QUANTIFYING TRANSIT-ORIENTED DEVELOPMENT'S POTENTIAL CONTRIBUTION TO FEDERAL POLICY OBJECTIVES ON TRANSPORTATION-HOUSING-ENERGY INTERACTIONS

Final Report

CTLS 10-01

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16. Abstract

This project involved a comprehensive and compact study of the built environment in light rail transit station areas in Denver, Colorado and travel behaviors in both TOD- and non-TOD areas in the region. Graduate students from the University of Connecticut and University Colorado Denver participated in a workshop in Denver in Spring 2011 to collaborate on designing questions for two comprehensive travel surveys and subsequently carry out an intensive field campaign to collect data. The principal objectives were to provide insight into how different types of TOD affect travel behavior patterns—specifically reductions in vehicle miles travelled—and to understand what prevents people from living in TOD areas. The latter information was intended to help assess the potential for region-wide reductions in VMT. An additional objective was to provide University of Connecticut students with experience of carrying out collaborative, integrative, and interdisciplinary research with students from a National Science Foundation (NSF) Integrative Graduate Education, Research and Training (IGERT) Program. The intention was to help to build a community of emerging scholars equipped to engage in trans-disciplinary work on policy-relevant issues, and help to better position faculty at the University of Connecticut to advance ongoing initiatives to establish an IGERT in Sustainable Urbanism.

The main findings of the research are that although the LRT system in Denver, Colorado, may have met its goals with respect to congestion relief and ridership, the fact that the system has been located in existing travel corridors housing freeways and heavy freight trains limits the extent to which the system can become integrated into the fabric of the built environment. A thorough and systematic index of pedestrian level-of-service shows a tremendous variation in the pedestrian accessibility of stations across the system. In addition, stations that have park-and-ride lots show similar levels of vehicle ownership and VMT to other locations across the metropolitan area that are nowhere near LRT systems. Only those stations defined as walk-and-ride locations (i.e. those without park-and-ride lots) register lower car ownership and lower levels of VMT.

The results of the research are in the process of being disseminated to academics, practitioners, and policymakers interested in the interactions between transportation, housing, and energy demand. To date, the research has resulted in one MA Thesis completed in May 2011, one MS Thesis due to be completed at the end of August 2013, one presentation at the Transportation Research Board January 2013 annual meeting, one presentation at the Annual Association of American Geographers' annual meeting in New York in March 2012, one paper in the Transportation Research Record, and one presentation at the Association of Collegiate Schools of Planning.

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EXCUTIVE SUMMARY

The LRT system in Denver, Colorado, connects the downtown with neighborhoods to the North, but primarily stretches southwards, travelling in existing transportation corridors carrying freeways and a heavy rail system. Outside of the downtown areas, the siting of the LRT system alongside the rigid infrastructure that comprises the heavy rail system and the freeway systems severely inhibits pedestrian accessibility to the transit system. To help further understand how the level of accessibility varies across the system, a systematic pedestrian level-of-service index for each station within the system was created that takes into account the formal, as well as informal street networks. This inaccessibility is highly likely to limit the potential that this system may have to generate development near station located that is fully integrated with the LRT system.

Primary data collected by surveying households across the metropolitan area revealed very little difference between car ownership rates and weekly VMT of survey respondents living within ½-mile of an LRT station and elsewhere in the metropolitan area. Differentiating between those station areas that were Park-and-Ride (that is, had a park-and-ride lot) versus Walk-and-Ride showed a more nuanced picture. Residents who live in Walk-and-Ride stations do have have lower VMT than those who live in Park-and-Ride station areas and those who do not live near an LRT station. This reinforces the fact that development needs to be more fully integrated with the LRT system in order to achieve some intended goals such as less dependence on automobiles.

Taken as a whole, the study suggests that while Denver may have achieved its goals with respect to ridership, locating the system within a heavy rail corridor and freeway corridor provides limited opportunities for more integration between the system and the built environment over the longer term. Building a system with the goal of congestion relief and placing an emphasis on creating transit points where drivers can switch to LRT may limit the extent to which that system is able to generate Transit-Oriented Development in the long-term, and reduce the potential that LRT has to reduce VMT and thereby GHG emissions.

1.0 INTRODUCTION

1.1 BACKGROUND

The principal objective of this project was to design and implement a compact yet comprehensive study that provides insights into the various impacts of different types of transit-oriented developments (TOD). The framework and results of this project are being used to produce a suite of research papers, most of which are still in progress. The original intention was that the project could help to inform a more comprehensive grant proposal to the National Science Foundation (joint review by Geography & Spatial Sciences and Engineering). We envisaged that the integrative and interdisciplinary approach and engagement with UC Denver IGERT teams would also help to advance ongoing efforts to secure a University of Connecticut IGERT in Sustainable Urbanism. The approach was guided by the premise that creating resilient places requires an understanding of two main areas. The first, sometimes termed "contextsensitive design", is an understanding that the policies designed to address these problems need to be place-specific.

The second is that academic research regarding integrated land use and transportation planning/engineering needs to extend into the policy realm. This entails not only recognizing that transportation projects have economic, environmental and social impacts, but also understanding that adopting policies entails making trade-offs between these effects. This guiding philosophy of considering transportation as an integral part of the urban fabric is echoed in the recent collaboration between federal agencies overseeing policies relating to housing, transportation, and energy.

The recent "sustainability turn" in U.S. federal policy underscores the critical societal relevance and timeliness of our research theme. The NSF IGERT program is a limited submission program, which means that each institution is limited to a certain number of proposals per round of awards. To date, our proposal has not been selected to advance by our institution. However, the University of Connecticut was invited by the University of Denver to take part in a Consortium on the topic of Livable Communities, and a grant proposal was submitted in March 2013.

1.2 PROBLEM STATEMENT AND RESEARCH QUESTIONS

The research focused on what integrated land use/transportation planning and transportation engineering strategies can be implemented in the U.S. – especially in built environments that have emerged during the automobile era – to reduce structural dependence on automobiles. Our project was organized around two interrelated questions: (1) How do various types of TOD affect vehicle miles travelled for those living within TOD communities? And (2) Why do people live in locations without access to transit? This unique approach weaved together and created synergies between three strands of literature on transportation and the built environment that have evolved separately.

1.3 BRIEF LITERATURE REVIEW

1.3.1 TOD Typologies

Discussion about TODs has recently taken a more spatial turn in that academics and practitioners have acknowledged that not all station areas will fulfill the same function within a transit system (Atkinson-Palombo and Kuby, 2010). Calthorpe (1993) identified neighborhood TODs that are primarily residential and urban TODs that emphasize job-generating uses. Dittmar & Poticha (2004) refined this distinction by offering a typology of TODs that included urban downtown, urban neighborhood, suburban town center, suburban neighborhood, neighborhood transit zone, and commuter town. More recently, the Federal Transit Administration sponsored a similar report that defined eight different station types including urban center, suburban center, transit town center, urban neighborhood, transit neighborhood, special use/employment district, and mixed-used corridor (Reconnecting America and the Center for Transit-Oriented Development 2008). Their criteria for distinguishing TODs included transit frequency, density, land use mix, the number of jobs in the district, floor-area ratio (FAR), and parking configurations. This relatively new debate has not yet extended to understanding variation in the impacts of these

1.3.2 Impacts of TOD

Proponents of transit and TODs assert that these public policies have societal benefits including reduced transportation costs and the ability to reduce traffic congestion and air pollution by encouraging people to reduce their VMT. Other potential benefits can include increasing transportation options that help facilitate increased resiliency to rising gas prices or emergency situations. The results of this study will provide quantitative data about travel behavior from a relatively new transit system in an automobile-oriented metropolitan environment.

