 million to over 3 million residents (Figure 4:1). A vast majority of this growth has occurred in

Figure 4:1 Denver Metropolitan Population, 1970 – 2010.



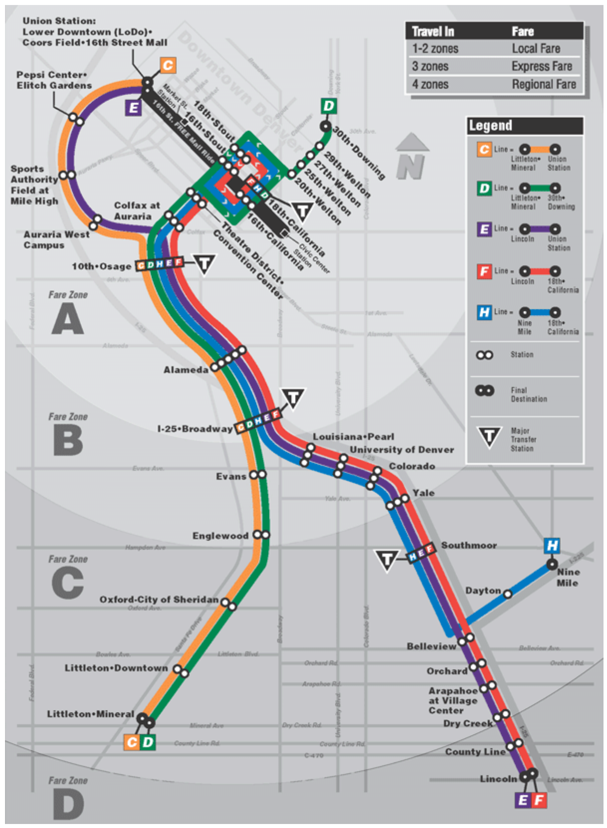
Source: US Census Bureau

four suburban counties surrounding the city: Adams County, Arapahoe County, Douglas County and Jefferson County. By 2010 the population of these four counties had reached 1.8 million and contained 60 percent of all residents in the metropolitan area. Denver's rapid population growth and suburbanization has led to problems with traffic congestion and sprawl. In 1998, the Sierra Club named Denver the sixth worst sprawling city in the United States (Kelly, 1998). In the 1970s there were two failed attempts to reintroduce rail transit to the city. However, neither of these two plans were ever implemented (Ratner and Goetz, 2010). Denver finally reintroduced light rail in 1994 with the unveiling of the RTD Light Rail system.

4.3 RTD Light Rail

Denver's Regional Transit District (RTD) unveiled a new light rail system beginning in 1994. By 2002 the initial project was completed, connecting downtown Denver with its suburbs of Littleton, Englewood and Sheridan as well as the Five Points neighborhood (Figure 4:2). The Transportation Expansion project, more commonly known as T-REX, was completed in 2006 and marked the first major expansion of the light rail system. The multimodal plan constructed a new 19 mile light rail line paralleling Interstate 25 and Interstate 225. The plan also included freeway widening to mitigate congestion in the corridor. One of the major weaknesses of the T-REX plan is that the corridor is bisected by limited access highways which act as hindrances to pedestrian accessibility. Most T-REX stations are surrounded by auto-oriented land uses which ac as an additional challenge to improving pedestrian accessibility. Currently, the RTD Light Rail system contains 5 lines and 36 stations serving the City of Denver and its southern suburbs (Figure 4:2). RTD has played an active role in promoting transit-oriented developments (TODs) near its transit stops. The region's first TOD center is Englewood Town Center, located adjacent to the Englewood RTD station on the Southwest Corridor Line. Englewood Town Center contains a mix of land uses including a cultural and civic center, ground level retail and over 500 residential units (Arrington, 2005).

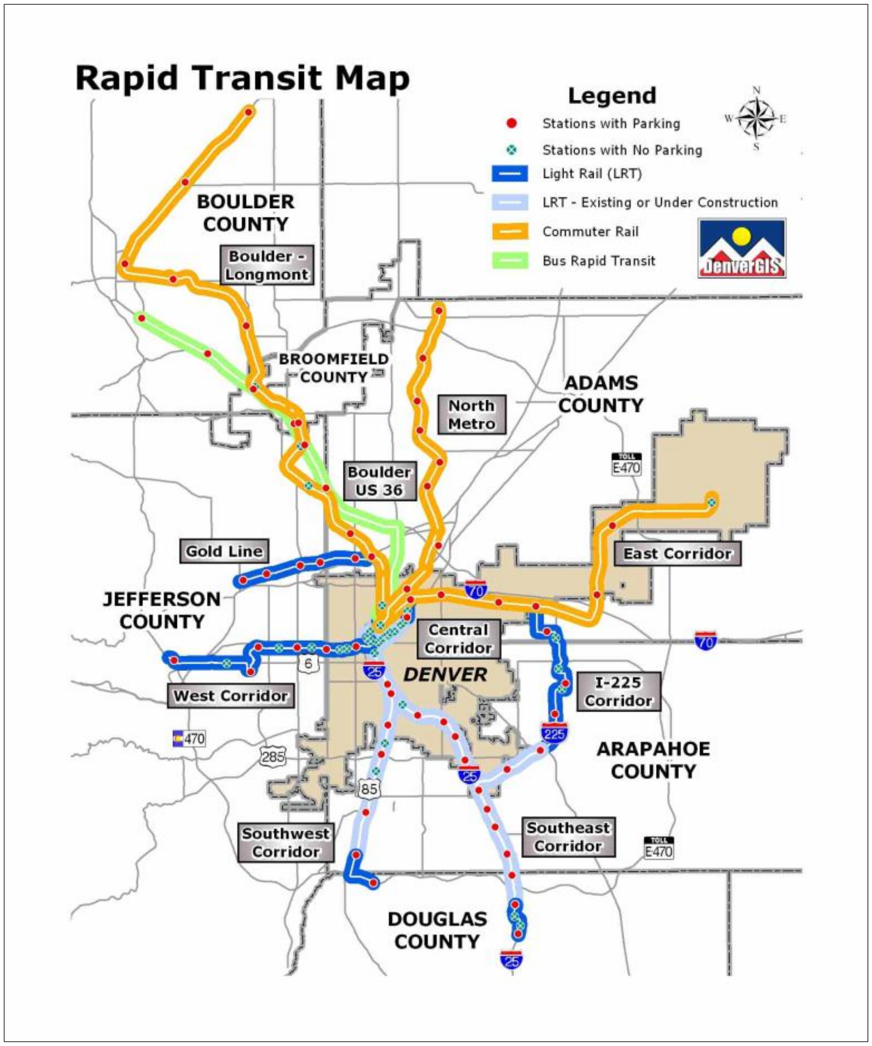
Figure 4:2 Current RTD Light Rail System



Source: Denver Regional Transit District

In 2004, the Denver Regional Transit District revealed perhaps the most ambitious rail transit plan for any city in the country. The plan, named FasTracks calls for the installation of nine rail transit lines and one bus rapid transit line. The plan will add approximately 93 miles of commuter rail, 28 miles of light rail and 18 miles of bus rapid transit (Seen in Figure 4:3).

Figure 4:3 Denver's FasTracks Plan



Source: Denver Regional Transit District

CHAPTER 5: DATA AND METHODOLOGY

5.1 Introduction

This chapter gives a detailed overview of data sources as well as the methodologies used in this study. The data section describes data sources, as well as the methods that were used to convert the data into a usable format. The methodology section of this chapter is broken up into two subsections. The first subsection examines methods used to create transit service-areas. Transit service-areas, which were calculated using the location on-off network (LOON) method, served as the spatial scale for the other variables. Finally, this section discusses the route-directness index and pedestrian catchment ratio which were used to analyze the impacts of social paths on transit service-area analysis. The second methodology subsection focuses on methods used to create the pedestrian level of service index for transit stops. It discusses K-Means cluster analysis which was used to break up each variable into six classes and hierarchical cluster analysis which was used to create the final pedestrian level-of-service scores for each station.

5.2 Data

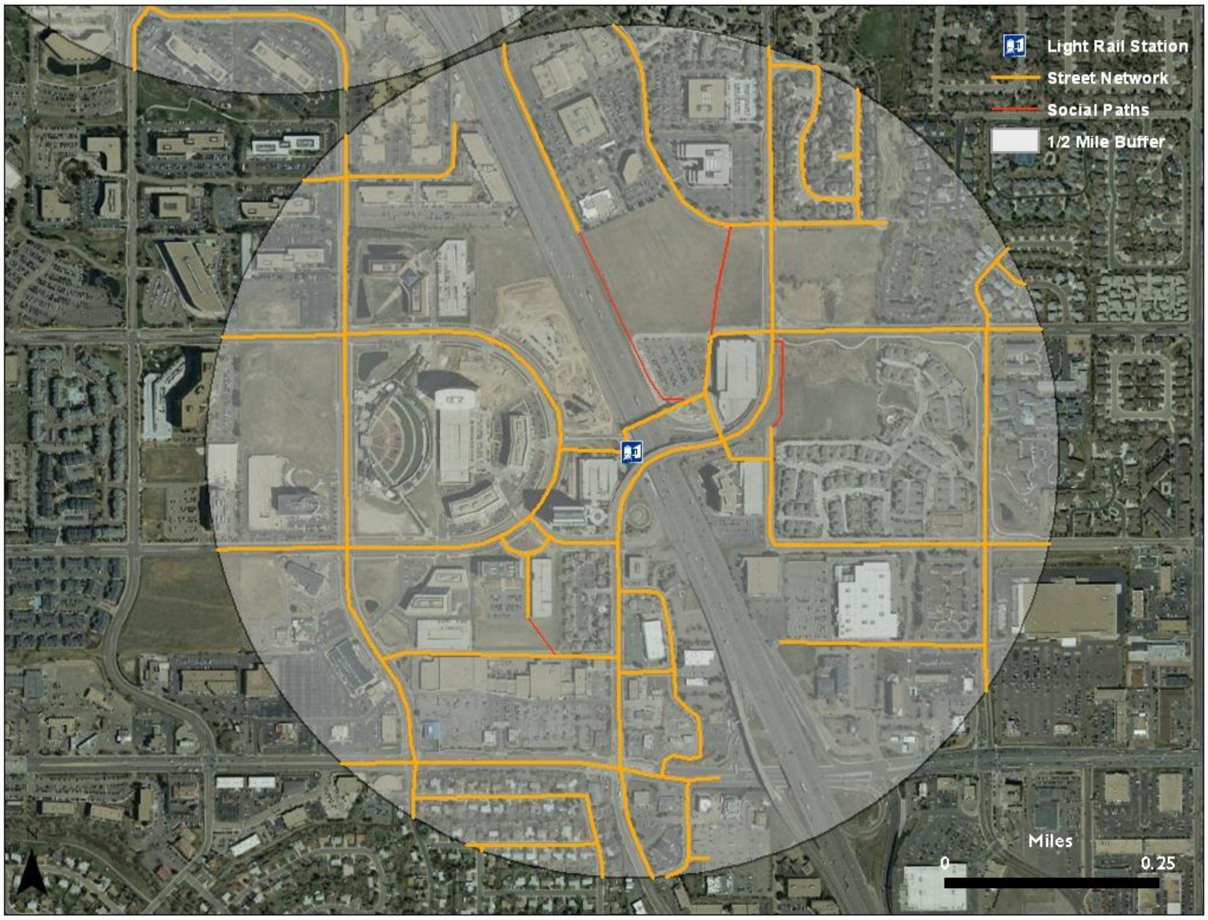
This thesis made use of a variety of geospatial data. Data could be broken up into two categories: (1) Network data, which were used to create transit service-areas; and (2) station area data which included of light rail stations, the density and diversity of land use, the number of station parking spaces and transit connectivity. Transit connectivity is based on how many other transit stops a particular light rail station was connected to without transferring.

NETWORK DATA

Transportation network data are vitally important to performing transit service-area analysis. Street network data were obtained from Douglass County, Arapahoe County and the

City and County of Denver. However, the street network is merely one means by which pedestrians access transit. Arapahoe County and Denver County both had additional data that included bicycle paths and multi-use trails. Social paths were also incorporated into the pedestrian network. Social paths were located by examining Bing Maps imagery which is now built into ArcGIS software. Unlike previous versions of the software, worldwide satellite imagery can be added into ArcGIS 10 as a base map. This imagery had a fine enough resolution to detect social paths. Built-in satellite imagery replaced the tedious process of downloading and stitching together digital orthophotos. In all, six stations, Littleton-Mineral, Orchard, Belleview, Englewood, Arapahoe at Village Center and Dry Creek stations had identifiable social paths. A common characteristic of social paths was that they traversed greenfields surrounding the light rail stops. Greenfields are vacant parcels surrounding transit stops. Bing Maps imagery also allowed all formal pedestrian connections to be connected to the network. The remotely-sensed data were supplemented by fieldwork undertaken in March 2011, where the ways in which pedestrians accessed the system were observed and diagramed. The final pedestrian network included street data, bicycle paths, formal pedestrian paths and social paths. The pedestrian network was then input into ArcGIS where several raster-based operations were performed. Limited access highways were omitted from the network since they are inaccessible to pedestrians (Upchurch et al, 2004). Because the pedestrian network was used in raster analysis, it was important to standardize the coordinate system which would in turn standardize raster cell size. This thesis followed Upchurch et al.'s (2004) recommendation and used a coordinate system whose units are in feet. All network shapefiles were converted to the Colorado State Plane (feet) coordinate system. A map showing the differences in street and pedestrian network can be seen in Figure 5:1.

Figure 5:1 Street Network and Social Paths, Arapahoe at Village Center Station



STATION AREA DATA

Station area data include the density and diversity of land use as well as environmental data for areas near light rail stations. Station area data were obtained from a wide range of sources including the US Census, Denver Regional Transportation District (RTD), the Denver Regional Council of Governments (DRCOG) and local county governments. A point shapefile containing the locations of the light rail stations was obtained from the Denver RTD. The station data served as the source point from which areas within walking distance were calculated. The station data also contained a field that showed the number of parking spaces dedicated to the station. This field would later be incorporated into pedestrian level-of-service index. Because raster analysis necessitates that the source raster (light rail stations) and cost raster (pedestrian network) overlap, light rail stations had to be connected to the pedestrian network. This was done by either connecting the stations to the network with new paths, or by moving the stations to the nearest network link. The stations were placed over satellite imagery to ensure that the points were located on top of the station platforms. Two downtown stations, 16^{th} Street and 18^{th} Street, contained both an inbound stop on California Street and an outbound stop located one block away on Stout Street. To prevent redundancy, inbound and outbound stations were consolidated into a single station located equidistant between California and Stout Streets. The Denver RTD also provided the locations of all light rail lines. The light rail line data, along with the station data were later used to create a connectivity matrix showing the number of direct station connections (without transferring) for each light rail station.

The United States Census provided population data at the census block level for 2010. A TIGER shapefile containing all of the census blocks in the state of Colorado was obtained. Census blocks needed to have their coordinate system units changed from decimal degrees to feet. Decimal degrees cannot be easily converted into square miles or square kilometers because it depends on your location on the earth’s surface. The coordinate system for census blocks was changed to the Colorado State Plane coordinate system whose units were in feet. Because TIGER shapefiles do not contain population data, it was necessary to join them to data tables provided by the US Census. Population data were obtained for Arapahoe, Denver and Douglas Counties through the American Community Survey. These data contained IDs that corresponded to IDs in the TIGER census block shapefile. Using the join function, these tables were joined to the corresponding census blocks.

The DRCOG also provided a wide range of GIS data. DRCOG provided employment and retail data at the traffic analysis zone (TAZ) level for all counties in metropolitan Denver. These data file contained two fields which were used as variables in the analysis: the numbers of retail employees and non-retail employees. Non-retail employees (which are represented by the employment density variable) were found in several sectors including the service, industry, and military sectors. The population employment and retail densities were calculated by clipping the polygon data (census blocks and TAZs) to the transit service-areas. The intersect tool allowed the polygons to be cut by borders of each transit service-area. The 'calculate areas' function was run in ArcGIS to give the new area of each polygon. Areal interpolation was used so that transit service-areas were given a summed proportion of the polygon attributes (population, employment & retail density, and area) that they contained. Dividing these new values by the area of the transit service-area gave the population, employment and retail density for each station. Areal interpolation has been used to overcome discrepancies in scale when working with spatial data (Goodchild et al. 1992; Fisher and Langford, 1995). One of the major weaknesses of this method is that it assumes that phenomena are equally distributed throughout a polygon.

Denver, Douglas and Arapahoe Counties provided parcel data that were used in the analysis. For the RDI analysis, the parcel data were converted to a point shapefile based on their centroids and clipped to within one half mile of a transit stop. Because it was also converted to raster format, it was necessary to convert the file to the Colorado State Plane Coordinate System. Polygon parcel data was also used to examine the diversity of land uses within the service area. Diversity was measured using two different variables. The first variable examined the percentage of land uses that were conducive to walking (residential, commercial, municipal and parks). Residential land uses contained both single and multi-family dwelling units. Commercial land uses only contained land uses that were zoned for business or retail uses. Industrial land uses were omitted from this class. Municipal land uses included government buildings, universities (such as UC Denver and University of Denver) as well as sporting venues. Finally, parks were used as a walking-conducive land use. While parks are generally designed for pedestrian use, they exhibit a wide variation in accessibility depending on their location and design. The second variable used an entropy index to examine the diversity of land uses. Entropy indexes are commonly used in the social sciences to examine the diversity of observations in a dataset. The most common applications apply to socioeconomic and land use studies (Iceland, 2004; Brown et al, 2009). The entropy index, also known as the Shannon Index (Shannon, 1948) was used to examine the diversity of the four walking-conducive land uses for each station. Stations with the greatest mix of land uses scored the highest while stations with single land uses scored the lowest. The equation for the land use diversity variable can be seen in Equation 5:1.