This evidence of changes in travel behavior and VMT will add to the debate about the impact that TODs—with the right set of complementary features—can have on an urban environment. Being able to quantify changes in VMT and associated greenhouse gases and vehicle emissions will be of interest to established transportation planning modelers, the growing numbers of researchers involved in establishing better sustainable transportation indicators (see Zheng et al., 2011 and the extensive references therein), as well as scientists and policy-makers interested in the debates concerning air quality and global climate change. Some literature does exist on the relationship between the travel benefits of individual TODs, but because the data focus on Washington, D.C., Portland, OR, and in California locations, concerns exist about the transferability of these data (Evans and Pratt 2007). The main point is that there are presently, no widely accepted methods for evaluating the effectiveness and broader impacts of TODs exist, let alone understanding that these would differ across TOD types (Dittmar and Ohland, 2004). Joining the research about TOD typologies with the research on TOD impacts in an effort to investigate how different types of TOD affect travel behavior will generate synergies that have not yet been explored.

1.3.3 Self-selectors

Much of the research to date has focused on in-movers, or people who self select to live in TODs. Other work has been done to address people who live in suburban environments (Levine and Frank, 2007). A very small amount of work has been done on under-optimization of locational preferences with respect to transit. Gathering information about people who do not live in TODs will shed light on specifically why they do not live there and what priorities that they have in terms of residential location decision-making that override their ability to live in a TOD. This will help provide the information necessary to determine what attributes should be considered when building future TODs with respect to the anticipated travel outcomes. This research is also innovative in that it also addressed directly why people choose NOT to live in TODs.

1.4 STUDY AREA

Our choice of a study area – Denver, Colorado – is an integral part of the research project. Denver represents an evolving light rail transit (LRT) system first established in October 1994. The initial 5.3 mile long Central Corridor was built without new taxes or any federal money (TREX 2006). The region currently has five light rail lines on over 25 miles of track, 125 light rail vehicles, and over 200,000 riders per day. Currently, there are over thirty TOD stations – with plans underway for forty more TOD stations.

As of 2000, driving mode share decreased to 87.1% from 87.5% in 1990. While this reduction in driving may not seem particularly significant, out of the top fifty large metropolitan statistical areas in the U.S., only ten others experienced any driving reduction whatsoever and only four other found a greater reduction in driving (Portland, OR, Seattle, WA, West Palm Beach, FL, and Las Vegas, NV) (FHWA 2000). Denver experienced a 31% growth in workers over this time with much of that increased growth being accommodated by the improving transit system. In fact, Denver is one of the few major cities in the U.S. to show an increase in transit mode share between 1990 and 2000. We therefore envisaged that this Denver case study would provide rich data that will inform the debate about the feasibility of introducing TODs into other automobile-dominant metropolitan landscapes and how various groups of people respond to these policy decisions and the built environment TOD attributes.

1.5 DATA AND METHODS

1.5.1 Data

Secondary data sources included the US Census, the Colorado Department of Transportation, the City of Denver, the Denver Regional Council of Governments (DRCOG), and the Regional Transportation District (RTD). This data incorporated transit system information, land use information, zoning information, socioeconomic data, journey-to-work data, and street network characteristics including the three fundamental measures of a street network: network density, connectivity, and patterns. Street level data will be collected for the half-mile area surrounding each stop including: total number of lanes, shoulder width, raised median width, on-street parking, curbs, curb-to-curb distance, traffic calming measures, painted median width, bike lanes and sidewalks. These data were geo-coded in a GIS database to facilitate a more comprehensive spatial analysis where specific factors are associated with travel outcomes, and also used to provide workshop participants with the information necessary to develop and implement an effective survey.

1.5.2 Creation of TOD Typology for Denver

One of the first goals of this project was to correlate specific built environment and urban design factors as well geographic variables and transit characteristics with the related transportation behaviors building upon the work done by Atkinson-Palombo and Kuby (2010). This research will therefore be able to provide other automobile-oriented cities and regions with a better idea of what factors help, what factors hinder, and what factors do not correlate with changes in transportation behaviors. This will be a marked improvement over the generalities surrounding the conventional TOD typology research strands as well as the more detailed literature based on Washington, D.C., Portland, OR, or California cities.

Built environment factors that have been shown to influence mode choice and travel behavior include street network characteristics such as street connectivity, street network density, street patterns, and street design features (Marshall and Garrick, 2010) as well as parking supply and parking management strategies. However, the fact remains that many of these factors have not been extensively studied – or studied in concert – at TODs. One study by Cervero and Gorham (1995) that did begin to specifically address street network measures with respect to transit found that denser and more connected transit-oriented street networks had much lower driving mode shares than what they considered to be more automobile-oriented neighborhoods. While their study compared transit-oriented and auto-oriented suburban neighborhoods, our study will weigh various transit-oriented neighborhoods against one another. By taking into account the built environment – in terms of factors such as street network measures, street characteristics, parking, zoning, land use, and the relationship to the city center and the region – we will determine what factors are enhancing and what factors are impeding travel behaviors and the overall effectiveness of TOD stations. This component of the research is close to being finalized by graduate student, Eric Dorsey, as part of his MS Thesis in Civil & Environmental Engineering (See Appendix A).

1.5.3 Workshop

The co-PI of this project, a recent graduate of the University of Connecticut, is now a faculty member in the Civil Engineering Department at the University of Colorado Denver (UCD). Thus, the research team held a workshop during UConn’s Spring break in 2011 that was attended by both PIs and students from both the University of Connecticut and the IGERT Sustainable Urban Infrastructure group at UCD (IGERT is the principal interdisciplinary training program funded by the National Science Foundation). During this intensive session, students gained hands-on experience of the collaborative research process. Specific areas of focus included translating broad intellectual research questions into operationalizable research questions; spatial sampling methods; and conducting boundary research with partner organizations. Before the workshop took place, students from UCD and UConn met for a full day of riding on the Light Rail system to get oriented to the study area.

Students who participated in the workshop to craft the questions also worked with faculty to conduct in-person surveys at the Denver LRT stations, tie these survey results to the theoretically-driven research questions, and collaborate on research papers. Graduate students are also using the data collected during the field campaign for their theses and/or dissertations. One student, Patrick Gallagher, based his MA Thesis on this work (see Appendix B). He also presented part of that work at the Annual Association of American Geographers (AAG) Conference in New York City in March 2012, at the Transportation Research Board's Annual Conference in Washington D.C. in January 2013, and had a paper based upon his work published in the Transportation Research Record (see Appendix C).

Figure 1.1: Graduate students at the Littleton-Mineral Transit Station, Denver, Colorado

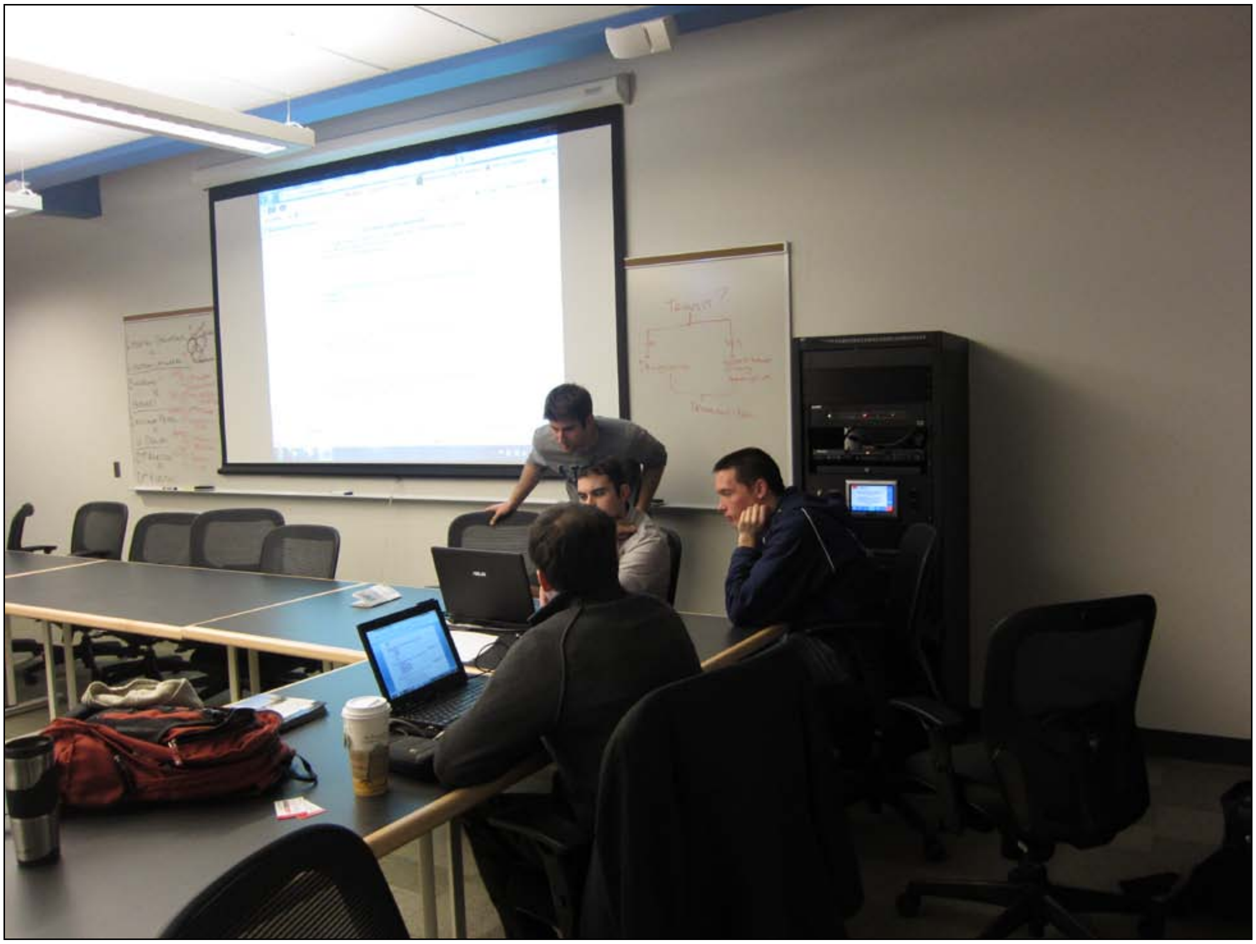


Figure 1.2: Graduate Students at Workshop in Denver, Colorado

1.5.4 Surveys

Two separate surveys were conducted to generate a better understanding of the degree to which TODs can succeed at a broader scale. The project will initially conduct an exploratory assessment of the extent to which people alter their travel patterns when moving into a TOD with a revealed preference survey. This study will also address the extent to which there is an unsatisfied demand for TODs with the region. This stated preference survey was intended to bolster the assessment of the extent to which people alter their travel patterns when moving into a TOD by revealing the unsatisfied demand for TODs and what motivations factor into 9 residential choices – such as perceived school quality – with respect to neighborhood preference. Determining the degree to which neighborhood preference corresponds with the built environment and tying these sets of surveys together with the built environment investigation would provide a much clearer picture of the potential for TODs to impact regional travel patterns and GHG emissions.

Figure 1.3: Graduate Student undertaking door-to-door research during the Denver Field Campaign

Figure 1.4: Example of postcards that were left if residents were not home during door-to-door campaign

1.5.5 Teaching Element

The PI and the co-PI taught a special seminar on TOD in both UConn and UCDenver so that students could enroll in a course on this topic and obtain funding to conduct hands-on research during the Spring 2011 semester and in Summer 2011.

1.6 ANTICIPATED RESULTS

1.6.1 Typologies and VMT Reduction

Although it is difficult to predict specifically what types of TOD would emerge ahead of time, one compelling and critically important finding that we expectd to get is that TODs that have mixed use developments and that have built environments that are more walkable will have the highest VMT reductions. In contrast, station areas that focused more on feeding passengers onto the LRT system, and therefore geared more towards increasing ridership of the system, would facilitate regional reductions in VMT.

1.6.2 Non-TOD Residents

We expected to find a strong unmet demand for transit for non-TOD residents who under optimize their locational preferences for transit because of competing priorities for locational attributes, such as quality of school districts.

2.0 FIELD OBSERVATIONS

2.1 LIGHT RAIL TRANSIT

The field trip provided a great deal of information about the LRT system, much of which would not have been evident from secondary data. First is that the system had few riders and that the Downtown was not very vibrant (although the orientation was conducted on a Sunday).

Figure 2.5: Deserted station platform, Sunday, March 6th 2011

Second, the fact that the right-of-way for the LRT system was located in the same channel as a heavy rail system in some places, and in others, main freeways, meant that the LRT system was somewhat cut off from the surrounding urban fabric.

Figure 2.6: LRT alignment next to a heavy rail track.

Third, while the downtown area had walkways and some pedestrian-friendly areas (such as the Sixteenth Street Mall), the built environment beyond that was more oriented towards the automobile, with few sidewalks, broad streets, and few pedestrian crossing areas.

Figure 2.7: Lack of pedestrian walkways near station areas, Denver, Colorado

Figure 2.8: Automobile-oriented built environment

2.2 GENERAL BUILT ENVIRONMENT

A fourth observation was that there was a high degree of variation in the built environment along the alignment. A number of new apartment buildings appeared to have been constructed near some of the transit stops, but in other places (notably the Louisiana-Pearl neighborhood), the stop was close to a tightly-gridded well-established neighborhood that contained a mix of uses such as housing, restaurants, local businesses, and schools. In other locations, there was evidence of “leapfrog development” (where development takes place beyond the urban fringe).

Figure 2.9: LRT vehicle advertising an apartment complex, Penterra Plaza, near the LRT station.

Figure 2.10: Moderate income apartment housing near Lincoln Station, Denver, Colorado

Figure 2.11: Apartment homes showing the LRT system as a marketing feature

Figure 2.12: Louisiana-Pearl Neighborhood with tightly-gridded street network and a mix of land uses

Figure 2.13: Evidence of “leapfrog” development with apartment homes constructed beyond the urban fringe in a difficult to access location.

2.3 PROVISION OF PARKING

It was also evident from the field observations that the entire metropolitan area had a considerable amount of space devoted to parking. Many of the LRT stations had parking lots associated with them. While this aspect of the system would have been apparent from official data, what was less obvious was the fact that in some cases (especially where stations were near shopping malls) there was abundant parking that may have been available to commuters above and beyond the official numbers associated with park-and-ride lots.

Figure 2.14: Example of concrete multi-storey parking lots near LRT station, Denver, Colorado


Figure 2.15: Parking, even in Denver's downtown, is cheap and abundant.


Figure 2.16: The built environment adjacent to the LRT stations consists of big-box retail land uses located in a sea of parking.

Figure 2.17: The existing built environment adjacent to the LRT stations is primarily automobile-oriented.

3.0 SURVEYS

3.1 INTERCEPT SURVEY

We were unable to obtain permission from the authorities in Denver to approach riders on LRT property (i.e. the train or the platform). We therefore conducted an intercept survey whereby we approached commuters once they had left the train platform, and handed them a postcard with details about our survey, including a URL to an online version that they could take if they had time.