Equation 5:1 Land Use Entropy Equation

$$\textbf{Land Use Diversity} = \frac{(-1 \sum_{n}^{1} p(\ln(p))}{\ln(n)}$$

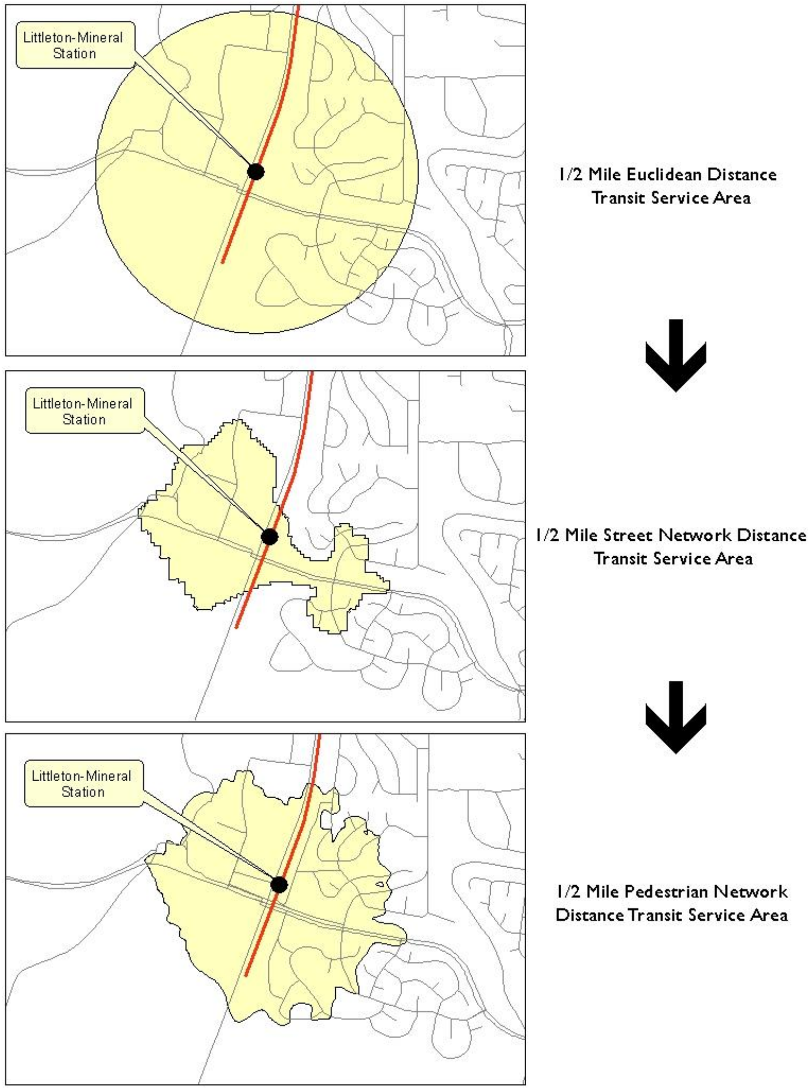
In equation 5:1, p represents the ratio of a particular land use while n represents the number of observations. For this analysis n = 4 and p was calculated for each of the four land use classes.

5.3 Methodology Part I: Social Paths and Transit service-areas

TRANSIT SERVICE-AREA CALCULATION

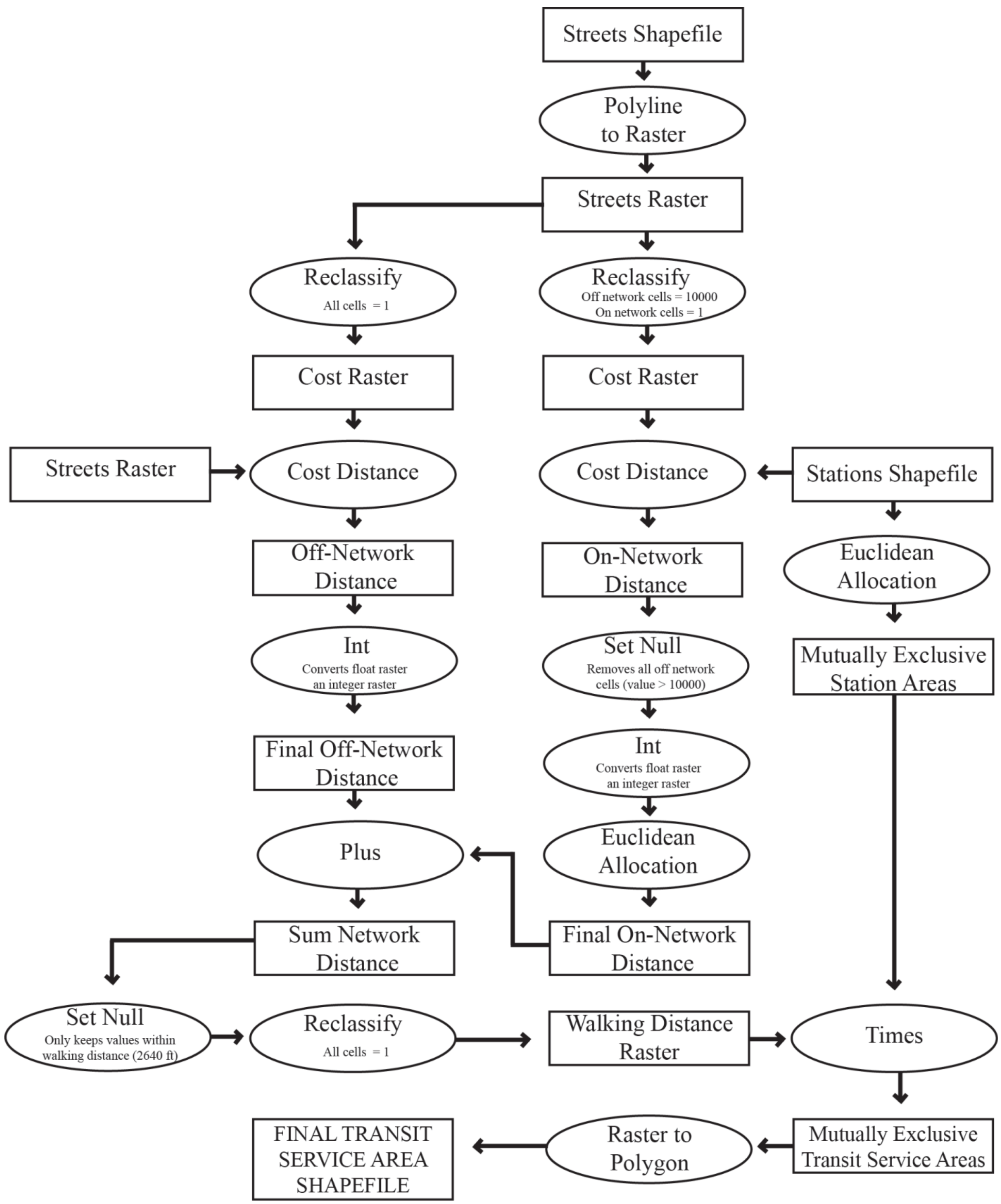
Transit service-areas were created using a python script in conjunction with ArcGIS 10. Python is a high level programming language that is incorporated into ArcGIS software. Python allowed GIS processes to be automated. This produced much faster results than manually performing operations. In addition it reduced the potential for error when doing complex, repetitive tasks (See Appendix C for the python script). This thesis used the location on-off network (LOON) method, created by Upchurch et al. (2004). This raster-based method creates mutually exclusive transit service-areas based on both on both on network and off network distance. ArcGIS has a built in service-area tools in its network analyst extension. Network analyst builds service-areas by connecting points that are desired distance from the source. Off-network sensitivity can be adjusted. The one weakness of network analyst is that it is not effective at incorporating off-network areas into the service-area. In an area with few roads, service-areas would be compact and would not accurately reflect off-network areas (Upchurch et al., 2004). This thesis used the LOON method to calculate transit service-areas based on the pedestrian network as opposed to the street network. A visual of the evolution of transit service-area methods can be seen in Figure 5:2.

Figure 5:2 The Evolution of Transit service-area Methodologies



Raster analysis required standardized environment settings in ArcGIS. Firstly, a 50 foot cell size was used for all rasters as suggested by Upchurch et al. (2004). This allowed raster math to be performed at a consistent spatial scale. The raster analysis performed in this thesis used a variety of tools in ArcGIS's spatial analyst and 3D analyst extensions. The final outputs of this process were transit service-areas for each light rail station. The methodology can be seen in Figure 5:3.

Figure 5:3 Transit Service-Area Methodology in ArcGIS



MEASURES OF EFFECTIVENESS

This thesis used two measures of effectiveness to examine the benefits of incorporating social paths in transit service-area analysis. The first measure was the pedestrian catchment ratio. The pedestrian catchment ratio was calculated by dividing the area of the transit service-areas by the area of a Euclidean distance buffer of the same distance (in this case one half mile). Because service-areas were mutually exclusive, Euclidean distance buffers did not have a uniform area. The equation for calculating the pedestrian catchment ratio is in Equation 5:2.

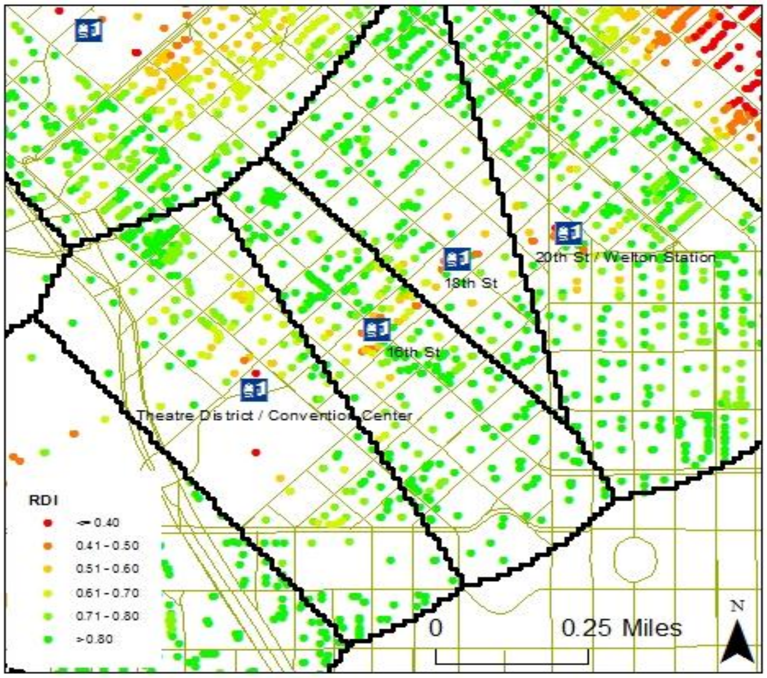
Equation 5:2 Pedestrian Catchment Ratio

$$\textbf{Pedestrian Catchment Ratio} = \frac{\textbf{Area of Network Service-area}}{\textbf{Area of Euclidean Service-area}}$$

Generally, a ratio of 0.50 to 0.60 characterizes an adequate pedestrian environment while a ratio of 0.30 or less characterizes service-areas that are inhospitable for pedestrians (Schlossberg and Brown, 2004; Schlossberg, 2006). The pedestrian catchment ratio was calculated by taking the areas of both the network-based service-area and the Euclidean based service-areas. The areas were calculated using the ‘Calculate Area’ function in the spatial statistics toolbox. These areas were then divided by each other to produce the final pedestrian catchment ratio (Equation 5:2).

A second measure of effectiveness that was used was the route directness index (RDI). The route directness index measures the ratio of straight line distance to actual walking distance between an origin and a destination. In this case, the origins were parcel centroids and the destinations were light rail stations. RDI is heavily influenced by network connectivity. Areas with a gridded street pattern produce high RDI values while areas with disconnected, suburban street patterns produce low RDI values. A visual of RDI can be seen in Figure 5:4.

Figure 5:4 Route Directness Index for Downtown Stations



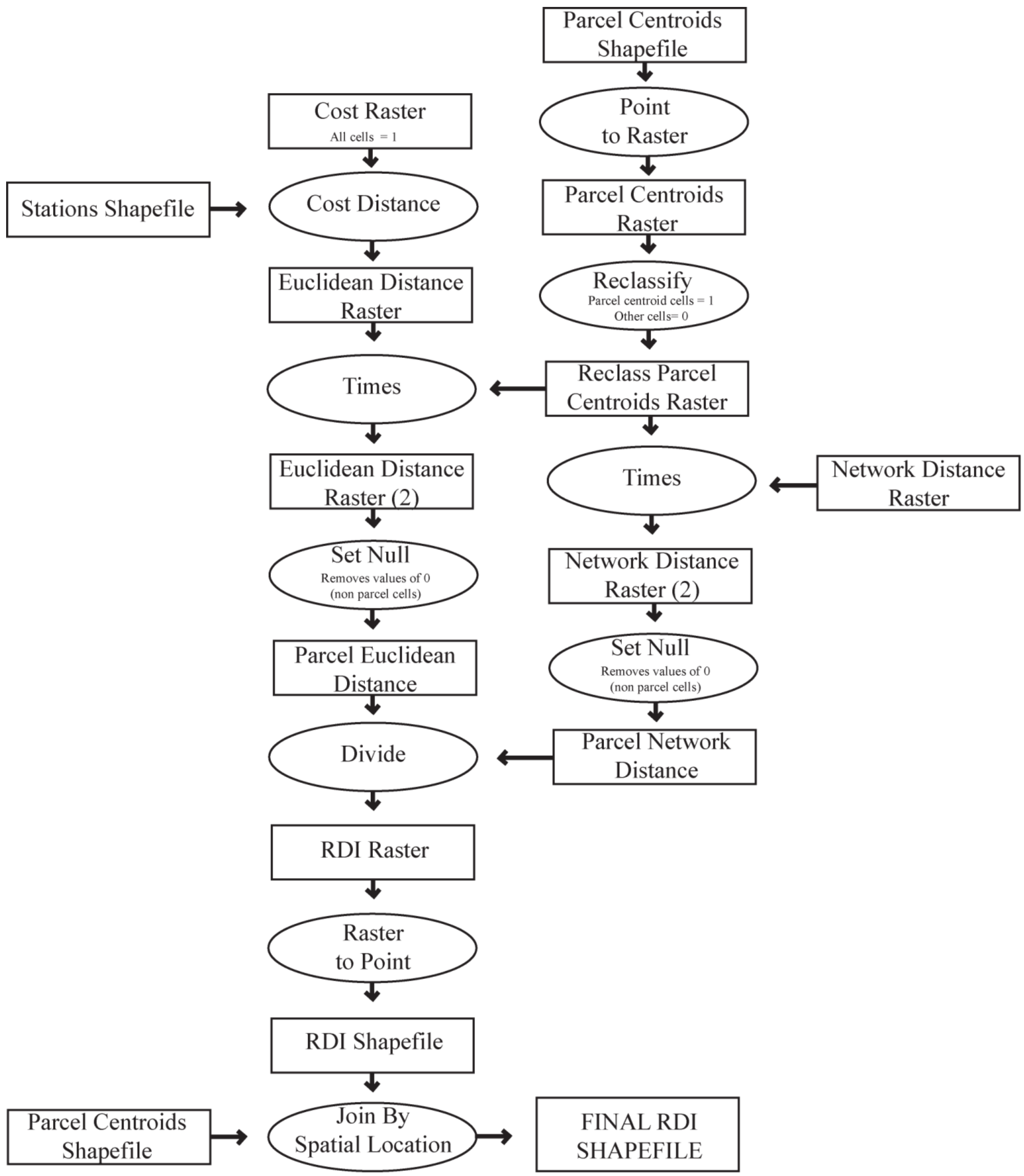
Only households within one half mile Euclidean distance of a transit stops were used. These households were examined using both the street network and the pedestrian network (street network, multi-use trails, bike paths and social paths). The equation for route directness index is shown below in Equation 5:3.

Equation 5:3 Route Directness Index

$$\textbf{Route Directness Index} = \frac{\textbf{Straight Line Distance}}{\textbf{Walking Distance}}$$

Like transit service-area analysis, RDI was calculated using a raster based method. Once again, environment settings were standardized. The final RDI values were between 0 and 1 with values close to 1 having the best RDI and values closer to 0 having the worst RDI. Generally, values of 0.60 to 0.70 are considered acceptable (Mortensen, 2009). The GIS methodology used to calculate RDI can be seen in Figure 5:5.

Figure 5:5 RDI Methodology in GIS



RDI and PC ratio were calculated for both the street network and the pedestrian network (with social paths). The differences in the street network and pedestrian network analyses will be discussed in Chapter 6.

5.4 Methodology Part II: The Pedestrian Level-of-Service Index

The pedestrian level-of-service index was built on seven different variables. As explained in the literature review, a myriad of studies have examined factors influencing pedestrian accessibility to transit. However, most of these studies focus on single factors (such as land use or the street network). Few studies have done a comprehensive index using a wide variety of spatial and amenity-based variables. Because of this lack of research on the relative importance of each variable, all variables were given equal weights. Because this index is the first of its kind, it can only analyze the relative accessibility of each station. This thesis used SPSS to perform a two part cluster analysis. The first cluster analysis used K-Means cluster analysis to divide each variable into six classes which were translated to a number of points (0 through 5). The scores for each of the nine variables were added together and used in a second hierarchical cluster analysis. This produced the final level-of-service grades for each transit stop.

K-Means cluster analysis was used to break each variable up into six classes. K-Means cluster analysis breaks up *n* observations into *k* clusters by minimizing within-cluster sum of squares (Hartigan and Wong, 1979). K-Means analysis has been applied to several transit studies (Krizek, 2006; Krizek and El-Genaidy, 2007). Before cluster analysis was performed, each of the nine variables was normalized, producing a number ranging from 0 to 1. This study had a total of 34 observations (one for each light rail station) which were divided into six clusters for each variable. Table 5:1 shows the variables that were used in the K-Means cluster analysis as well as their data, sources and spatial scale.

Table 5:1 Pedestrian Level-of-Service Index Variables

Variable	**Data**	**Data Sources**	**Spatial Scale**
PC Ratio	Transit service-areas and Euclidean service-areas	DRCOG, CDOT RTD	Transit service-areas
Transit Connectivity	Number of direct light rail connections	RTD	Light Rail Stations
Station Parking	Number of station parking spaces	RTD	Light Rail Stations
Route Directness	Euclidean distance and network distance for each parcel centroid	Counties, DRCOG, CDOT, RTD	½ Mile Euclidean Distance Buffer
Population Density	Population density per square mile	US Census	Census Blocks Aggregated to transit service-areas
Retail Density	Number of retail employees per square mile	DRCOG	TAZs Aggregated to transit service-areas
Employment Density	Number of non-retail employees per square mile	DRCOG	TAZs Aggregated to transit service-areas
Walking Land-Uses	Percentage of land-uses that are conducive to walking	Counties	Parcels aggregated to transit service-areas
Land Use Diversity	Diversity of walking-conducive land uses	Counties	Parcels aggregated to transit service-areas

Hierarchical clustering (HC) was performed to create the final pedestrian level-of-service index. HC analysis creates groups of the most similar or dissimilar observations in a dataset (Bailey, 1976; Mikelbank, 2004; Zheng, 2010). HC starts by giving each observation its own cluster. Subsequent iterations create fewer clusters that minimize within-group (or maximize out-of-group) variance until all observations are put in a single cluster (Mikelbank, 2004). Six clusters were used in this analysis corresponding to each A through F letter grade. The summed score of the nine variables was used as the input for the final HC. This thesis used between-group linkages which maximized the variance between groups. This ensured that the differences between clusters of light rail stations were maximized. Euclidean distance was used as the interval for HC. The letter grades and descriptions of each cluster can be seen in Table 5:2.

Table 5:2 Final Scores for the Pedestrian Level-of-Service Index

Letter Grade	**Description**
A	Excellent Pedestrian Accessibility
B	Good Pedestrian Accessibility
C	Moderate Pedestrian Accessibility
D	Poor Pedestrian Accessibility
E	Inadequate Pedestrian Accessibility
F	No Pedestrian Accessibility

Each of the six clusters corresponds to a different level of pedestrian accessibility. Stations in the cluster that had the highest scores will receive a letter grade of A. It is hypothesized that these stations will be located downtown, be pedestrian focused and have excellent accessibility. Downtown stations have dense, diverse land use, gridded street patterns and limited station parking suggesting that they will do well across all nine variables. Stations in the second highest cluster will receive a grade of B, coinciding to good pedestrian accessibility. Downtown fringe stations such as the Welton street stations, while still maintaining a dense, diverse environment with a gridded street pattern, are not likely to score as high as their nearby downtown stations. Stations in the third highest cluster will receive a grade of C corresponding to moderate pedestrian accessibility. It is hypothesized that these stations will be located in urban neighborhoods that have dense but singular land uses (such as Louisiana-Pearl station) or in suburban neighborhoods that have promoted TOD (such as Englewood station). The fourth cluster will be comprised of stations with poor pedestrian accessibility that will receive a grade of D. It is hypothesized that these stations will be located in commuter town centers such as Littleton-Downtown station. It is hypothesized that these stations will be more auto-oriented than pervious clusters but still have some pedestrian accessibility. The second lowest cluster will receive a grade of E, coinciding with inadequate pedestrian accessibility. It is hypothesized that these stations will be located in suburban locations with large park and rides. The lowest scoring cluster will receive a grade of F corresponding to no pedestrian accessibility. It is hypothesized that terminal park and ride stations such as Nine Mile station (which have large automobile catchment area) will fall into this category.

5.5 Conclusion

Methodologies for measuring pedestrian accessibility have improved dramatically over the last few years thanks to advancements in GIS software (Upchurch et al. 2004). Complex network-based approaches are now able to calculate accurate transit service-areas. Similarly, new literature is emerging on pedestrian behavior in the informal environment. By combining these two distinct bodies of literature, this thesis was able to calculate transit service-areas that reflect both formal and informal aspects of the pedestrian environment. Transit service-area analysis is a simple and effective way to measure pedestrian accessibility because it only requires road and transit stop data. In addition, the pedestrian level-of-service index seeks to build a comprehensive measure of pedestrian accessibility based on a variety of data. Results the social path analysis and the level-of-service index will be discussed in detail in Chapter 6.

CHAPTER 6: RESULTS

6.1 Introduction

This chapter will be broken up into three sections. The first section will examine the benefits of using social paths in transit service-area analysis. It will examine how the pedestrian catchment (PC) ratio and the route directness index (RDI) were improved by including social paths in the pedestrian network. In all, six stations were found to have social paths. The second section will focus on the pedestrian level-of-service index. This section will examine the final scores of all transit stops as well as examining some of the general trends that impact the station scores. The final section will examine how the pedestrian accessibility can be used to analyze pedestrian accessibility of a future commuter rail station along Denver's East Corridor, slated to open in 2016.

6.2 Social Paths and Transit service-area Analysis

This thesis hypothesized that informal social paths would improve pedestrian accessibility to light rail stations. Out of Denver's 34 light rail stations, 6 were found to contain social paths. These six stations were Littleton-Mineral, Orchard, Belleview, Englewood, Arapahoe at Village Center and Dry Creek stations. Several of the stations have large greenfields surrounding the station which contain social paths. It is important that if these greenfields are developed, they preserve the pedestrian activity created by social paths.

Social paths dramatically improved pedestrian accessibility at some stations, but did not improve accessibility in others. The effects of social paths on PC ratios can be seen in Table 6:1 while the effects of social paths on RDI can be seen in Table 6:2. Littleton-Mineral station saw the most dramatic improvement in accessibility. Both the transit service-area and PC ratio increased by over 60 percent if social paths were included. Belleview, Englewood and Arapahoe at Village Center stations all saw their PC ratio increase by over 15 percent. These dramatic increases suggest that ridership studies are likely to underestimate the number of users that access these light rail stations by walking. In addition, the increase in in the size of the transit service-area could create more opportunities to build transit-oriented developments.

While the PC ratios increased dramatically for some stations, RDI did not increase as dramatically. Once again, Littleton-Mineral station saw the greatest improvement. Households within one half mile of Littleton-Mineral station saw their route directness improve by nearly 34 percent from 0.325 to 0.529. For example, a household that lived one quarter mile Euclidean distance from the station would, on average, have to walk 0.769 miles to access the station using the street network. This would put the household outside of the transit service-area. However, using social paths, the same household would have their walking distance reduced to an average of 0.473 miles, an improvement of nearly three-tenths of a mile. That would mean that this household can now be considered within walking distance to the station. Belleview, Englewood and Arapahoe at Village Center stations only had modest improvements in their route directness index. Englewood had the second best improvement in RDI with 6.00 percent. Belleview and Arapahoe at Village Center only had improvements 0.85 and 5.55 percent respectively. All three of these stations had good route directness using the street network, with values of over 0.700.

Two stations saw very little improvement in their PC ratio or RDI. Orchard station saw only a small increase in both its PC ratio and no increase average RDI. The PC ratio increased from 0.452 to 0.467, an improvement of only 3.38 percent. Meanwhile, RDI did not improve at all. Dry Creek station did not see any improvement in its transit service-area size, PC ratio or

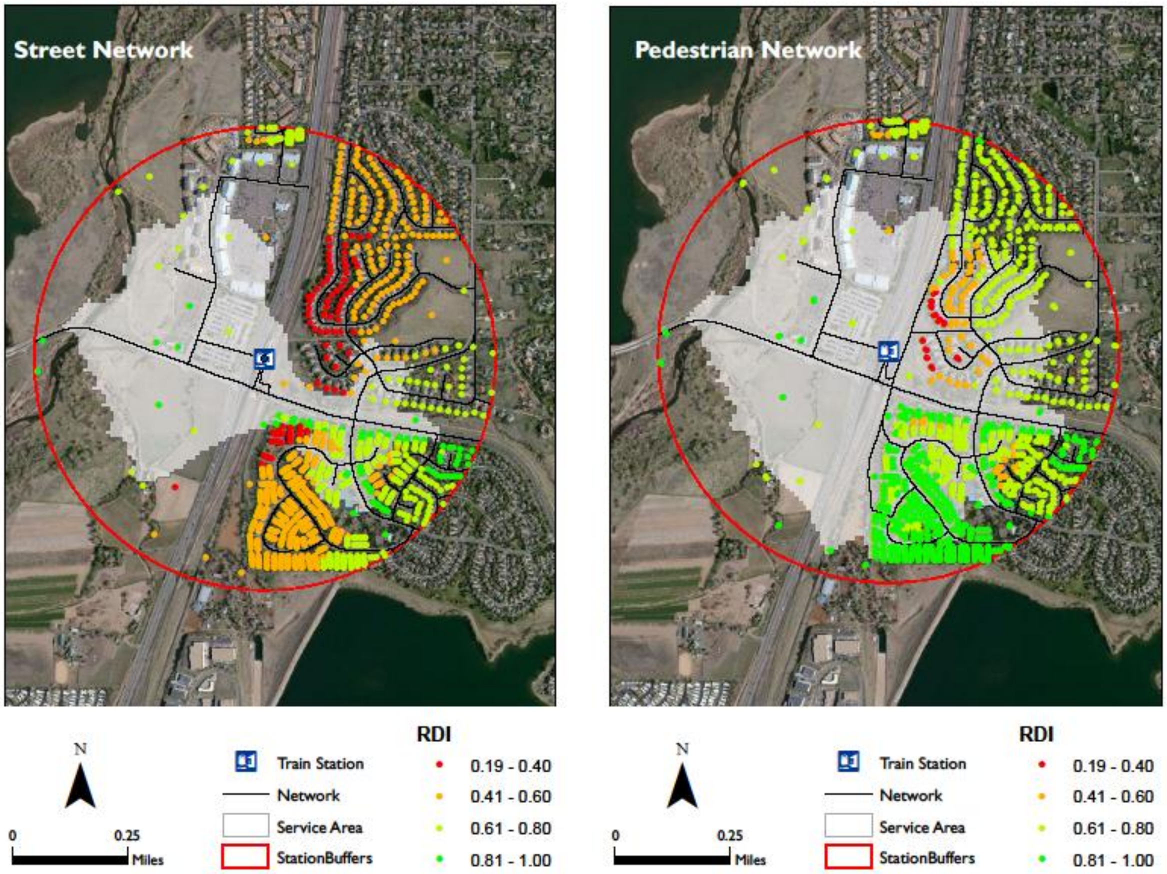
Table 6:1 Social Paths and Pedestrian Catchment (PC) Ratio

STATION	Streets Network PC Ratio	Pedestrian Network PC Ratio	Increase	%
Littleton-Mineral	0.325	0.529	0.204	62.93%
Orchard	0.452	0.476	0.024	5.31%
Belleview	0.373	0.458	0.085	22.77%
Englewood	0.325	0.388	0.063	19.50%
Arapahoe	0.390	0.503	0.113	29.10%
Dry Creek	0.403	0.403	0.000	0.00%
AVERAGE	**0.378**	**0.460**	**0.082**	**21.61%**

Table 6:2 Social Paths and Route Directness Index (RDI).

STATION	Street Network RDI	Pedestrian Network RDI	RDI Increase (%)
Littleton-Mineral	0.576	0.769	33.51%
Orchard	0.752	0.752	0.00%
Belleview	0.708	0.714	0.85%
Englewood	0.700	0.742	6.00%
Arapahoe	0.703	0.742	5.55%
Dry Creek	0.774	0.774	0.00%
AVERAGE	**0.702**	**0.749**	**6.65%**

Figure 6:1 Littleton-Mineral Using Street Network and Pedestrian Network Methods



RDI. Like the previous stations discussed, the lack of improvement in RDI can be attributed to the relatively high RDI values for the street network (greater than 0.70). There could be three additional potential reasons why social paths did not impact accessibility at Dry Creek and Orchard stations. The first is that pedestrians could be walking greater than one half mile to the transit stop. Therefore no improvement was seen at the half mile level. Secondly, social paths at Dry Creek station may be use to access something other than transit. A third potential reason is that social paths were used as shortcuts, rather than to improve pedestrian connectivity. All three of these reasons should be examined in future research.

On average social paths increased the PC ratio of stations by over 21 percent. Similarly, RDI increased by an average of nearly 7 percent. The increase in PC ratio and RDI shows that stations should consider converting their social paths into permanent sidewalks. A first reason for converting social paths into permanent pedestrian paths would be that it would increase the area of within walking distance of a transit stop. A second reason is that it is likely that social paths undergo fluctuations in their use based on seasonality, weather conditions and lack of amenities. Because social paths run simply over grassy surfaces, it is likely that they are unused in the snow and rain. Another major fluctuation has to do with the lack of amenities, notably the lack of lighting. Lack of lighting poses both a perceived and real safety concern. Lack of lighting makes pedestrians feel less safe and therefore less likely to use a particular path (RTD Transit Access Committee, 2009). Lack of lighting can potentially cause injuries for pedestrians (particularly those with limited mobility) as well as fostering an environment for criminal activity (RTD Transit Access Committee, 2009). The lack of lighting also limits the use of these paths to the daylight hours. During the winter season, it is likely that many peak hour light rail users would be entering and exiting the light rail station in the dark. All of these factors prevent social paths from being used to their fullest extent. Many pedestrians may drive to the light rail station despite being within walking distance (when social paths are included). Conversion of social paths to social paths should increase the number of pedestrians who access each station.

One of the problems that social paths face is that many of their locations are likely to be developed in the ensuing years, severing important pedestrian connections. Preserving these pedestrian connections may prove to be complicated, especially since greenfields are likely to be sold to private developers. This creates a battle over public vs. private space. In many ways, TODs built on top of social paths will counteract TODs goal of creating a walkable environment. TODs often contain private walking paths and may even contain pedestrian barriers such as fences. Land use planners should include ordinances that preserve important pedestrian connections in new TODs adjacent to transit stops.

6.3 Pedestrian Level-of-Service Index

VARIABLE SCORING

The pedestrian level-of-service index was calculated first by performing K-Means clustering on each of the nine variables (as explained in Chapter 5). The first variable that was scored was the number of station parking spaces. K-Means clustering divided the number of parking spaces into six classes as seen in Table 6:3. Station parking was normalized so that stations that had 0 parking spaces had a value of 1 while the station with the most parking spaces had a value of 0. Stations had a wide number of parking spaces ranging from 1,734 at Lincoln

Table 6:3 Clusters for Parking Spaces

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**	**Cluster 6**
Number of Stations	20	6	1	2	3	2
Normalized Mean	0.990	0.817	0.689	0.510	0.289	0.043
Mean Parking Spaces	18	317	540	849	1,233	1,660
High Value	129	388	540	910	1,248	1,734
Low Value	0	235	540	788	1,225	1,585
POINTS AWARDED	5	4	3	2	1	0

station to a low of 0 at several downtown and urban stations. All of the downtown stations contained 0 parking spaces and received the highest score while the terminal suburban stations (Lincoln, Littleton-Mineral and Nine Mile) had among the most parking spaces and received either 0 or 1 point. Results for all stations can be found in Figure A:1 in Appendix A and Table B:1 in Appendix B.

The next variable that was used in the analysis was transit connectivity. This variable examined the number of stations that were directly connected to a specific light rail station (without transferring). K-Means clustering divided transit connectivity into six classes as seen in Table 6:4. Three stations (Alameda, 10th & Ossage and I-25/Broadway) had transit connectivity with all stations and received all 5 points. On the contrary, the Welton and I-225 corridor stations were connected to only about half of the light rail stations and did not receive any points. Results for all stations can be seen in Figure A:2 in Appendix A and Table B:2 in Appendix B.

Table 6:4 Clusters for Transit Connectivity

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**	**Cluster 6**
Number of Stations	3	4	4	5	11	7
Normalized Mean	1.000	0.879	0.727	0.697	0.623	0.494
Mean Connectivity	33	29	24	23	21	16
High Value	33	29	24	23	21	17
Low Value	33	29	24	23	20	16
POINTS AWARDED	5	4	3	2	1	0

The third variable that was analyzed was the average route directness index (RDI) for all parcel centroids within one half mile of each transit stop. It was decided to use one half mile Euclidean distance over one half mile network distance as to not create spatial bias for stations with small transit service-areas. K-Means clustering divided RDI into six classes as seen in Table 6:5. Two of the Welton street stations and Louisiana-Pearl received all 5 points. All three of

Table 6:5 Clusters for RDI

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Number of Stations	3	7	12	5	5	2
Mean RDI	0.863	0.805	0.755	0.704	0.657	0.478
High Value	0.871	0.810	0.777	0.714	0.663	0.498
Low Value	0.858	0.781	0.735	0.690	0.599	0.458
POINTS AWARDED	5	4	3	2	1	0

these stations are characterized by gridded street patterns and large transit service-areas. Two stations (Southmoor and Lincoln) which were characterized by suburban street patterns and small transit service-areas received 0 points. Results for all stations can be seen in Figure A:3 in Appendix A and Table B:3 in Appendix B.

The fourth variable that was examined was the pedestrian catchment (PC) ratio. The PC ratio was calculated by dividing the area of transit service-area by the area of a one-half mile Euclidean distance buffer. K-Means clustering divided PC ratio into six classes as seen in Table 6:6. Five stations, all of which were located in downtown Denver received all five points. In

Table 6:6 Clusters for PC Ratio

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Number of Stations	5	3	5	8	11	2
Mean PC Ratio	0.905	0.796	0.688	0.521	0.424	0.240
High Value	0.930	0.816	0.720	0.555	0.465	0.284
Low Value	0.869	0.777	0.632	0.476	0.333	0.196
POINTS AWARDED	5	4	3	2	1	0

addition to a gridded street pattern, the downtown stations are located in close proximity to one another. This further improves their PC ratio scores. The lowest scoring stations were Southmoor and Nine Mile. In both cases, interstate highways located adjacent to the stations sever pedestrian connections and lead to poor PC ratios. Full results for this variable can be seen in Figure A:4 in Appendix A and Table B:4 in Appendix B.