3.2 LONG FORM OF SURVEY

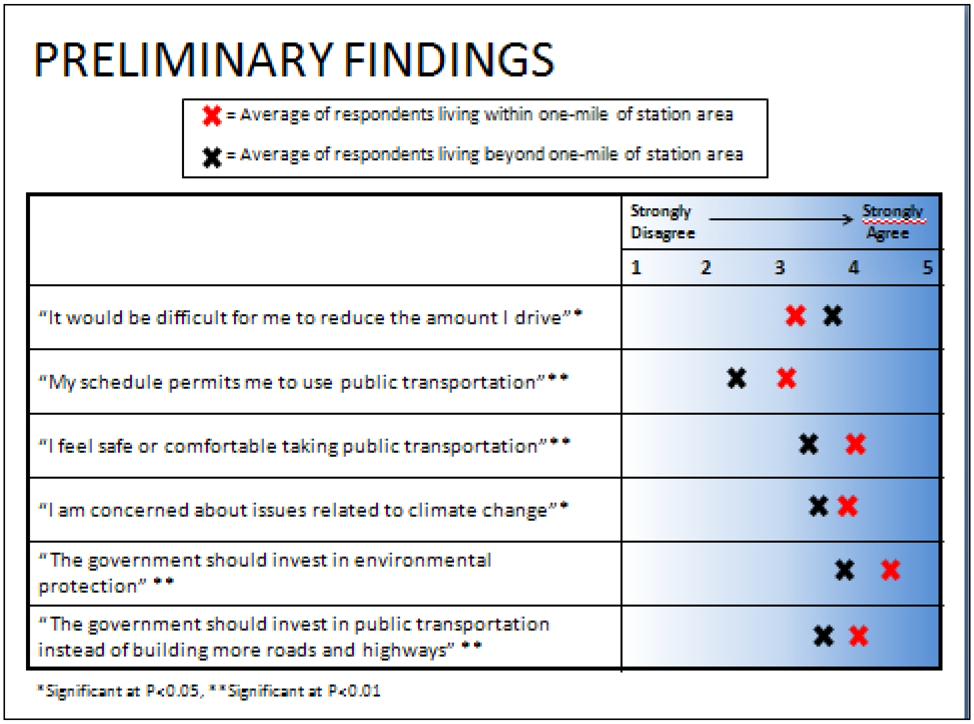
Three approaches were used to gain information for the long form of the survey. First, graduate students went door-to-door in the neighborhoods near the LRT system. If people were not home, copies of a postcard were left at their door that gave them information about the survey and the link to a website so that they could take the survey electronically. Second, the electronic version of the survey was sent out to various electronic mailing lists and posted on Facebook pages of potentially interested parties; e.g. Friends of Transit, Denver. Third, we mailed out 1,000 randomly-sampled households in two counties that contain 34 out of 36 of the stations. We oversampled households within select station areas (for a total of 500), and sent a further 500 surveys to households within selected station areas. We received a total of 256 responses (a 14% response rate).

4.0 PRELIMINARY ANALYSIS OF SURVEY DATA

4.1 FINDINGS

Images showing the preliminary findings of the survey data analysis are depicted below.

4.1.1 General Attitudes, Car Ownership, LRT Usage, and VMT



PRELIMINARY FINDINGS

✖ = Average of respondents living within one-mile of station area

✖ = Average of respondents living beyond one-mile of station area

"It would be difficult for me to reduce the amount I drive"*

"My schedule permits me to use public transportation"**

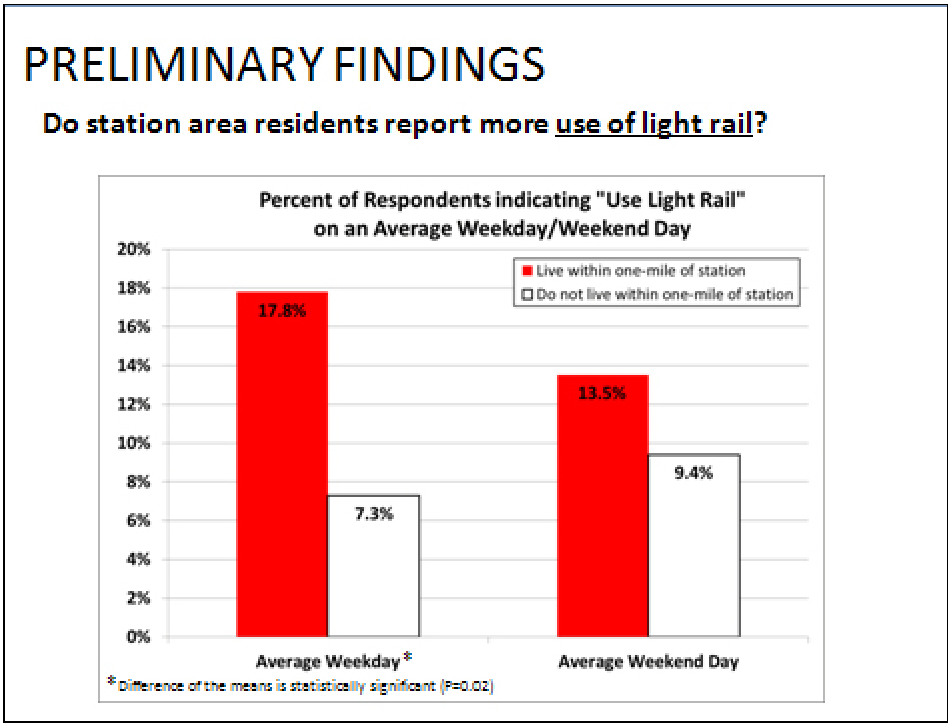
"I feel safe or comfortable taking public transportation"**

"I am concerned about issues related to climate change"*

"The government should invest in environmental protection" **

"The government should invest in public transportation instead of building more roads and highways" **

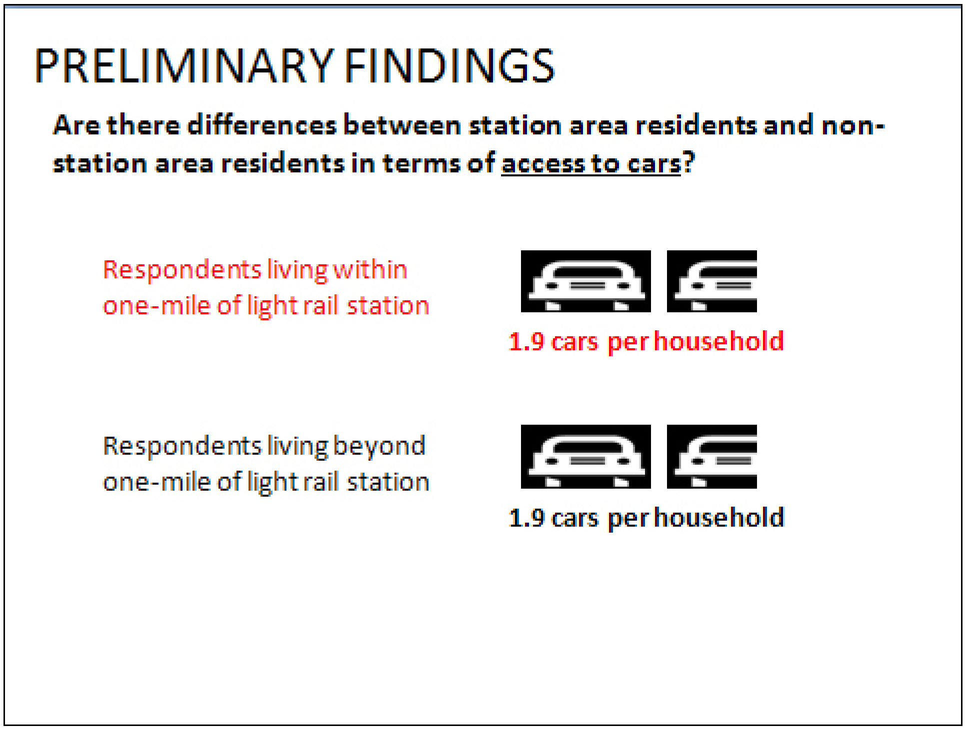
*Significant at P<0.05, **Significant at P<0.01



PRELIMINARY FINDINGS

Do station area residents report more <u>use of light rail</u>?