The next variable that was calculated was retail density per square mile. Retail density was calculated by dividing the number of retail employees within walking distance by the area of the transit service-area. K-Means clustering divided retail density into six classes as seen in Table 6:7. 16th Street station was the only station to receive all 5 points. 18th Street station scored 4 points. Twenty-two stations did not score any points at all and had retail densities of less than 1,000 per square mile. Many of these stations were suburban stations or special events stations. Full results for retail density can be seen in Figure A:5 in Appendix A and Table B:5 in Appendix B.

Table 6:7 Clusters for Retail Density

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**	**Cluster 6**
Number of Stations	1	1	2	1	7	22
Normalized Mean	1.000	0.710	0.365	0.279	0.097	0.023
Mean Retail Density	20,465	14,530	7,466	5,710	1,990	475
High Value	20,465	14,530	7,966	5,710	2,571	918
Low Value	20,465	14,530	6,966	5,710	1,404	108
POINTS AWARDED	5	4	3	2	1	0

The sixth variable that was analyzed was employment density. This variable examined the number non-retail employees per square mile within each transit service-area. Included in this variable was the service, industrial, military and self-employed sectors. K-Means clustering divided employment density into six classes as seen in Table 6:8. Only one station (Theater District/Convention Center) was put in the first cluster and received all 5 points. Orchard station, located adjacent to the Denver Tech Center scored 4 points while 18th Street station scored 3 points. Fourteen stations were put in the cluster that received 0 points. These stations included the Welton corridor and three terminal suburban stations. Full results for employment density can be found in Figure A:6 in Appendix A and Table B:6 in Appendix B.

Table 6:8 Clusters for Employment Density

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Number of Stations	1	1	1	6	11	14
Normalized Mean	1.000	0.610	0.497	0.343	0.176	0.062
Mean Emp Density	34,766	21,220	17,293	11,930	6,114	2,151
High Value	34,766	21,220	17,293	13,830	7,973	3,535
Low Value	34,766	21,220	17,293	9,491	4,427	462
POINTS AWARDED	5	4	3	2	1	0

The seventh variable that was examined was population density. Population density was based on the total population of census blocks for the 2010 census. This data was aggregated to calculate the population density per square mile within each transit service-area. K-Means clustering divided population density into six classes as seen in Table 6:9. Two of the Welton

Table 6:9 Clusters for Population Density

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Number of Stations	2	5	7	8	6	6
Normalized Mean	0.954	0.849	0.601	0.345	0.206	0.078
Mean Pop Density	10,792	9,603	6,806	3,901	2,336	879
High Value	11,317	10,080	7,434	4,952	2,985	1,431
Low Value	10,266	9,055	5,677	3,171	1,772	0
POINTS AWARDED	5	4	3	2	1	0

Street stations were put in the highest group and awarded all 5 points. The remainder of the Welton street stations received 4 points. Six stations were put in a cluster receiving 0 points. Included in this group was County Line station, which did not have a single person within walking distance. This can be attributed to the presence of a suburban shopping mall and surrounding surface parking. Full results for the population density analysis can be seen in Figure A:7 in Appendix A and Table B:7 in Appendix B.

The final two variables examined the diversity of land uses within the transit service-area using parcel data. The first variable examined the percentage of land uses that were conducive to walking (residential, commercial, municipal and park parcels). This was done by dividing the area of walking-conducive land uses by the area of the transit service-area. The six classes for this variable can be seen in Table 6:10.

Table 6:10 Clusters for Walking-Conducive Land Uses

	Cluster 1	**Cluster 2**	**Cluster 3**	**Cluster 4**	**Cluster 5**	**Cluster 6**
Number of Stations	3	1	8	15	5	2
Mean % Conducive	1.000	0.854	0.691	0.574	0.488	0.387
High Value	1.000	0.854	0.731	0.623	0.522	0.458
Low Value	1.000	0.854	0.641	0.545	0.475	0.392
POINTS AWARDED	5	4	3	2	1	0

Values ranged from a high of 1 at Colfax at Auraria, Pepsi Center and Theatre District / Convention Center to a low value of 0.392 at Littleton-Mineral station. Littleton-Mineral is surrounded by undeveloped land which resulted in its low score. Results for all stations can be seen in Figure A:8 in Appendix A and Table B:8 in Appendix B.

The final variable used an entropy index to examine the diversity of transit-conducive land uses for each station. The six classes for land use diversity can be seen in Table 6:11. Values ranged from a high of 0.965 at Littleton Downtown station (resulting in 5 points) to a low of 0.274 at Orchard station (resulting in 0 points). Littleton Downtown station is adjacent to Littleton's main street and contains a mix of parks (12 percent), residential (33 percent), commercial (26 percent) and municipal (27 percent). Orchard station, which serves the Denver

Table 6:11 Clusters for Land Use Diversity

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
Number of Stations	3	12	9	3	5	3
Mean Diversity	0.942	0.826	0.704	0.578	0.464	0.387
High Value	0.965	0.878	0.745	0.590	0.503	0.341
Low Value	0.903	0.770	0.661	0.557	0.419	0.274
POINTS AWARDED	5	4	3	2	1	0

Tech Center contained mostly commercial land-uses (88 percent) and didn't score any points. Results for all stations can be seen in Figure A:8 in Appendix A and Table B:8 in Appendix B.

FINAL INDEX SCORING

The scores of the nine variables were summed for each station and used in a hierarchical cluster (HC) analysis. HC analysis divided up stations into six classes, each corresponding to a letter grade. The results of the HC analysis can be seen in Table 6:12. Four stations received a letter grade of 'A' scoring between 32 and 35 points. These stations were characterized by excellent pedestrian accessibility. Two stations received a letter grade of 'B' scoring between 26 and 28 points. These stations were characterized by good pedestrian accessibility. Seven stations received a letter grade of 'C,' scoring between 24 and 22 points. These stations were characterized by moderate pedestrian accessibility. Twelve stations scored between 17 and 21 points and received a letter grade of 'D'. These stations were characterized by poor pedestrian accessibility. Seven stations scored between 11 and 14 points and were given a grade of 'E'. These stations were characterized by inadequate pedestrian accessibility. Finally, two stations were given between 7 and 9 points, thus receiving a letter grade of 'F'. These stations were characterized as inaccessible to pedestrians. Averages for each letter grade can be seen in Table 6:13 while and the final grades for each station can be seen in Table 6:14 and Figure 6:2.

Table 6:12 Hierarchical Cluster Analysis Results

	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5	Cluster 6
FINAL GRADE	A	B	C	D	E	F
Number of Stations	4	2	7	12	7	2
Mean Points	34	27	22	18	12	8
High Value	35	28	24	21	14	9
Low Value	32	26	22	16	11	7

Table 6:13 Averages for Each Accessibility Grade Class

	Parking	Trans Connect	RDI	PC Ratio	Retail	Emp	Pop	% Walk LU	LU Diversity
A	0	29	0.765	0.914	10,970	19,493	7,594	0.817	0.820
B	0	29	0.754	0.631	3,708	4,289	8,571	0.631	0.931
C	47	22	0.786	0.698	1,111	4,581	5,112	0.688	0.775
D	302	21	0.739	0.526	824	6,652	4,820	0.563	0.685
E	657	21	0.698	0.410	1,476	4,981	2,924	0.562	0.512
F	1,480	19	0.561	0.419	365	4,774	3,060	0.585	0.496

Four stations, 16^{th} Street, 18^{th} Street, Colfax at Auraria and Theater District / Convention Center scored a letter grade of ‘A’ by scoring at least 32 points. These stations were characterized by dense, mixed use developments, good transit connectivity, lack of park and rides and gridded street patterns. These three stations averaged a retail density of over 10,000 per square mile, employment density of over 19,000 per square mile and population density of over 7,500 per square mile. Employment and retail density were significantly higher than any other class. The PC ratio was also very high, averaging 0.914. This can be attributed to the gridded street pattern and the density of light rail stations in downtown. In downtown Denver it is possible to be within walking distance to two or more light rail stations. Walking-conducive land uses made up over 80 percent of land and the land use diversity index averaged 0.820. 16th Street and 18th Street stations and Theatre District / Convention Center had the highest score 35 points each. These three stations are located centrally in downtown Denver. 16th Street station is located adjacent to the 16th street pedestrian mall. The pedestrian mall serves as the retail hub for downtown and connects the Denver state capitol with Union Station. The other station that received a letter grade of ‘A’ was Colfax at Auraria station which scored 32 points. This station was also located in downtown Denver and serves the campus of University of Colorado at Denver. It performed well in all categories except retail density. This can be attributed to its location adjacent to the college campus as well as its location on the edge of downtown. These four stations satisfy the hypothesis that stations that score in the highest class will be located in downtown Denver. Because of the density and diversity of land use and pedestrian friendly environment, these stations were ranked as the most accessible to pedestrians.

Two stations received a letter grade of ‘B’ by scoring between 26 and 28 points. The three stations were Union station and 10th and Osage. As initially expected, these two stations were located on the downtown fringe. These stations were characterized by a mix of at least two of the three land use variables, good transit connectivity and good pedestrian connectivity. Stations in this class actually outperformed their downtown counterparts in two categories. They had the highest population density averaging over 8,500 people per square mile (compared to 7,594 for downtown stations) as well as the highest land use diversity score (0.931). PC ratio declined significantly, in large part due to the small service area of 10th / Osage station. 10th / Osage station is located adjacent to freight rail tracks and only has pedestrian accessibility on one side of the tracks. RDI values remained above 0.750 which can once again be attributed to the gridded street pattern. Similar to downtown stations, these stations lacked station parking and scored all 5 points. There was a sharp decline in both employment and retail density compared to downtown. Retail density declined from 10,970 to 3,708 per square mile. Similarly, employment density declined from 19,493 to 4,289 per square mile. This suggests that there is a sharp transition from the retail & employment land uses to residential land uses that occurs on the downtown fringe. While there was a decline in the percentage of walking-conducive land uses, this class scored the highest in land use diversity, with both stations scoring in the top 3 (with values of over 0.90). Despite declines in some variables, these stations retained good pedestrian activity and received the second highest classification.

Seven stations received a grade of ‘C’ by scoring between 22 and 24 points. This corresponded to moderate pedestrian accessibility. It was hypothesized that these stations would be either urban in character or suburban stations with TODs. All seven of the stations in this group were located in urban neighborhoods within 5 miles of downtown. These stations averaged 47 parking spaces, and maintained employment and population densities over 5,000 and 4,500 per square mile respectively. Once again there was a sharp decline in retail density, with this class averaging only 1,111 retail employees per square mile. The land use diversity score also declined to 0.775. The decline in these two variables suggests that singular land uses are more prevalent the further one gets from the central business district. This class outperformed downtown stations in RDI, averaging 0.786 which can be attributed to a gridded street pattern. Nearly 70 percent of land at these stations was conducive to pedestrian activity, scoring the second highest of any class. No suburban TOD stations such as Englewood and Belleview were located in this class as originally hypothesized.

Twelve stations received a letter grade of ‘D’, scoring between 21 and 17 points. These stations were characterized by poor pedestrian accessibility. The mean number of parking spaces increased to an average of 302 per station. However, these values varied significantly from station to station. Four stations in this group had no parking spaces while I-25/Broadway had over 1200. The variable that saw the biggest change was the PC ratio. PC ratio averaged only 0.526, just over half the area of Euclidean service-area. PC ratios were dramatically impacted by the presence of limited access highways. Six of the twelve stations were located along Interstate 25 while four others were located along the limited access Santa Fe Drive. Population density decreased to 4,820 persons per square mile. Once again there was much variation. 25th and Welton had the highest population density of any station (11,317 per square mile), while Oxford/City of Sheridan station had only 1,352 people per square mile. Employment density was the second highest overall at 6,652 per square mile. This can be largely attributed to Belleveiw and Orchard stations, which serve the Denver Tech Center. Belleview station is also home to several TODs. Despite the presence of these developments, the population density of the station area was less than 3,500 per square mile. There were also decreases in the percentage of walking-conducive land uses and land use diversity. Once again however, there was great variation from station to station. Littleton-Downtown station, located adjacent to a suburban main street, attained the highest land use diversity (at 0.965) while Orchard station attained the lowest (0.274). Because all of these stations are located in suburban locations, the hypothesis that commuter town centers would be located in this class can be confirmed.

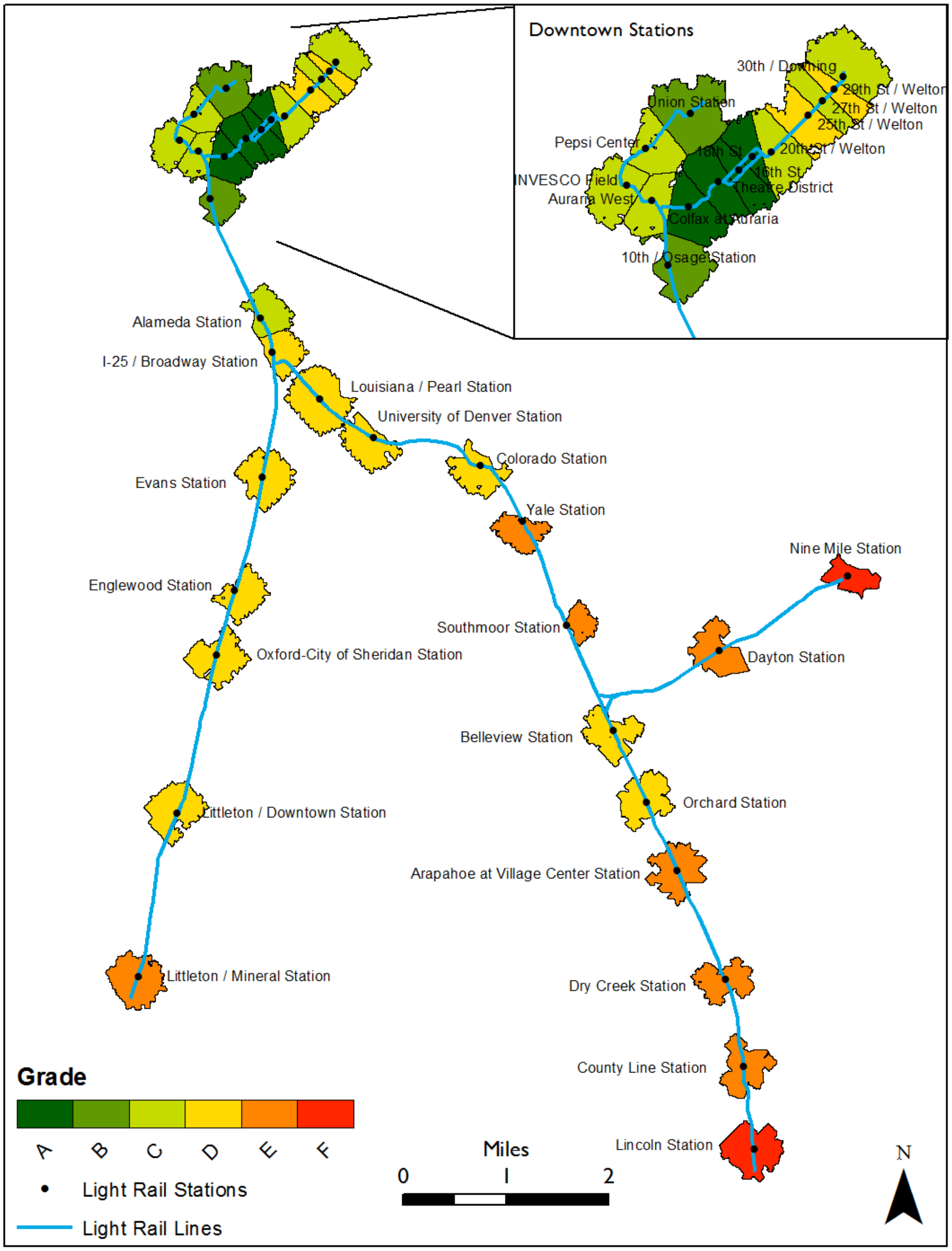
Seven stations received the second lowest grade of ‘E’ by scoring between 11 and 14 points. These stations were found to have inadequate pedestrian accessibility. All of these stations were located along limited access highways. Five were located along I-25, one along I-225 and one along Santa Fe Drive. This led to a decline in PC ratio (0.410) and RDI (0.698). Stations in this class had an average of 657 parking spaces (with only one station having less than 200 spaces). This is consistent with the hypothesis that suburban park and rides would be located in this group. Land use patterns also point to suburban style development. Population and employment densities averaged only 2,924 and 4,981 per square mile respectively. Retail density was the third highest of any group, but this can be partially explained by the County Line station, which serves a regional shopping mall (and scored in the top five in retail density). Once again walking-conducive land uses and land use diversity decreased. Walking-conducive land uses were the lowest of any group, averaging just over 56 percent of the total land. The land use diversity index also decreased to 0.512 the second lowest of any group. One terminal station, Littleton-Mineral station was also put in this group.

Finally, two stations received a letter grade of 'F' by scoring between 7 and 9 points out of 45. These two stations, Nine Mile and Lincoln stations are both terminal park and ride stations that primarily serve the automobile. These two stations averaged 1,480 parking spaces and had poor transit connectivity. This group had the lowest average RDI and the second lowest PC ratio. Population density was just over 3,000 persons per square mile and employment density was only 4,774 per square mile. Retail density averaged a meager 365 per square mile. Land use diversity of these stations also scored the lowest, with a score of less than 0.50. The land use variables hint at the sprawling, singular land uses at terminal stations. Nine Mile station's location in the median of I-225 also contributes to a lack of pedestrian friendly environment. The major station pedestrian path is located in the middle of a cloverleaf interchange, making it dangerous for pedestrians. These two stations satisfied the hypothesis that terminal stations would be put in the worst group.

Table 6:14 Final Pedestrian Level-of-Service Index Scores

STATION NAME	TOTAL SCORE	LETTER GRADE
10th / Osage Station	26	B
16th St Station	35	A
18th Street Station	35	A
20th St / Welton Station	24	C
25th St / Welton Station	19	D
27th St / Welton Station	23	C
29th St / Welton Station	21	D
30th / Downing Station	23	C
Alameda Station	23	C
Arapahoe at Village Center Station	11	E
Auraria West Campus Station	22	C
Belleview Station	17	D
Colfax at Auraria Station	32	A
Colorado Station	19	D
County Line Station	12	E
Dayton Station	14	E
Dry Creek Station	14	E
Englewood Station	16	D
Evans Station	20	D
I-25 / Broadway Station	19	D
INVESCO Field at Mile High Station	22	C
Lincoln Station	9	F
Littleton / Downtown Station	20	D
Littleton / Mineral Station	11	E
Louisiana / Pearl Station	21	D
Nine Mile Station	7	F
Orchard Station	18	D
Oxford-City of Sheridan Station	17	D
Pepsi Center / Elitch Gardens Station	22	C
Southmoor Station	13	E
Theatre District / Convention Center	35	A
Union Station	28	B
University of Denver Station	17	D
Yale Station	14	E

Figure 6:2 Final Pedestrian Level-of-Service Index Map



One of the variables that resulted in some error was the station parking variable. The two special events stations (Pepsi Center/Elitch Gardens and Invesco Field at Mile High) were surrounded by surface parking. Because none of it is RTD parking the stations were each awarded 5 points for station parking. In reality, the dominance of surface parking would be a hindrance to pedestrian activity. Because surface parking (including non-RTD parking) could not be obtained for all stations only RTD parking was used. While some of the error was reduced by the walking-conducive land use variable, future studies should attempt to get more accurate data on surface parking.

6.4 Applications in Pedestrian Planning

One application of the pedestrian level-of-service index is that it can be used to examine the pedestrian accessibility of future transit stops and make suggestions on how they can improve their accessibility. This application examined Stapleton station, slated to open in 2016. Stapleton station, located on the future East Corridor commuter rail line was chosen for this analysis because it will serve the Stapleton neighborhood of Denver. Stapleton, being built on the site of the former Stapleton airport, is the largest new urbanist community in the United States. This analysis was conducted to see if Stapleton Station lives up to the pedestrian standards of new urbanist design. The number of parking spaces was taken from a conceptual plan provided by the City of Denver (2009). Upon opening, the station will have 1,648 parking spaces. This placed Stapleton station in the worst cluster, resulting in 0 points. The conceptual plan also pinpointed the locations of new streets and pedestrian paths which were incorporated into the pedestrian network. Despite the new pedestrian connections, the station had a low PC ratio of only 0.499. This resulted in only 2 points being awarded. RDI had a better result, with a score of 0.731, leading to 3 points being awarded. In accord with new ubanist design, the gridded street pattern (at least to the south of the station) resulted in a good RDI score. This thesis assumed that Stapleton station received all 5 points in transit connectivity. Because the East Corridor will be heavy rail as opposed to light rail, rail cars will not be compatible with existing light rail lines. By the time it is completed in 2015, the Stapleton station will have direct connections to all other existing commuter rail stations. Most importantly, the station will have direct access to both Union Station in downtown Denver and Denver International Airport. It was assumed that current land use patterns were reflective of station area land use when the station opens in 2016. This resulted in very low scores for the land use density variables. Out of a possible 15 points for land use variables, the station did not score any points. Population density was less than 500 persons per square mile. Employment density was slightly higher with 1,268 per square mile while retail density was only 865 employees per square mile. The station also scored poorly in the walking-conducive land use and land use diversity variables. Walking-conducive land uses made up only 41 percent of all land within walking distance to the transit stop. In addition, the land use diversity score was only 0.45. This resulted in a score of 0 and 1 point respectively. Because the Stapleton neighborhood is currently under construction, it is likely that land use density and diversity variables will improve by the time the station opens. However, developers should make an effort to increase land use diversity and density before the station opens. Pursuing advance TODs, such as those pursued in Phoenix (Atkinson-Palombo and Kuby, 2011) could be an effective strategy at promoting land use change before the station opens.

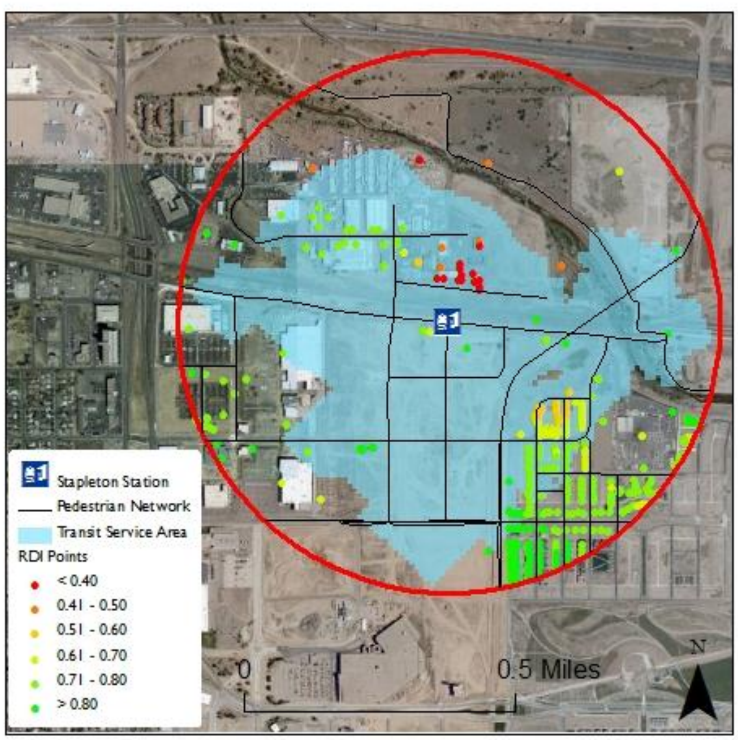
Overall, Stapleton station only scored 11 points resulting in a letter grade of ‘E’ corresponding to inadequate pedestrian accessibility. This is especially poor because of Stapleton’s commitment to new urbanist design. The final results for this analysis can be seen in

Table 6:15. A visual showing the transit service-area and RDI values can be seen in Figure 6:3. While the score is likely to improve by the time the station opens, the pedestrian level-of-service

Table 6:15 Stapleton Station Scoring

Variable	Scoring	Points
Parking Spaces	1,648	0
PC Ratio	0.499	2
Average RDI	0.731	3
Transit Connectivity	All stations	5
Retail Density	865 per sq mile	0
Employment Density	1,268 per sq mile	0
Population Density	436 per sq mile	0
Walking-Conducive LU	0.417	0
Land Use Mix	0.454	1
	TOTAL	11

Figure 6:3 Stapleton Transit service-area and RDI



index can help policymakers target specific areas of improvement. Most importantly, dense, mixed use advance TODs such as those in Phoenix (Atkinson-Palombo and Kuby, 2011) should be built before the station opens to accelerate land use change. RTD recommends TOD residential densities of at least 10 units per acre (5,400 per square mile). If Stapleton station achieves the minimum standard for TOD population density it would receive 3 additional points. Increasing both retail and employment density to 5,000 per square mile would award the station an additional 3 points. These targets would also increase the scores for walking-conducive land use and land use diversity. If Stapleton station achieves these land use targets by the time it opens, it would move up to a letter grade of 'C,' corresponding to moderate pedestrian accessibility. A letter grade of 'B' could be achieved if the station significantly reduced the number of parking spaces in additional to promoting land use change.

6.5 Conclusion

This chapter showed how social paths should be included in transit service-area analysis. Social paths were found to improve RDI and increase the size of transit service-areas. This chapter made the argument that social paths should be converted into permanent paths to improve accessibility. In addition, this paper discussed the pedestrian level-of-service index and its application to Denver's light rail system. By focusing on multiple variables including pedestrian connectivity, land use and station parking this index was able to produce a comprehensive index which measured a station's accessibility to pedestrians. Grades for Denver's light rail stations varied significantly. Downtown stations scored in the highest category while two terminal park and ride stations scored in the lowest category. Stations closer to downtown tended to score higher than their suburban counterparts. The final letter grades made the index simple to understand for planners and the general public. This chapter also showed how the pedestrian level-of-service index can be used to examine the pedestrian accessibility of future transit stops. By comparing it to existing stations, the pedestrian level-of-service index was able to show which factors were hindering or conducive to pedestrian accessibility at Stapleton station. The results showed that the station performed particularly poor in the land use density variables. Planners and developers should focus on increasing land use density and diversity of land uses before the station opens.

CHAPTER 7: CONCLUSION

7.1 Findings

This thesis was able to conclude that social paths are an important part of the pedestrian network and should be included in transit service-area analysis. Social paths formed at six light rail stations with inadequate pedestrian facilities. Social paths were found to increase the PC ratio by over twenty percent and RDI by over six percent. Both of these factors showed that social paths help improve pedestrian connectivity around light rail stops. Social paths are not utilized to their full potential due to problems of seasonality and safety. Social paths, which are formed over grass or dirt are unlikely to be used during inclement weather. In addition, social paths lack lighting and can only be used during the daylight hours. Social paths also pose safety problems for those with limited mobility. Future work should study the impacts weather and time of day on social path use. It would also be helpful to perform pedestrian counts to see just how many people are using social paths to access transit. Converting social paths into permanent paths would allow them to be used by all pedestrians regardless of weather or time of day. Paving over the surfaces would allow the paths to be used by the handicapped and those with limited mobility. The addition of lighting would allow these paths to be used at night and during poor weather. Several social paths formed over open space surrounding the transit stop. It is likely that these spaces will be developed in the future. One concern is that once these spaces are developed they will cut off important pedestrian paths. Because developments are private spaces it will likely create a debate over public vs. private pedestrian spaces. If new developments act as barriers to pedestrians, it is likely that they will create new social paths to overcome the obstacles. Future studies should examine how pedestrians respond when their social paths become developed.

The pedestrian level-of-service index was the first of its kind to grade transit stops on their pedestrian accessibility. Pedestrian accessibility is vital to the success of transit systems because users are likely to walk on at least one end of their trip. An increase in pedestrian accessibility is likely to increase transit ridership. The index focused on a variety of factors such as land use density and diversity, pedestrian connectivity and station parking. As expected, the downtown stations were found to have the best pedestrian accessibility. Meanwhile, a terminal park and ride station received a failing grade and was characterized by no pedestrian accessibility. Work needs to be done to increase pedestrian accessibility on several of Denver's light rail stations. Because the index combines spatial and amenity-based approaches, stations can create individualized pedestrian improvement plans. Some stations should focus their pedestrian improvement programs on land use change while other stations should focus their improvements on improved pedestrian connectivity and less competition with the automobile.

The pedestrian level-of-service index was shown to an application examining pedestrian accessibility for a future station along Denver's future East Corridor. Serving a large new urbanist community, Stapleton station will have direct connections to both downtown Denver and Denver International Airport. Despite new urbanism's commitment to pedestrian scale development, the station scored very poorly in the pedestrian level-of-service index with a grade of 'E' by scoring only 11 points out of a possible 45. The land use density and diversity variables scored particularly low. This can be attributed largely to the lack of development within the transit service-area. Beginning land use change through advance TODs would be one strategy to improve pedestrian accessibility by the time the station opens. Reductions in parking could also help produce more pedestrian activity.

7.2 Critique and Future Research

While social paths are an important part of the pedestrian network, they remain an understudied topic. Existing literature has been done by a handful of authors and focused more on pedestrian behavior than pedestrian accessibility. Several studies focused on how social paths form but said little about where they form or who uses them. It is important to know who uses social paths and where they are most likely to occur. Social paths are not the only elements of the informal pedestrian environment. Pedestrians are just as likely to walk over surface parking lots to access transit as they are over grassy areas. However, walking over a parking lot does not leave behind any mark of pedestrian use. Because social paths were found using aerial photographs it is likely that some social paths were missed. This thesis made use of nine variables to measure overall pedestrian accessibility for transit stops. These variables had several weaknesses. The first is that the three land use variables were aggregated. This meant that each variable was assumed to be uniformly distributed throughout its area. To minimize error, this thesis used the smallest areal units possible. However, future research should examine land use using intelligent interpolation using things such as parcel data. Other variables were omitted due to a lack of data. Safety plays an important role in pedestrian accessibility. Crime data could be an additional variable that could be used to measure pedestrian accessibility. Transit users may be less likely to walk in an area of high crime than they are in a safer neighborhood. Pedestrian safety is another potential variable that can be included in future analysis. Indexes such as the pedestrian environmental quality index take factors such as vehicle speeds, presence of sidewalks and crosswalk safety into consideration (San Francisco Department of Public Health, 2008). All three of these factors influence a pedestrian's ability to access a transit stop. The RTD transit access committee (2009) mentioned several other 'soft' variables that may influence pedestrian accessibility including presence of streetscaping, station platform cover, terrain, climate and whether or not there is a TOD master plan in place. These variables could be included in future analyses. This index can be easily customized to fit additional variables. Future studies should attempt to reduce colinearity by picking variables that measure different aspects of pedestrian accessibility. Variable weights are another element that should be examined in greater detail. Due to lack of consensus, this study assumed that all variables should be given equal weights. However, as work on pedestrian accessibility continues to improve, new research may show that some variables are more important than others.

There is an ongoing debate over what constitutes walking distance. Upchurch (2012) noted that pedestrians are likely to underreport their walking distances to transit in surveys. Walking distance is dependent on both the pedestrian environment as well as characteristics of individuals. One person may be willing to walk one mile to transit while another may only be willing to walk one-quarter mile. It is also noted that people are willing to walk further to light rail than they are to bus stops. The half-mile walking distance threshold can easily be changed to fit a bus system.

This thesis introduced a comprehensive, cross-discipline pedestrian level-of-service index that measures pedestrian accessibility to transit stops. This thesis seeks to create a new way for planners and policy makers to examine pedestrian accessibility to transit. By focusing strictly on transit service-areas, planners and policy makers can focus their efforts on improving accessibility in areas within walking distance to a transit stop. The pedestrian level-of-service index can also be used to measure the effectiveness of pedestrian improvement projects for existing or future stations. It is hopeful that others will take this approach and make their own additions and improvements. This thesis seeks to bridge the gap between the ways geographers, planners and civil engineers study accessibility by incorporating elements of each into a comprehensive index. It is hopeful that more cross-disciplinary research will emerge. As public transit continues to grow in American cities, it is likely that there will be increased emphasis on pedestrian accessibility. Planning and design paradigms have slowly shifted towards designing places that are dense, mixed use, pedestrian friendly and transit accessible. Finally, this study was only able to analyze the relative pedestrian accessibility of light rail stations in Denver. Future work should include light rail stations in several cities. A larger sample of light rail stations would create a more accurate classification system using clustering.

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APPENDIX A: FIGURES NOT INCLUDED IN TEXT