* Difference of the means is statistically significant (P=0.02)



PRELIMINARY FINDINGS

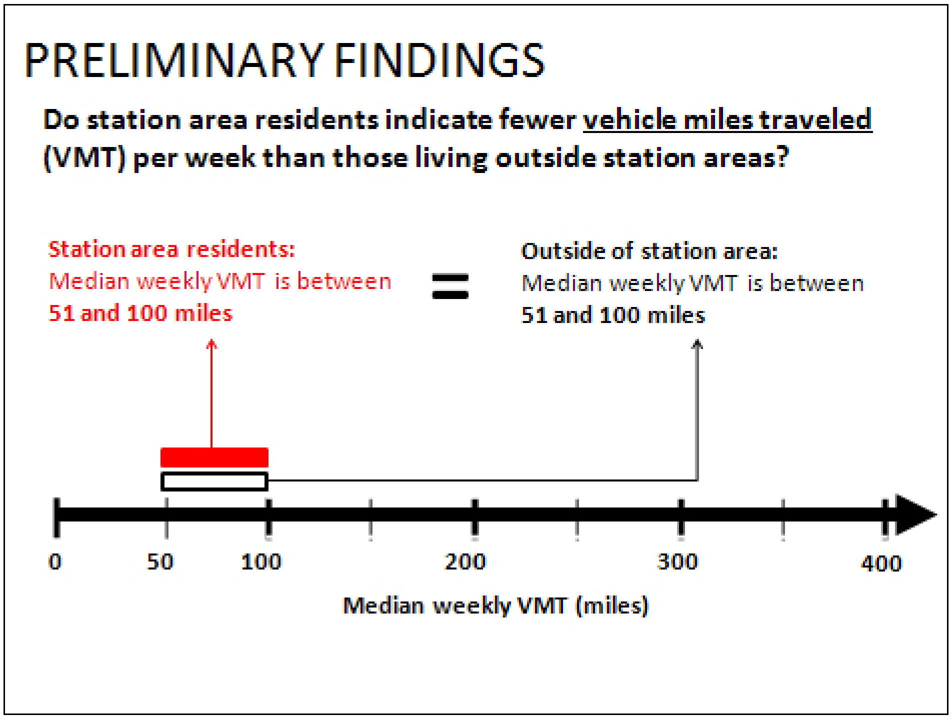
Are there differences between station area residents and non-station area residents in terms of <u>access to cars</u>?

Respondents living within
one-mile of light rail station

1.9 cars per household

Respondents living beyond
one-mile of light rail station

1.9 cars per household



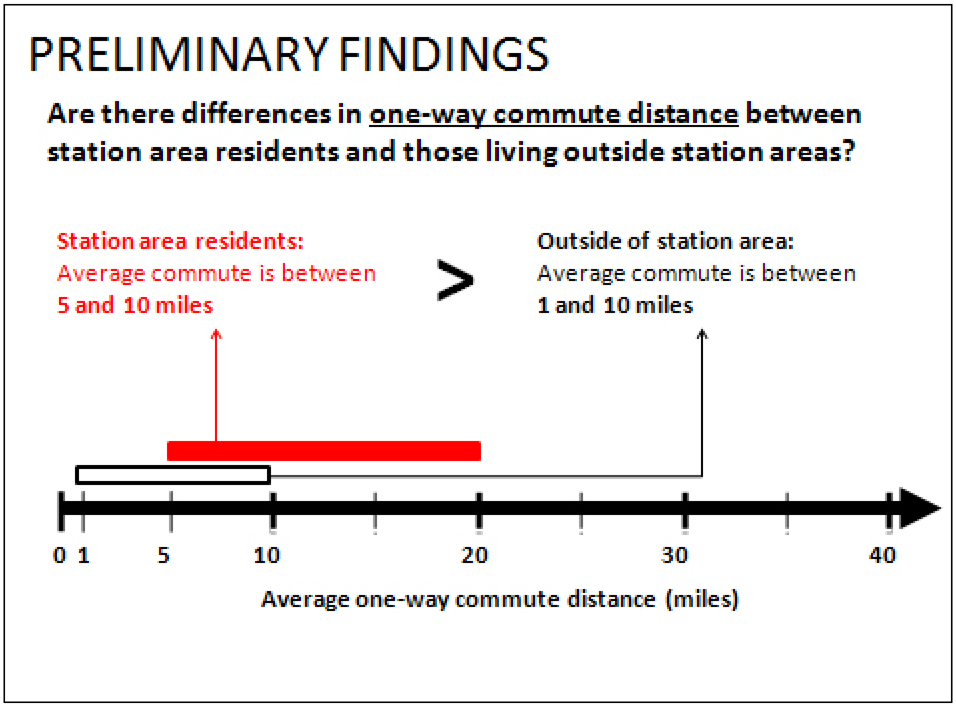
PRELIMINARY FINDINGS

Do station area residents indicate fewer vehicle miles traveled (VMT) per week than those living outside station areas?

Station area residents:
Median weekly VMT is between
51 and 100 miles

=

Outside of station area:
Median weekly VMT is between
51 and 100 miles



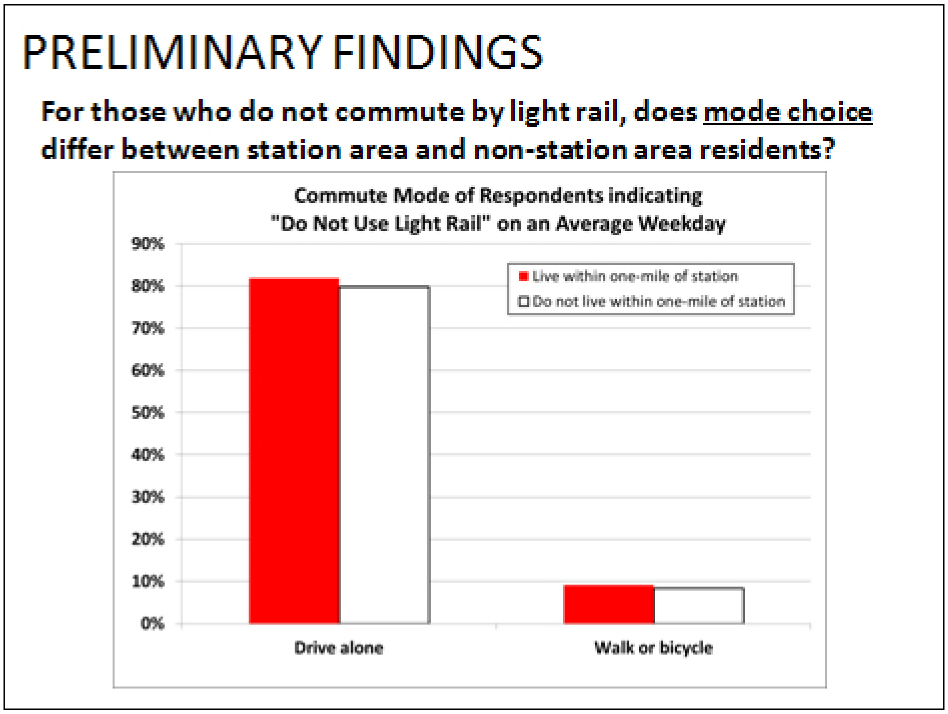
PRELIMINARY FINDINGS

Are there differences in one-way commute distance between station area residents and those living outside station areas?

Station area residents:
Average commute is between
5 and 10 miles

>

Outside of station area:
Average commute is between
1 and 10 miles



PRELIMINARY FINDINGS

For those who do not commute by light rail, does <u>mode choice</u> differ between station area and non-station area residents?