Figure A:1 Station Parking Scoring

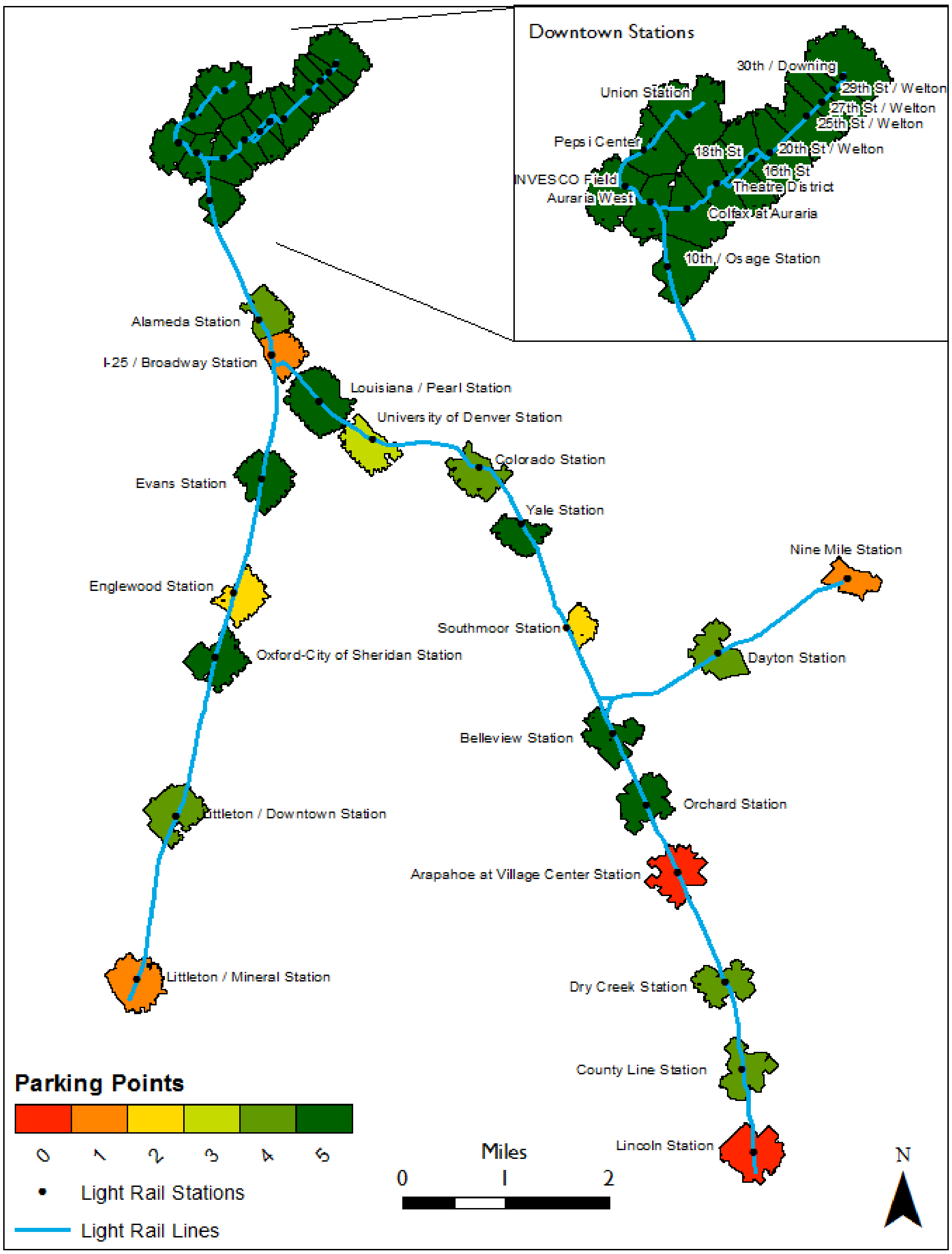


Figure A:2 Transit Connectivity Scoring

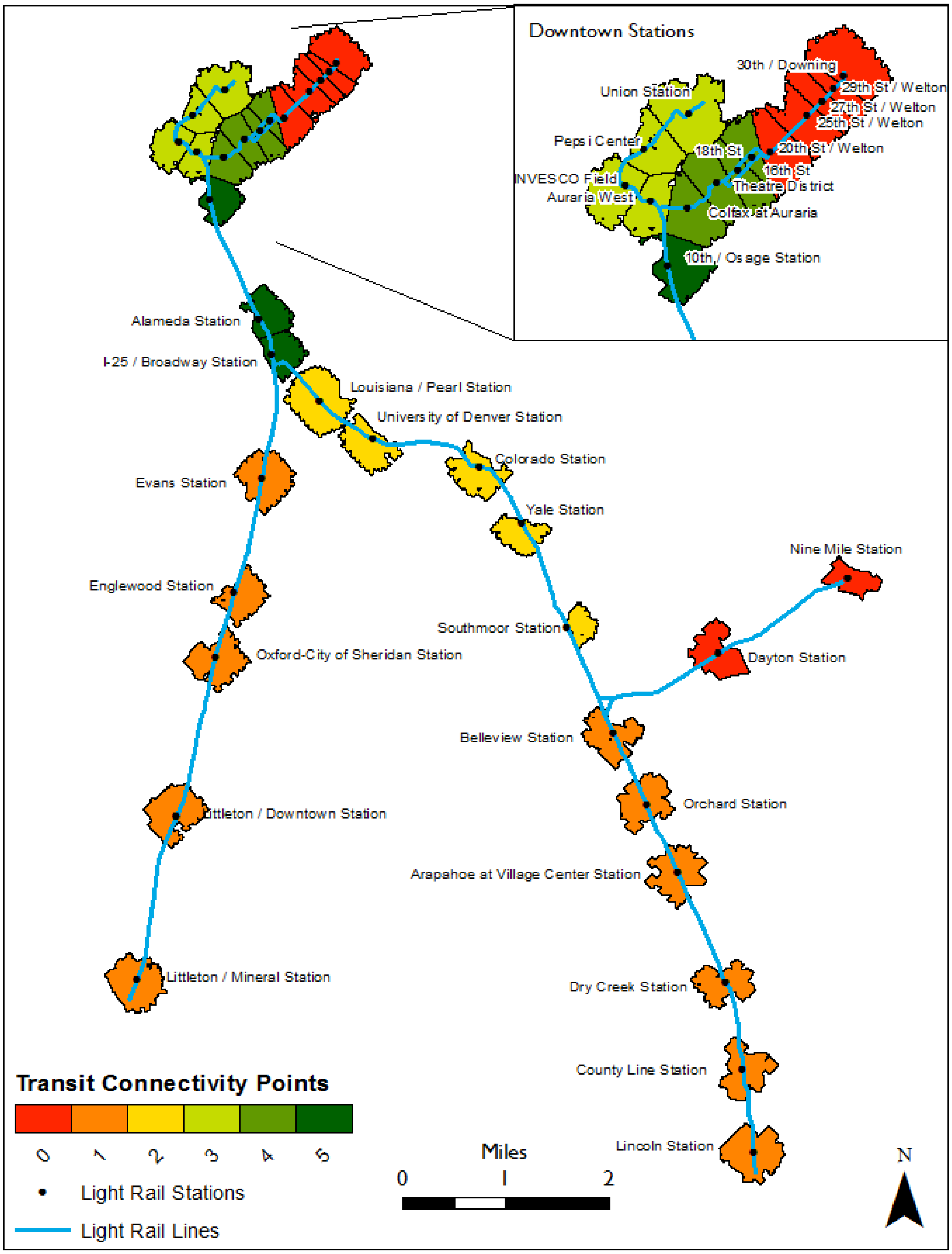


Figure A:3 Average RDI Scoring

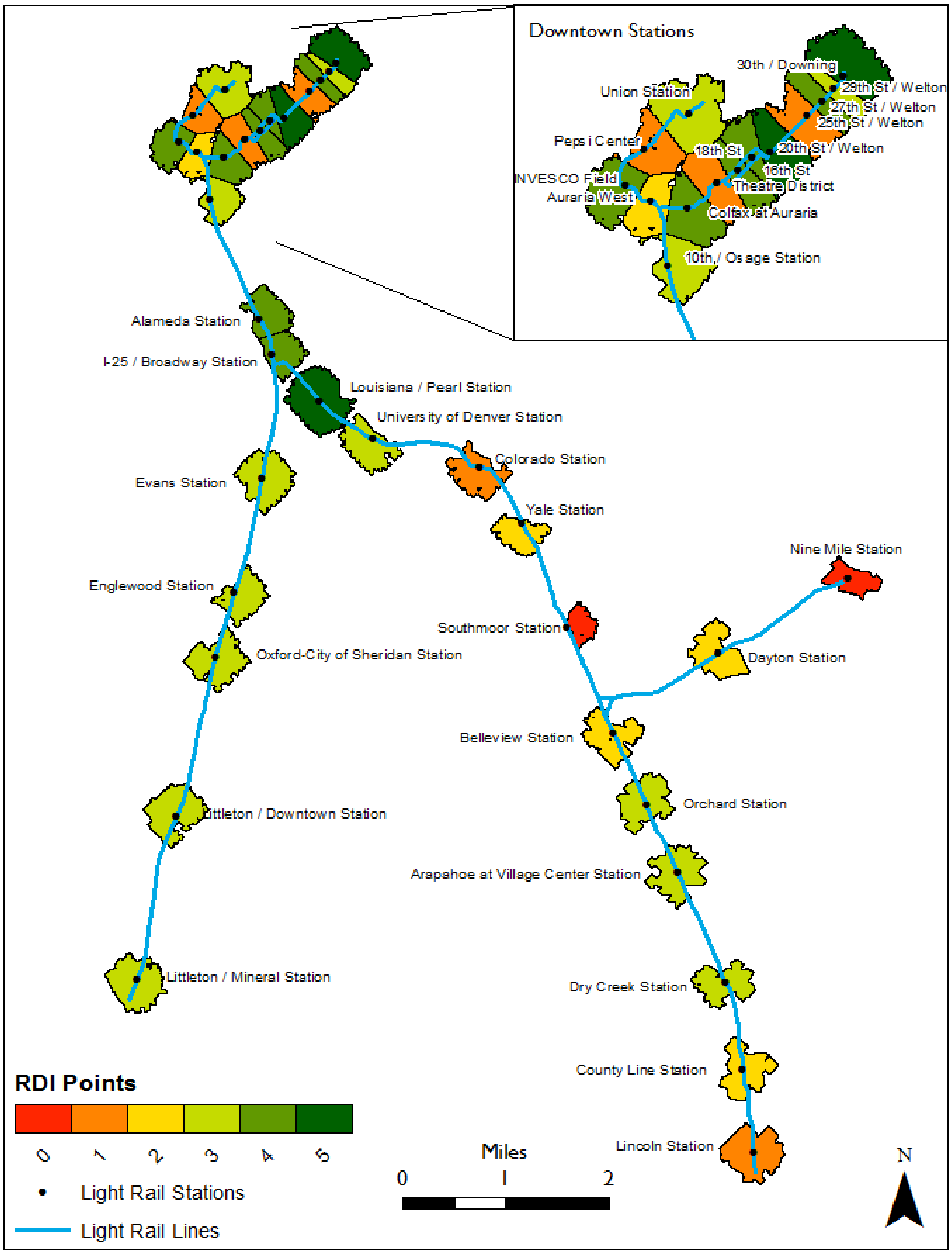


Figure A:4 PC Ratio Scoring

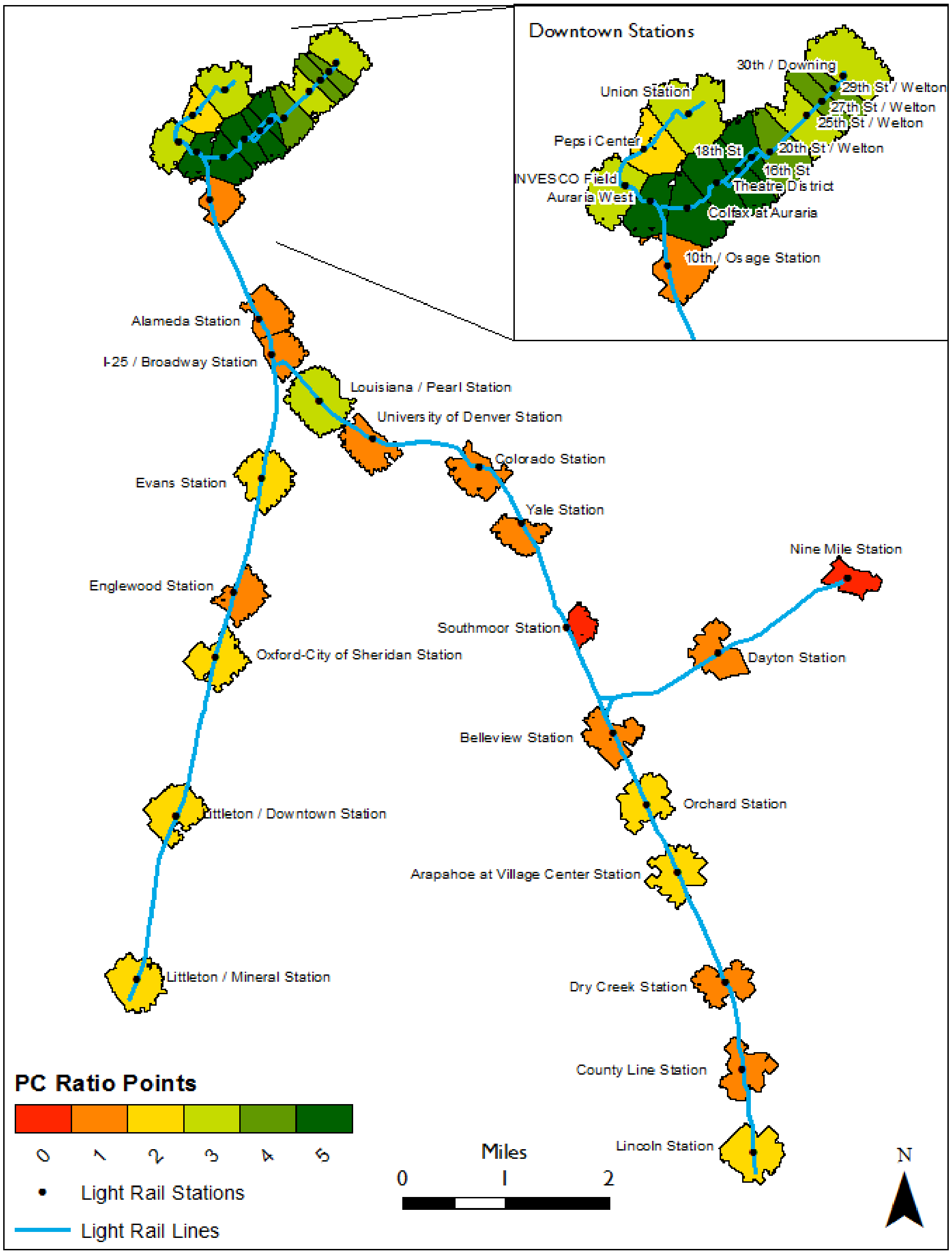


Figure A:5 Retail Density Scoring

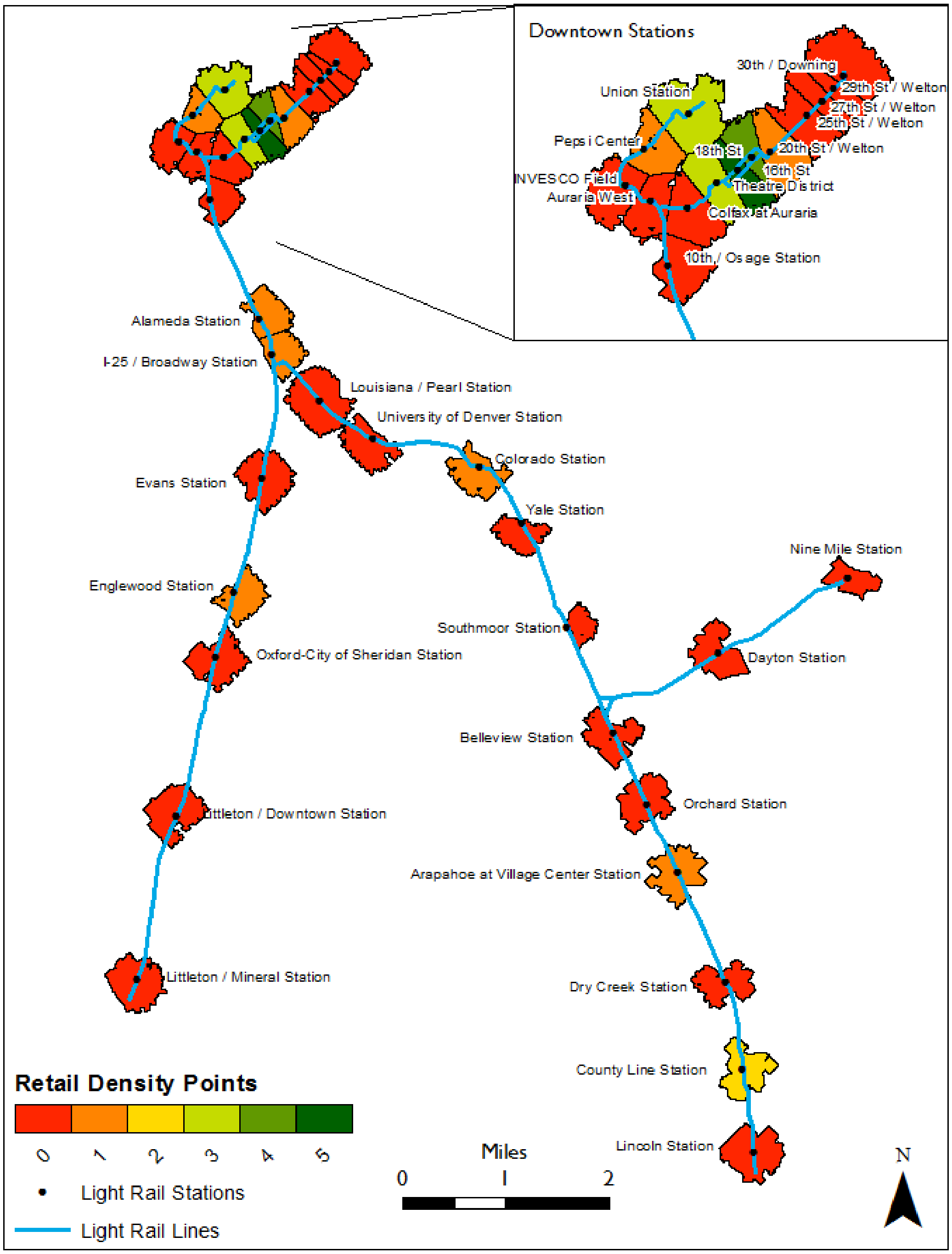


Figure A:6 Employment Density Scoring

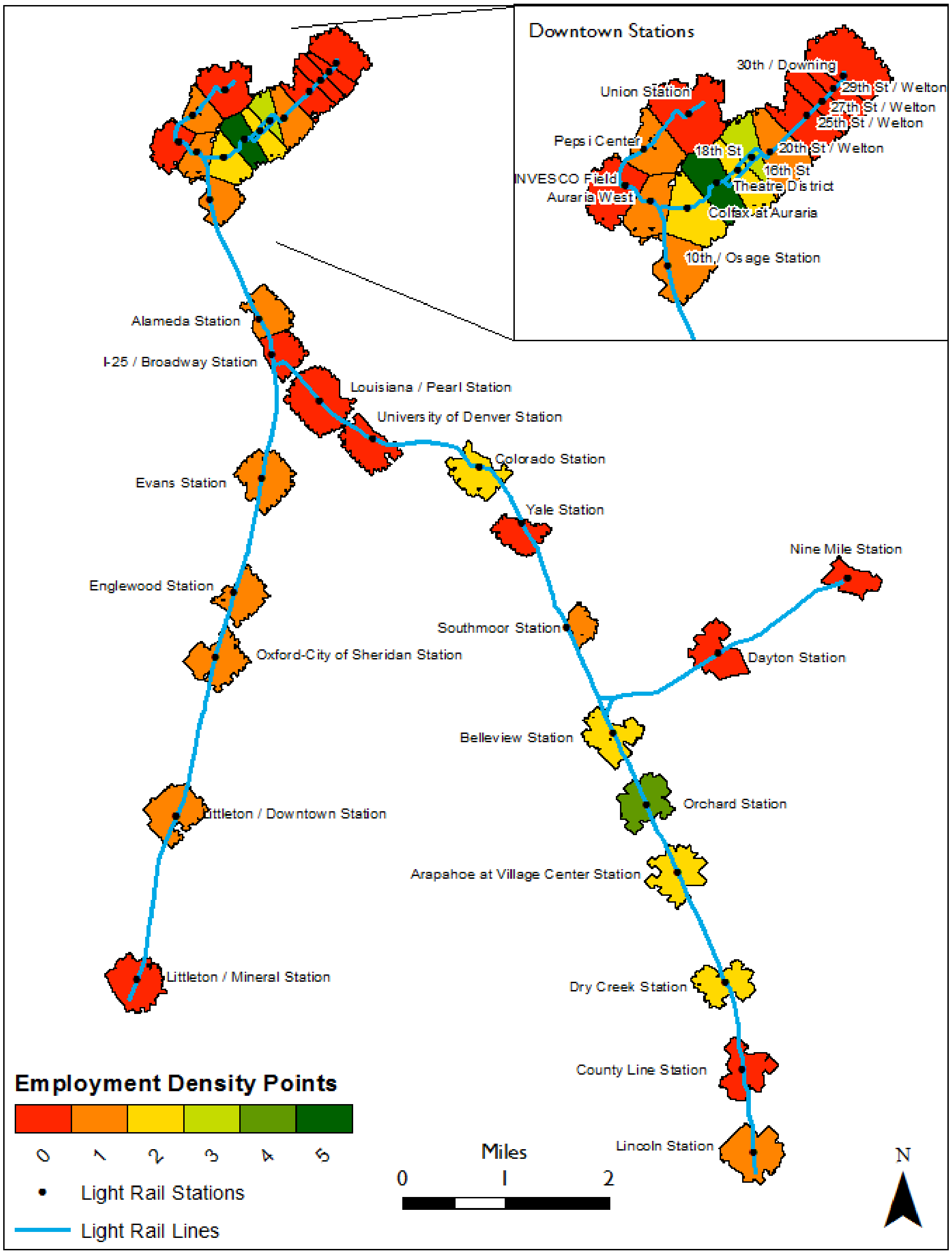


Figure A:7 Population Density Scoring

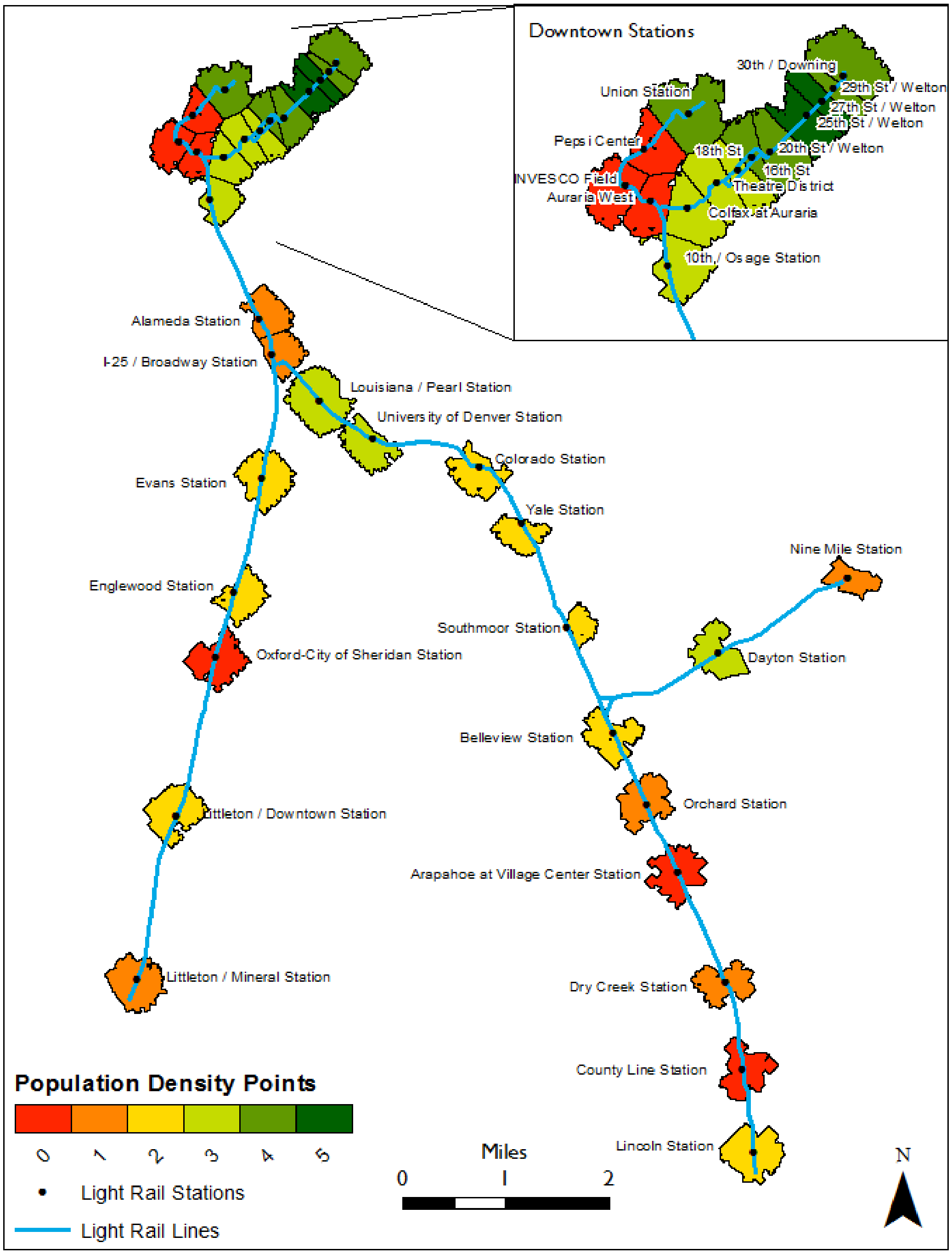


Figure A:8 Walking-Conducive Land Use Scoring

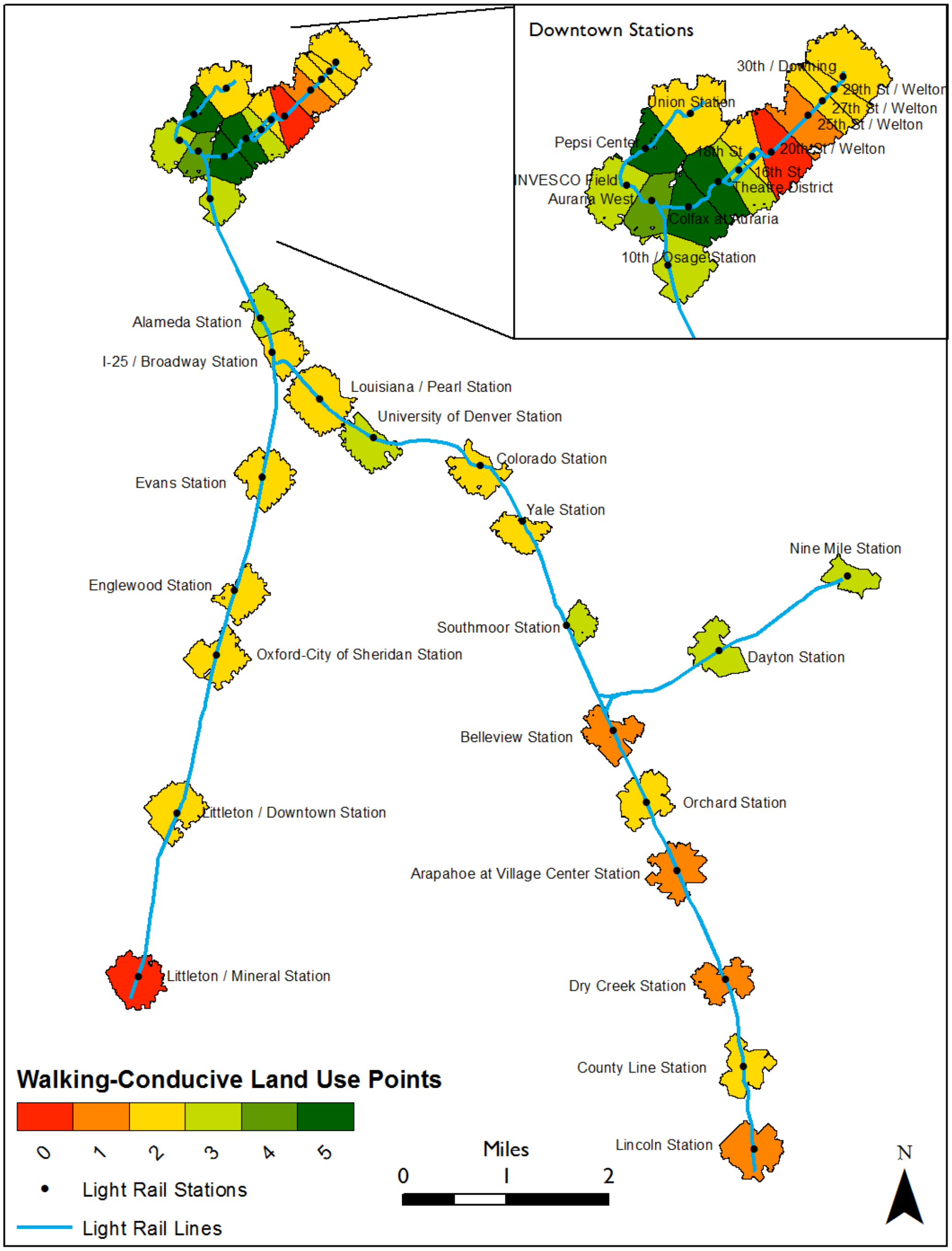
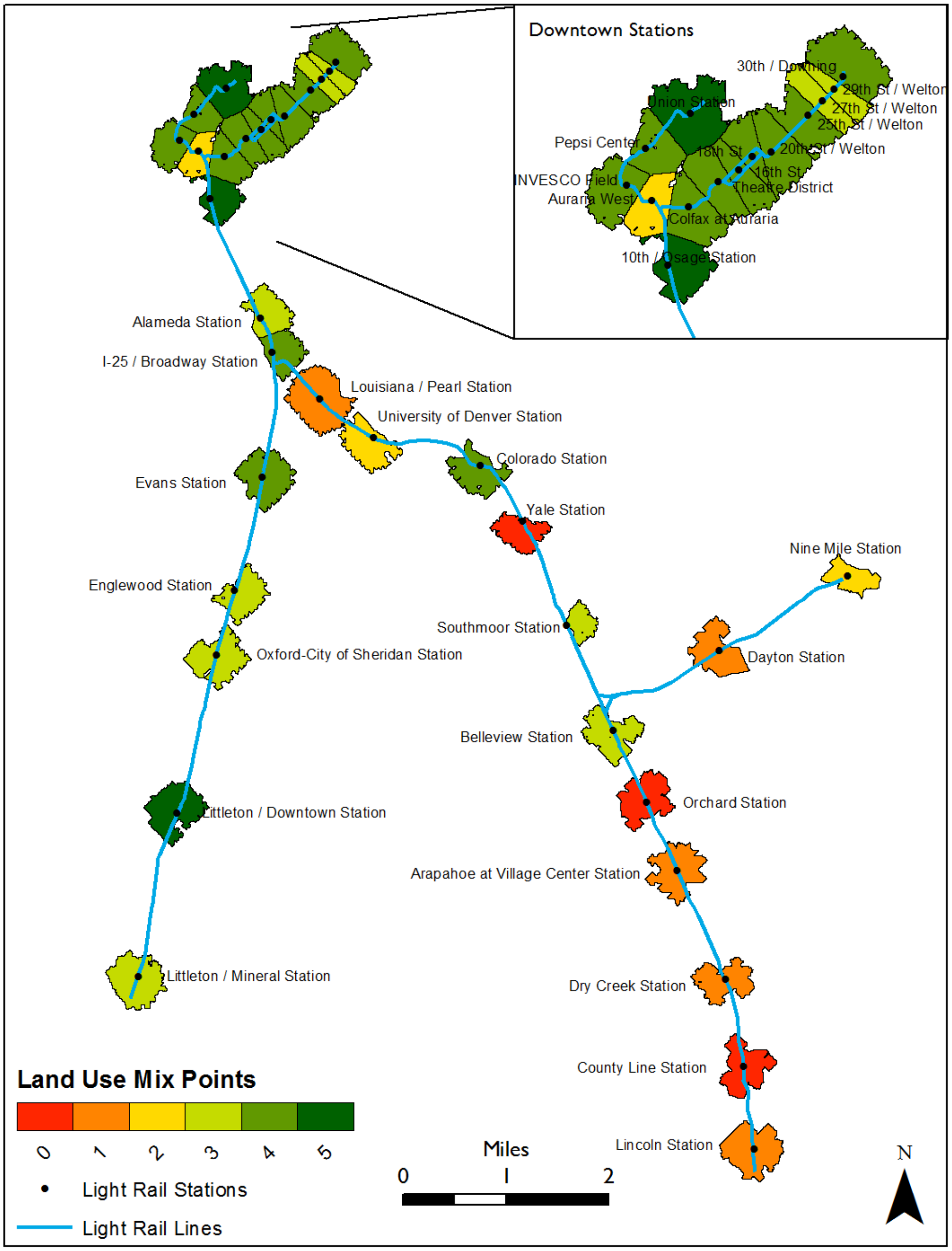


Figure A:9 Land Use Diversity Scoring



APPENDIX B: TABLES NOT INCLUDED IN TEXT

Table B:1 Station Parking and Scoring

STATION NAME	PARKING SPACES	POINTS
10th / Osage Station	0	5
16th St Station	0	5
18th St Station	0	5
20th St / Welton Station	0	5
25th St / Welton Station	0	5
27th St / Welton Station	0	5
29th St / Welton Station	0	5
30th / Downing Station	27	5
Alameda Station	302	4
Arapahoe at Village Center Station	1585	0
Auraria West Campus Station	0	5
Belleview Station	59	5
Colfax at Auraria Station	0	5
Colorado Station	363	4
County Line Station	388	4
Dayton Station	250	4
Dry Creek Station	235	4
Englewood Station	910	2
Evans Station	99	5
I-25 / Broadway Station	1248	1
INVESCO Field at Mile High Station	0	5
Lincoln Station	1734	0
Littleton / Downtown Station	361	4
Littleton / Mineral Station	1227	1
Louisiana / Pearl Station	0	5
Nine Mile Station	1225	1
Orchard Station	48	5
Oxford-City of Sheridan Station	0	5
Pepsi Center / Elitch Gardens Station	0	5
Southmoor Station	788	2
Theatre District / Convention Center	0	5
Union Station	0	5
University of Denver Station	540	3
Yale Station	129	5

Table B:2 Station Transit Connectivity and Scoring

STATION NAME	TRANSIT CONNECTIVITY	POINTS
10th / Osage Station	33	5
16th St Station	29	4
18th St Station	29	4
20th St / Welton Station	16	0
25th St / Welton Station	16	0
27th St / Welton Station	16	0
29th St / Welton Station	16	0
30th / Downing Station	16	0
Alameda Station	33	5
Arapahoe at Village Center Station	21	1
Auraria West Campus Station	24	3
Belleview Station	21	1
Colfax at Auraria Station	29	4
Colorado Station	23	2
County Line Station	21	1
Dayton Station	17	0
Dry Creek Station	21	1
Englewood Station	20	1
Evans Station	20	1
I-25 / Broadway Station	33	5
INVESCO Field at Mile High Station	24	3
Lincoln Station	21	1
Littleton / Downtown Station	20	1
Littleton / Mineral Station	20	1