4.2 CONCLUSIONS

Station area residents, compared to those living outside station areas:

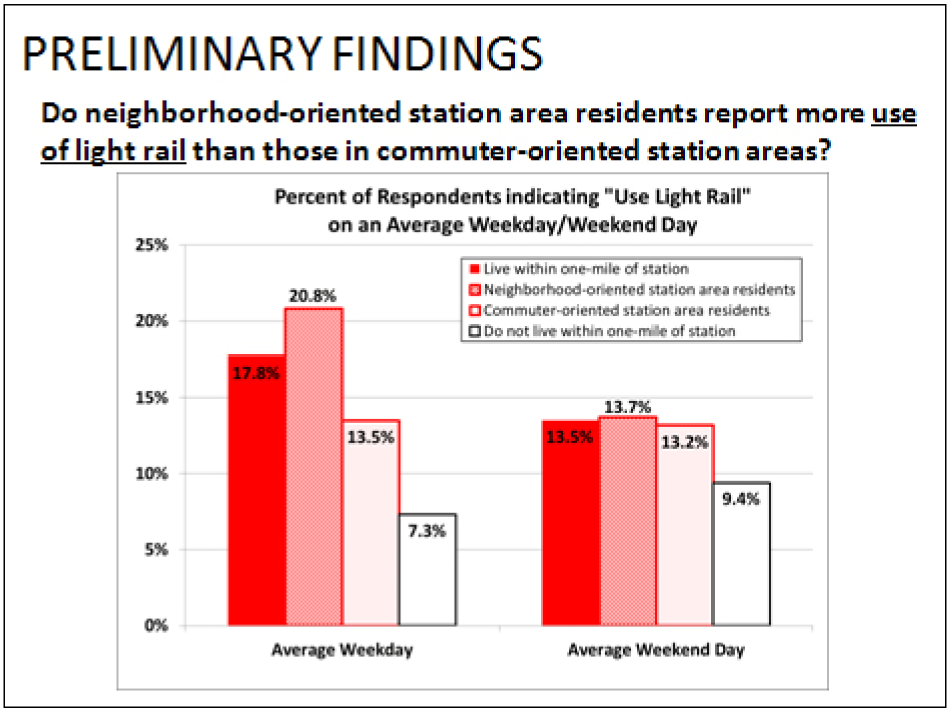
- **Do** use light rail more
- **Do not** own fewer cars
- **May tend** to drive significantly fewer vehicle-miles
- **Do not** commute by bike or foot more, and by cars less

4.3 POSSIBLE EXPLANATIONS

One hypothesis for the fact that there was no discernible difference between the VMT and car ownership rates of those residents who lived near LRT stations and those who lived elsewhere in the metropolitan could relate to the lack of integration between stations and the built environment, specifically the high level of parking that was seen at some of the station areas during the field observation.

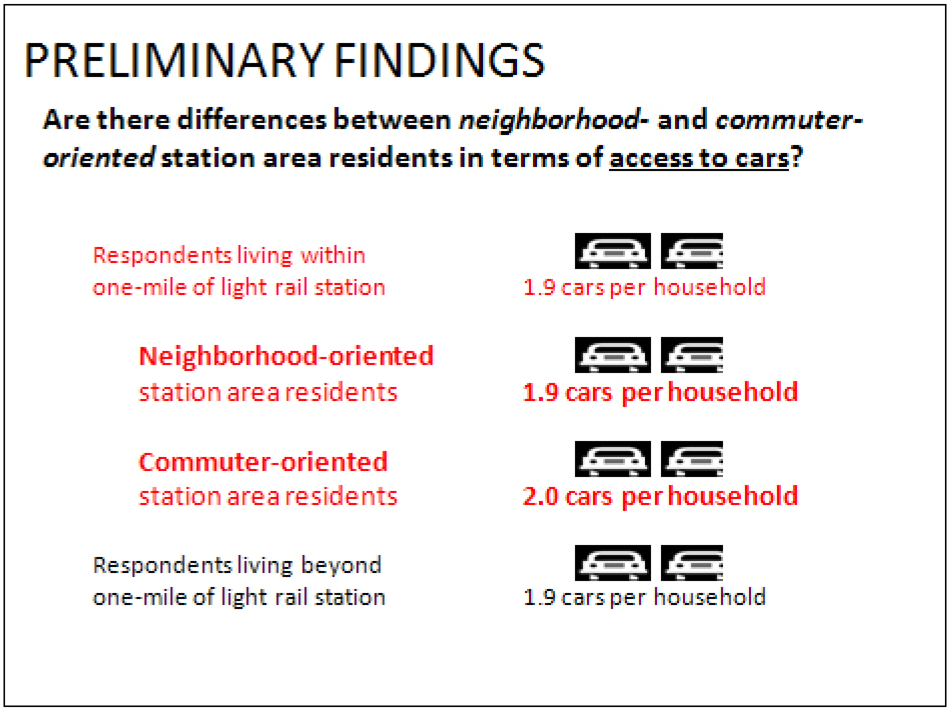
We therefore differentiated between those stations that did and did not have park-and-ride lots, labeling them walk-and-ride stations or “Neighborhood-oriented” station areas, and park-andride or “Commuter-oriented” station areas.

4.4 RESULTS DISAGGREGATED BY NEIGHBORHOOD TYPE



PRELIMINARY FINDINGS

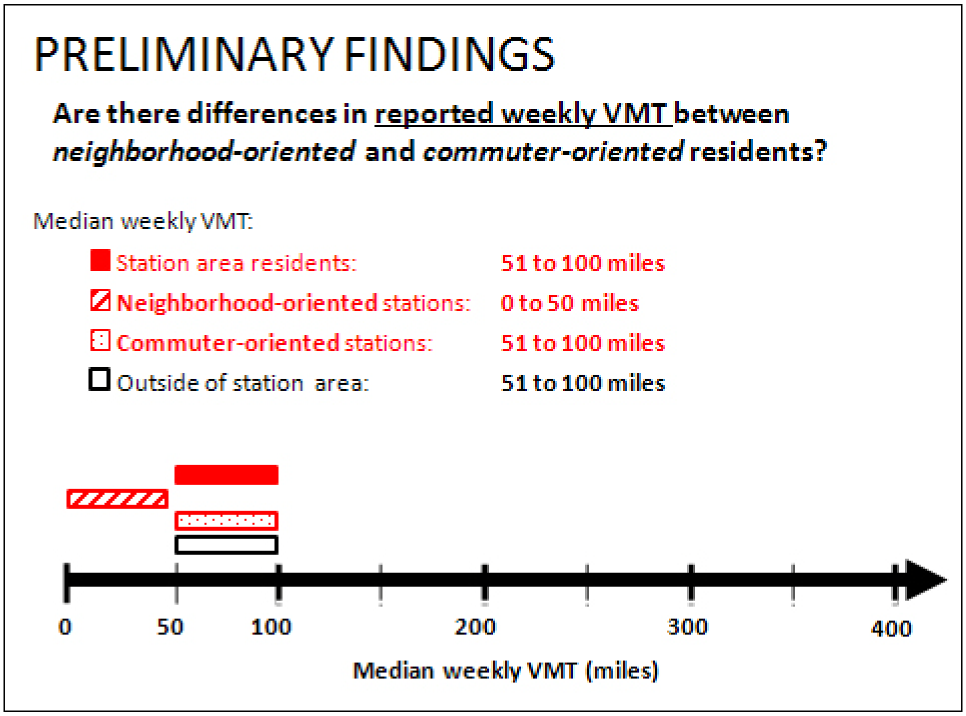
Do neighborhood-oriented station area residents report more <u>use of light rail</u> than those in commuter-oriented station areas?



PRELIMINARY FINDINGS

Are there differences between *neighborhood-* and *commuter-oriented* station area residents in terms of <u>access to cars</u>?

Respondents living within one-mile of light rail station	1.9 cars per household
Neighborhood-oriented station area residents	**1.9 cars per household**
Commuter-oriented station area residents	**2.0 cars per household**
Respondents living beyond one-mile of light rail station	1.9 cars per household

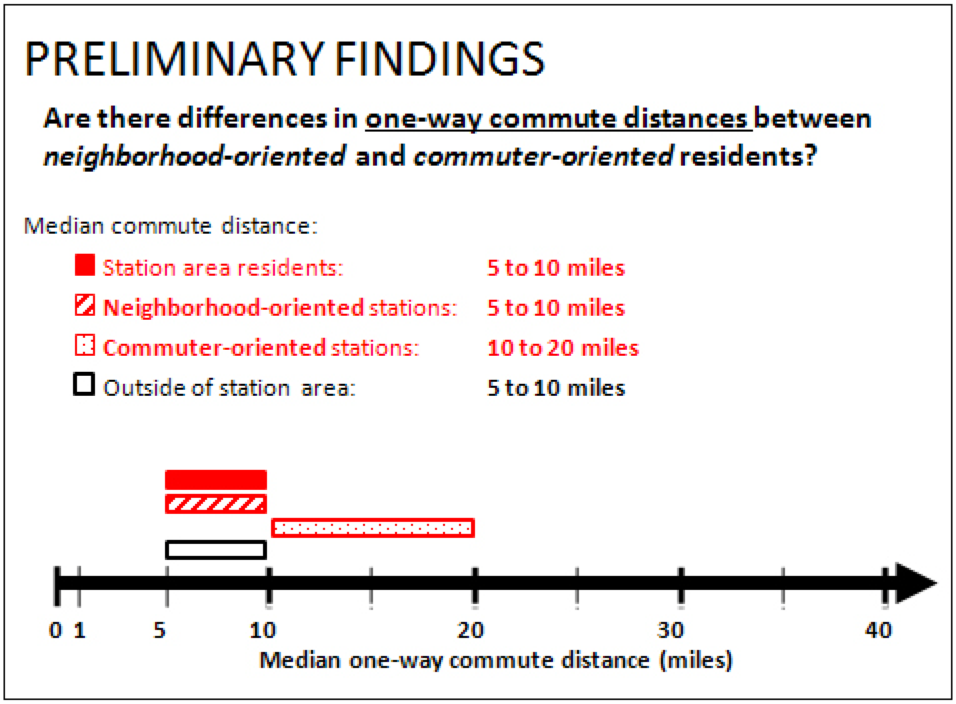


PRELIMINARY FINDINGS

Are there differences in <u>reported weekly VMT</u> between *neighborhood-oriented* and *commuter-oriented* residents?

Median weekly VMT:

■ Station area residents:	**51 to 100 miles**
▨ Neighborhood-oriented stations:	**0 to 50 miles**
⊡ Commuter-oriented stations:	**51 to 100 miles**
□ Outside of station area:	**51 to 100 miles**



PRELIMINARY FINDINGS

Are there differences in <u>one-way commute distances</u> between *neighborhood-oriented* and *commuter-oriented* residents?

Median commute distance:

■ Station area residents:	**5 to 10 miles**
▨ Neighborhood-oriented stations:	**5 to 10 miles**
⊡ Commuter-oriented stations:	**10 to 20 miles**
□ Outside of station area:	**5 to 10 miles**

4.4.1 Conclusions Based on Data Split by Station Type

Differences in travel behavior of station area and non-station areas are not as significant as expected. However, differences between neighborhood- and commuter-oriented stations tell a more nuanced story. Neighborhood stations are likely more able to achieve travel goals while commuter stations (defined as those with parking lots) show patterns more akin to non-station area residents.

4.5 SUMMARY OF MAIN FINDINGS FROM SURVEY DATA

The findings suggest that in the case of Denver, Colorado, transit access alone is not likely to be “enough” to achieve station-level travel goals, in terms of reducing VMT. Instead, the level of integration between the LRT system and the broader urban fabric is important. While Denver may have achieved its goals with respect to ridership, locating the system within a heavy rail corridor and freeway corridor provides limited opportunities for more integration between the system and the built environment. Building a system with the goal of congestion relief and placing an emphasis on creating transit points where drivers can switch to LRT may limit the extent to which that system is able to generate Transit-Oriented Development in the long-term, and limit the extent to which it is able to reduce VMT and thereby GHG emissions.

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APPENDIX A

M.SC. DRAFT THESIS FOR ERIC DORSEY

Freeway Corridor Impacts on Light Rail Ridership in the Transit-Oriented-Development Framework

Eric Dorsey

B.S.C.E., University of Connecticut, 2010

A Thesis

Submitted in Partial Fulfillment of the

Requirements for the Degree of

Master of Science

at the

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APPROVAL PAGE

Master of Science Thesis

Freeway Corridor impacts on Light Rail Ridership in the Transit-Oriented-Development Framework

Presented by

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Abstract

In 2006, the city of Denver completed the first major phase of the T-REX expansion project for a Light Rail Transit (LRT) system, building 13 stations along the corridors of Interstates 25 South and 225. While many welcomed the expansion of LRT, some expressed concern that locating the system alongside freeway corridors could limit the extent to which station areas could transition into transit oriented developments, which are pedestrian-friendly environments that remake place and promote the best ridership. This concern prompted a study to consider whether the built environment in station areas located alongside freeway corridors have the capacity to support the kind of place-making that is associated with traditional transit oriented development outcomes. We identified numerous geographic variables that are considered to impact ridership such as land use, socio-economic features of the population, the street network, and features of the light rail stations. We then performed a factor and cluster analysis of different station typologies using the street network and land use data that illustrates the built environment and divides stations into unique typologies, identifying if freeway stations produced a unique built environment. ANOVA tests were run to examine if there was a significant relationship between ridership counts and typologies. Using these results, we could model potential ridership at stations through a multiple regression analysis using the typology results as well as the socio-economic and rail station characteristics as independent variables for each station. This can determine whether the built environment impacts ridership significantly, and/or if cultural and station characteristics better capture ridership statistically at a transit corridor.

Introduction

Over the past several decades, environmental concerns at the global scale have brought attention to how society must behave in sustainable manners to continue to provide a high quality of life. Growing concern about accumulating greenhouse gas (GHG) emissions in addition to the conflicts surrounding peak oil crisis, has directed focus on high levels of Vehicle Miles Traveled (VMT) in daily auto use that accounts for approximately 40% of emissions in some places, leaving policy makers to consider new approaches in designing for sustainable transportation in U.S. cities. (Duane, Malaczynski, 2009) Many of these metropolitan areas have planned away from sustainable development growth patterns, allowing their urban fabrics to transform towards an auto-dependent system, which has been tied to the daily concerns of sprawl, congestion, and inability to provide efficient accessibility to places. (Littman, 2012) The last few decades have seen numerous efforts into reversing these trends by aiming to reduce VMT, which has been correlated with reduced GHG emissions and improved environmental and functional efficiency of transportation systems (Washington Climate Action Team 2008).

Light rail transit (LRT) has been recognized by policy makers as a method of reducing GHG emissions in the urban realm as it has been observed that on average, regions with transit corridors see lower levels of VMT including areas not serviceable directly by rail. (Littman 2012) VMT reduction is an observed byproduct that stems from a planning strategy known as smart growth, where the built environment around station corridors is designed towards improved accessibility by providing a sense of place within the proximity of transit in the form of mixed uses that are compact and dense while supported by road designs that encourage pedestrian activity. (Leigh and Hoelzel, 2012) The application of smart growth near transit has gained universal attention from researchers and policy makers as a sustainable design approach known commonly as Transit Oriented Development (TOD). (Transit Cooperative Research Program: Report 95, 2007).