Louisiana / Pearl Station	23	2
Nine Mile Station	17	0
Orchard Station	21	1
Oxford-City of Sheridan Station	20	1
Pepsi Center / Elitch Gardens Station	24	3
Southmoor Station	23	2
Theatre District / Convention Center	29	4
Union Station	24	3
University of Denver Station	23	2
Yale Station	23	2

Table B:3 Station Average RDI and Scoring

STATION NAME	AVG RDI	POINTS
10th / Osage Station	0.766	3
16th St Station	0.809	4
18th St Station	0.808	4
20th St / Welton Station	0.858	5
25th St / Welton Station	0.634	1
27th St / Welton Station	0.788	4
29th St / Welton Station	0.759	3
30th / Downing Station	0.859	5
Alameda Station	0.810	4
Arapahoe at Village Center Station	0.742	3
Auraria West Campus Station	0.705	2
Belleview Station	0.714	2
Colfax at Auraria Station	0.807	4
Colorado Station	0.599	1
County Line Station	0.697	2
Dayton Station	0.714	2
Dry Creek Station	0.774	3
Englewood Station	0.742	3
Evans Station	0.760	3
I-25 / Broadway Station	0.781	4
INVESCO Field at Mile High Station	0.827	4
Lincoln Station	0.663	1
Littleton / Downtown Station	0.735	3
Littleton / Mineral Station	0.769	3
Louisiana / Pearl Station	0.871	5
Nine Mile Station	0.458	0
Orchard Station	0.752	3
Oxford-City of Sheridan Station	0.777	3
Pepsi Center / Elitch Gardens Station	0.652	1
Southmoor Station	0.498	0
Theatre District / Convention Center	0.635	1
Union Station	0.741	3
University of Denver Station	0.743	3
Yale Station	0.690	2

Table B:4 Pedestrian Catchment Ratios and Scoring

STATION NAME	PC RATIO	POINTS
10th / Osage Station	0.404	1
16th St Station	0.910	5
18th St Station	0.930	5
20th St / Welton Station	0.795	4
25th St / Welton Station	0.632	3
27th St / Welton Station	0.816	4
29th St / Welton Station	0.777	4
30th / Downing Station	0.720	3
Alameda Station	0.465	1
Arapahoe at Village Center Station	0.503	2
Auraria West Campus Station	0.869	5
Belleview Station	0.458	1
Colfax at Auraria Station	0.910	5
Colorado Station	0.431	1
County Line Station	0.450	1
Dayton Station	0.457	1
Dry Creek Station	0.403	1
Englewood Station	0.388	1
Evans Station	0.527	2
I-25 / Broadway Station	0.424	1
INVESCO Field at Mile High Station	0.682	3
Lincoln Station	0.555	2
Littleton / Downtown Station	0.531	2
Littleton / Mineral Station	0.529	2
Louisiana / Pearl Station	0.712	3
Nine Mile Station	0.284	0
Orchard Station	0.476	2
Oxford-City of Sheridan Station	0.511	2
Pepsi Center / Elitch Gardens Station	0.535	2
Southmoor Station	0.196	0
Theatre District / Convention Center	0.906	5
Union Station	0.693	3
University of Denver Station	0.446	1
Yale Station	0.333	1

Table B:5 Station Retail Density and Scoring

STATION NAME	RETAIL DENSITY (SQ MILES)	POINTS
10th / Osage Station	451	0
16th St Station	20,465	5
18th St Station	14,529	4
20th St / Welton Station	1,463	1
25th St / Welton Station	346	0
27th St / Welton Station	396	0
29th St / Welton Station	131	0
30th / Downing Station	340	0
Alameda Station	2,571	1
Arapahoe at Village Center Station	1,911	1
Auraria West Campus Station	295	0
Belleview Station	867	0
Colfax at Auraria Station	918	0
Colorado Station	1,404	1
County Line Station	5,716	2
Dayton Station	982	0
Dry Creek Station	673	0
Englewood Station	2,238	1
Evans Station	370	0
I-25 / Broadway Station	1,887	1
INVESCO Field at Mile High Station	253	0
Lincoln Station	622	0
Littleton / Downtown Station	861	0
Littleton / Mineral Station	465	0
Louisiana / Pearl Station	766	0
Nine Mile Station	108	0
Orchard Station	508	0
Oxford-City of Sheridan Station	157	0
Pepsi Center / Elitch Gardens Station	2,456	1
Southmoor Station	383	0
Theatre District / Convention Center	7,966	3
Union Station	6,966	3
University of Denver Station	353	0
Yale Station	200	0

Table B:6 Station Employment Density and Scoring

STATION NAME	EMP DENSITY (SQ MILES)	POINTS
10th / Osage Station	5,672	1
16th St Station	13,830	2
18th St Station	17,293	3
20th St / Welton Station	5,213	1
25th St / Welton Station	2,316	0
27th St / Welton Station	2,798	0
29th St / Welton Station	2,462	0
30th / Downing Station	1,499	0
Alameda Station	5,476	1
Arapahoe at Village Center Station	9,491	2
Auraria West Campus Station	5,829	1
Belleview Station	13,111	2
Colfax at Auraria Station	12,085	2
Colorado Station	10,293	2
County Line Station	2,375	0
Dayton Station	1,088	0
Dry Creek Station	12,772	2
Englewood Station	7,343	1
Evans Station	4,463	1
I-25 / Broadway Station	3,333	0
INVESCO Field at Mile High Station	3,535	0
Lincoln Station	7,834	1
Littleton / Downtown Station	7,973	1
Littleton / Mineral Station	462	0
Louisiana / Pearl Station	1,875	0
Nine Mile Station	1,714	0
Orchard Station	21,220	4
Oxford-City of Sheridan Station	4,627	1
Pepsi Center / Elitch Gardens Station	7,718	1
Southmoor Station	5,108	1
Theatre District / Convention Center	34,766	5
Union Station	2,905	0
University of Denver Station	808	0
Yale Station	2,941	0

Table B:7 Station Population Density and Scoring

STATION NAME	POP DENSITY (SQ MILES)	POINTS
10th / Osage Station	7,270	3
16th St Station	6,803	3
18th St Station	9,055	4
20th St / Welton Station	10,080	4
25th St / Welton Station	11,317	5
27th St / Welton Station	10,266	5
29th St / Welton Station	9,157	4
30th / Downing Station	9,851	4
Alameda Station	2,685	1
Arapahoe at Village Center Station	1,015	0
Auraria West Campus Station	1,431	0
Belleview Station	3,335	2
Colfax at Auraria Station	7,086	3
Colorado Station	3,616	2
County Line Station	0	0
Dayton Station	5,677	3
Dry Creek Station	1,772	1
Englewood Station	4,203	2
Evans Station	3,422	2
I-25 / Broadway Station	2,985	1
INVESCO Field at Mile High Station	1,265	0
Lincoln Station	3,990	2
Littleton / Downtown Station	3,171	2
Littleton / Mineral Station	2,531	1
Louisiana / Pearl Station	6,142	3
Nine Mile Station	2,131	1
Orchard Station	1,911	1
Oxford-City of Sheridan Station	1,352	0
Pepsi Center / Elitch Gardens Station	209	0
Southmoor Station	4,952	2
Theatre District / Convention Center	7,434	3
Union Station	9,871	4
University of Denver Station	7,226	3
Yale Station	4,521	2

Table B:8 Station Walking-Conducive Land Uses and Scoring

NAME	% Walking Conducive	Points
10th / Osage Station	0.70145	3
16th St	0.71688	3
18th St	0.54996	2
20th St / Welton Station	0.38166	0
25th St / Welton Station	0.50629	1
27th St / Welton Station	0.58388	2
29th St / Welton Station	0.59013	2
30th / Downing Station	0.59197	2
Alameda Station	0.71861	3
Arapahoe at Village Center Station	0.45765	1
Auraria West Campus Station	0.85422	4
Belleview Station	0.47496	1
Colfax at Auraria Station	1.00000	5
Colorado Station	0.58837	2
County Line Station	0.56656	2
Dayton Station	0.68686	3
Dry Creek Station	0.47826	1
Englewood Station	0.58478	2
Evans Station	0.56032	2
I-25 / Broadway Station	0.57764	2
INVESCO Field at Mile High Station	0.68471	3
Lincoln Station	0.52168	1
Littleton / Downtown Station	0.54515	2
Littleton / Mineral Station	0.39226	0
Louisiana / Pearl Station	0.58091	2
Nine Mile Station	0.64909	3
Orchard Station	0.55567	2
Oxford-City of Sheridan Station	0.54572	2
Pepsi Center / Elitch Gardens Station	1.00000	5
Southmoor Station	0.73093	3
Theatre District / Convention Center	1.00000	5
Union Station	0.55976	2
University of Denver Station	0.64107	3
Yale Station	0.62300	2

Table B:9 Station Land Use Diversity and Scoring

STATION NAME	LAND USE DIVERSITY	POINTS
10th / Osage Station	0.90364	5
16th St	0.85439	4
18th St	0.76993	4
20th St / Welton Station	0.87769	4
25th St / Welton Station	0.80966	4
27th St / Welton Station	0.74531	3
29th St / Welton Station	0.72290	3
30th / Downing Station	0.82414	4
Alameda Station	0.68938	3
Arapahoe at Village Center Station	0.50251	1
Auraria West Campus Station	0.59045	2
Belleview Station	0.66059	3
Colfax at Auraria Station	0.82941	4
Colorado Station	0.79701	4
County Line Station	0.34067	0
Dayton Station	0.48640	1
Dry Creek Station	0.47606	1
Englewood Station	0.66655	3
Evans Station	0.83118	4
I-25 / Broadway Station	0.78599	4
INVESCO Field at Mile High Station	0.83042	4
Lincoln Station	0.43479	1
Littleton / Downtown Station	0.96452	5
Littleton / Mineral Station	0.71053	3
Louisiana / Pearl Station	0.41894	1
Nine Mile Station	0.55730	2
Orchard Station	0.27398	0
Oxford-City of Sheridan Station	0.70155	3
Pepsi Center / Elitch Gardens Station	0.86933	4
Southmoor Station	0.73875	3
Theatre District / Convention Center	0.82782	4
Union Station	0.95848	5
University of Denver Station	0.58546	2
Yale Station	0.32967	0

APPENDIX C: PYTHON SCRIPT

```
###### Getting Started
# set up arcpy...
import arcpy
# Set processing extent so its a max of the inputs
# overwrite outputs
arcpy.env.overwriteOutput = 1
# check out spatial analyst extension...
arcpy.CheckOutExtension("spatial")
# set arcpy workspace to your Final Project folder...
arcpy.env.workspace = r"Z:\Denver GIS"
# set arcpy scratch workspace (in the env submodule)
# to your Temp folder. Spatial analyst will output
# files to the scratch workspace...
arcpy.env.scratchWorkspace = r"Z:\Denver GIS\temp"
#____________________________________________________________________________
###### Convert shapefiles to Rasters
# Create variables for the streets shapefile, the output raster and cellsize
inStreets = "Half_Mile_Roads_Ft.shp"
stations = "Stations.shp"
R_streets = "CITY_streets"
cellSize = 50
# Convert shapefile to a raster based on the "FID" field
arcpy.PolylineToRaster_conversion(inStreets, "FID", R_streets, "MAXIMUM_LENGTH" , "", cellSize)
# Set the processing extent = to the R_Streets Raster
```

```
arcpy.env.extent = R_streets

#___________________________________________________________________________

######### Create a Euclidean Distance Allocation for Each Transit Stop

# Create variables for the Maximum Distance and the Source Field for the Allocation Analysis

maxDist = 5000

sourceField = "FID"

# Perform Euclidean Allocation so that each cell gets allocated to its nearest station

Alloc = arcpy.sa.EucAllocation(stations, maxDist, "", cellSize, sourceField)

# Save the Euclidean Allocation Raster to the workspace

Alloc.save("CITY_alloc")


#___________________________________________________________________________

######## Reclassifying the Streets Raster

# get minimum value in the streets raster...

minVal = arcpy.GetRasterProperties_management("CITY_streets", "MINIMUM").getOutput(0)

# get maximum value in the streets raster...

maxVal = arcpy.GetRasterProperties_management("CITY_streets", "MAXIMUM").getOutput(0)

# set up remapTable

remapTable = [[minVal,maxVal,1],["NODATA",0]]

# create remap range object...

remap = arcpy.sa.RemapValue(remapTable)

# Reclassify (Spatial Analyst) Streets using the "Value" field and the remap object...

newRaster = arcpy.sa.Reclassify("CITY_streets", "Value", remap)

# Save the reclassified raster to the workspace

newRaster.save("CITY_sts_g")
```

```
#_______________________________________________________________________________
######## Creating a Streets Cost Raster
# Create a remap table so street cells have a cost of 1 and non street cells have an
# arbitrarily high cost (10000)
remapTable = [[1,1],[0,10000]]
# create remap range object...
remap = arcpy.sa.RemapValue(remapTable)
# Reclassify (Spatial Analyst) CITY_sts_g using the "Value" field and the remap object...
newRaster = arcpy.sa.Reclassify("CITY_sts_g", "Value", remap)
# Save the cost raster to the workspace
newRaster.save("CITY_cost")


#_______________________________________________________________________________
######## Creating a Constant Cost Raster (All cells = 1)
# Create a remap table so all cells will have a value of 1
remapTable = [[1,1],[0,1]]
# create remap range object...
remap = arcpy.sa.RemapValue(remapTable)
# Reclassify (Spatial Analyst) CITY_sts_g using the "Value" field and the remap object...
newRaster = arcpy.sa.Reclassify("CITY_sts_g", "Value", remap)
# Save the cost raster to the workspace
newRaster.save("CITY_flatgrid")


#_______________________________________________________________________________
######## Cost Distance Analysis
# Perform Cost Distance Analysis (Input = Stations, Cost raster = CITY_cost)
```

```
newRaster = arcpy.sa.CostDistance(stations, "CITY_cost", "", "")

# Save the cost distance raster to the workspace

newRaster.save("CITY_dist2")


#______________________________________________________________________________

######## Set Null Values

# Create an expression so that only values with a value of 10000 or less are kept

#(only on network)

expression = "Value > 10000"

# Perform SetNull for CITY_dist2 using the epxression variable

Null = arcpy.sa.SetNull("CITY_dist2", "CITY_dist2", expression)

# Save the Set Null raster to the workspace

Null.save("CITY_dist_nd")


#______________________________________________________________________________

######## Converting to an integer raster

# convert raster into an int raster

Int = arcpy.sa.Int("CITY_dist_nd")

Int.save("CITY_dist_int")


#______________________________________________________________________________

######## Cost Distance Analysis 2

# perform a second cost distance analysis to get the distance to the nearest

# on network cell for all off network cells

Dist2 = arcpy.sa.CostDistance("CITY_dist_int", "CITY_flatgrid", "", "")

# Save the second cost distance raster
```

```
Dist2.save("CITY_2rd_dist")

#______________________________________________________________________________

######## Euclidean Allocation
# Create a Euclidean allocation raster that allocated the nearest on network
# distance to all off network cells
rd = arcpy.sa.EucAllocation ("CITY_dist_int", "", "", 50, "Value", "", "")
# Save the allocated raster to the workspace
rd.save("CITY_rd_dist")

#______________________________________________________________________________

######## Raster Addition
# Add the rd_dist and 2rd_dist rasters to get the total distance from the transit stop
sumRaster = arcpy.sa.Plus ("CITY_rd_dist", "CITY_2rd_dist")
# Save the sum raster to the workspace
sumRaster.save("CITY_sum")

#______________________________________________________________________________

######## Converting to an integer raster
# convert the sum raster to an integer so it can be reclassified
sumInt = arcpy.sa.Int("CITY_sum")
# Save the integer raster to the workspace
sumInt.save("CITY_sum_int")

#______________________________________________________________________________

######## Reclassifying the Final Sum Raster
```

```
# get minimum value in the sum_int raster...

minVal = arcpy.GetRasterProperties_management("CITY_sum_int", "MINIMUM").getOutput(0)

# get maximum value in the sum_int raster...

maxVal = arcpy.GetRasterProperties_management("CITY_sum_int", "MAXIMUM").getOutput(0)

# set up remapTable so that only cells within walking distance are kept ( value < 2640 feet)

remapTable = [[minVal,2640,1],[2641,maxVal,"NODATA"]]

# create remap range object...

remap = arcpy.sa.RemapValue(remapTable)

# Reclassify (Spatial Analyst) CITY_sum_int using the "Value" field and the remap object...

newRaster = arcpy.sa.Reclassify("CITY_sum_int", "Value", remap)

# Save the new raster to the workspace

newRaster.save("CITY_mask")


#___________________________________________________________________________

######## Raster Multiplication (Creating Mutually Exclusive Service-areas)

# Multiply this value by a Euclidean Distnace Allocation for each transit stop

timesRaster2 = arcpy.sa.Times("CITY_alloc", "CITY_mask")

# Save the mutual exclusive service-area raster

timesRaster2.save("CITY_final")


#___________________________________________________________________________

######## Converting Raster to Polygon

# Set up a variable for the output service-area feature class.

outPolygons = "Service_Areas.shp"

# Covert the raster service-areas back to polygons
```

```
arcpy.RasterToPolygon_conversion("CITY_final", outPolygons, "NO_SIMPLIFY", "Value")


##________________________________________________________________________________

###### Clip Households to Station Buffers

# Set up a variable for the input Address feature class

inputHH = "Station_Parcel_Points.shp"

# Perform clip analysis so only address points within the service-area are kept

arcpy.Clip_analysis(inputHH, "StationBuffer.shp", "HHpnts.shp")

# convert points to raster using the FID field

arcpy.PointToRaster_conversion("HHpnts.shp", "FID", "Households", "MAXIMUM" , "", cellSize)


##________________________________________________________________________________

######## Reclassify the raster so that household cells are 1 and non household cells are 0

# get minimum value in the Household raster...

minVal = arcpy.GetRasterProperties_management("Households", "MINIMUM").getOutput(0)

# get maximum value in the Household raster...

maxVal = arcpy.GetRasterProperties_management("Households", "MAXIMUM").getOutput(0)

# set up remapTable

remapTable = [[minVal,maxVal,1],["NODATA",0]]

# create remap range object...

remap = arcpy.sa.RemapValue(remapTable)

# Reclassify (Spatial Analyst) Households using the "Value" field and the remap object...

RCRaster = arcpy.sa.Reclassify("Households", "Value", remap)

# Save the reclassified raster to the workspace

RCRaster.save("Household_RC")
```

```
##________________________________________________________________________________
####### Raster Math to get the Euclidean Distance and Network Distance for all Households
# Multiply the HH_RC and sum network distance rasters together
timesRaster = arcpy.sa.Times ("Household_RC", "CITY_sum_int")
# Save the new raster to the workspace
timesRaster.save("Household_ND")
# Create a Euclidean Distance Raster to get the 'as the crow flies'
CFD_Raster = arcpy.sa.CostDistance(stations, "CITY_flatgrid", "", "")
# Save the Euclidean Distance Raster to the workspace
CFD_Raster.save("CF_dist")
# Multiply the HH_RC and the Euclidean distance rasters together
timesRaster2 = arcpy.sa.Times("Household_RC", "CF_dist")
# Save the new raster to the workspace
timesRaster2.save("Household_CFD")

##________________________________________________________________________________
####### Set null values so that values that are = 0 become "NoData"
# Create a variable for the SQL expression
expression = "Value = 0"
# Perform SetNull for the Household ND Raster
Null = arcpy.sa.SetNull("Household_ND", "Household_ND", expression)
# Save the Set Null Raster
Null.save("HH_ND_RC")
# Perform SetNull for the Household CFD Raster
Null = arcpy.sa.SetNull("Household_CFD", "Household_CFD", expression)
```

```
# Save the Set Null Raster

Null.save("HH_CFD_RC")


##________________________________________________________________________________

######## Calculate the Route Directness Index for Each Household

# Divide the two Crow Flies Distance Raster by the Network Distance Raster

DivRaster = arcpy.sa.Divide("HH_CFD_RC", "HH_ND_RC")

# Save the new raster to the workspace

DivRaster.save("RDI_Raster")


##________________________________________________________________________________

########## Convert the rater back to a point file

# Convert Raster Back to Point Data (Attribute "GRID_CODE" is the RDI value)

arcpy.RasterToPoint_conversion("RDI_Raster", "RDI_Points", "VALUE")
```