TOD has been deemed successful when it has been found to support the theory that densely developed mixtures of land use types that produce a walk-able environment within the LRT corridor produce the most ridership, which simultaneously reduces auto-use (Dittmar and Ohland, 2004). Researchers and policy makers globally have compromised what the TOD typology should look like to support the objectives and benefits that come from it, which has led to evidence that TOD is not a one size fit all approach. (Renne and Wells, 2005) The NCHRP found that various policy makers identified 56 benefits/objectives that TOD could support in neighborhoods, given that different stakeholders in various communities would seek out different benefits from transit implementation in their communities. (Transit Cooperative Research Program: Report 102, 2004) This evidently shows that corridors must develop in numerous ways and seek varying objectives to attract a variety of users. Encouraging the need to develop station corridors with unique mixtures of land use activity with different demographics and densities in development, tend to increase system wide transit demand to support Renne and Wells theory.

In spite of diversity in transit planning, some approaches in TOD design have overlooked the concept of walk-able places, building stations in heavily used auto-corridors to advertise an alternative mode choice to travelers such as the new Southeast LRT Corridor in Denver, Colorado. (Moler, 2001) This approach has overlooked LRT's ability to permanently attract users away from auto, by labeling it as joint development, which is contingent on external factors such as gas prices and congestion. A Duke study found that cross price elasticity of light rail boardings ranged from -.103 to .507 on the basis of gas price, while the Victoria Transport Policy Institute (VTPI) found that auto vs. transit use in a shared corridor will usually approach equilibrium in regards to travel time. (Littman, 2004) This method attempts to optimize ridership by misinterpreting transit accessibility with mobility, overlooking that larger capacities of ridership come from a walk-able setting given that high levels of population, employment, and percentage of renters within walking distance was found to be correlated with higher ridership. (Kuby 2004)

Such approaches are prominent in systems that have developed their stations adjacent with freeways, or divided roadways that design for the highest mobility within a corridor like the Southeast Corridor. While building near freeways can promote ridership by attracting a large capacity of potential users, it contains a ridership threshold that is not only dependent on external factors such as gas and congestion, but overlooks the blueprint the transportation and land use connection provides for producing a large catchment of walk and ride users (Handy, 2002). Freeways or arterials are the building blocks of an auto-dependent street network, in that where-ever the freeway has existed for a prolonged time the adjacent built environment is reflective of accessibility to the freeway in precedence with the automobile. (Federal Highway Administration, 1989) These corridors consist mainly of box retail, strip malls, and chain restaurants with a lot of space designated for parking and wider streets to sustain accessibility towards automobiles for these places, consuming too much land use towards the automobile and provide an environment that is unappealing towards the pedestrian. (American Society of Planning Officials, 1963) The preservation of auto-dependent characteristics fall short of providing the basic TOD objectives, which suggests that a non-TOD compatible built environment would play a negative role in transit feasibility.

This paper will look at the city of Denver, to validate this relationship at all LRT stations on the RTD light rail system. The results will provide evidence to show the variety of typologies that exist at all the stations on a system and if there is a presence of a built environment that fits the description of non-TOD compatible environments that exist frequently at stations near freeways. Given these typologies, we can model it with other factors that have been found to impact ridership and quantify the extent built environments and freeways have on ridership in a corridor. This paper contains a review of pertinent literature in section 2, the description of study area in section 3, data and methodology in sections 4 and 5 respectively, results in section 6, and a discussion of results in section 7.

Literature Review

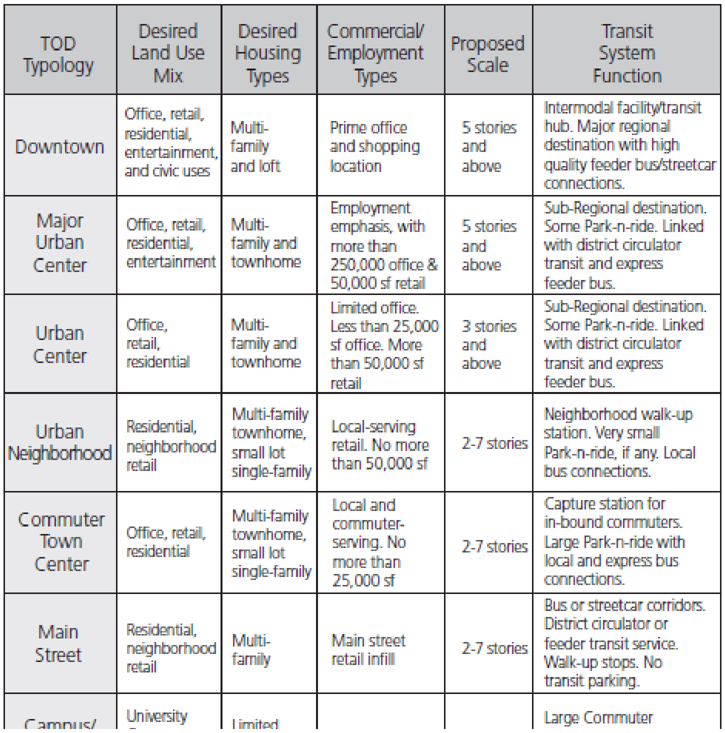
It is difficult to suggest there has ever been a universal definition of TOD, as it has evidently been a reflection of the vision researchers and policy makers hold on such design standards. (Transit Cooperative Research Program: Report 102, 2004) Because there is no universal definition, how it is defined by various professionals can impact collaboration surrounding the topic and how it is designed and implemented. TOD has been classified as a design standard under smart growth which can be summarized by many as focusing on the 3 D's in Density, Diversity, and Design by providing compact, mixed-use, location efficient development that promotes a pedestrian friendly atmosphere adjacent to transit. (Wilhelm and Winters, 2009; Cervero and Kockelman, 1997; Dittmar, 2004)

TOD has also been looked at more logistically with strategies such as producing node like places, which can be easily confused with achieving transportation node places as opposed to real urban centers that have a true sense of place for pedestrian behavior with various activities. (Bertolini and Split, 1998) From a spatial standpoint, stakeholders have quantified the approach in terms of a walking buffer, using research on perceived maximum walking time and distance as a threshold stations have to work with to encourage development that will most likely encourage pedestrian activity to and around a transit station, usually 2 000 feet to a ½ mile. (Calthorpe, 1993) While the variability in defining TOD may be valid, the objectives should all focus on connecting transit with the surrounding built environment in a multi-modal fashion. Researchers have concluded from this that a one size fits all approach is not only unnecessary, but strongly discouraged to promote unique places so long as the transit system becomes a foundational transportation asset of the urban realm. (Renne and Wells, 2005)

While academia has been able to collaborate towards defining TOD and provide the best insight on TOD practice, its interpretation at the planning profession level has continued to shy away from universal comprehension. The Capital Region Council of Government (CRCOG) in Connecticut state that TOD is a planning approach that calls for high density, mixed used development, where transit can serve pedestrians while the Denver Regional Council of Government (DRCOG) defines TOD as "a mix of uses at various densities within a half mile radius or walking distance, of a transit stop. (Ferrucci, 2002; Park, 2006) While both definitions echo the key concepts that researchers use to illustrate successful TOD, the discrepancy between various and high density and a Euclidian vs. walking distance scale are certain examples that show the potential for extreme variability in station typology, and perceived LRT ridership.

Transit agencies have in contrast looked for approaches that maximize transit ridership, which can under emphasize the importance of land use planning. The RTD Light Rail Agency in Denver mentions the need for more compact development than existing development patterns within a 10 minute walk of transit, with a mix of vertical and horizontal building uses that's pedestrian oriented. (RTD, 2010) The Chicago Transit Authority refers to TOD as transit friendly development defined as, "Development which is oriented towards and integrated with adjacent transit. The development incorporates accessibility and connectivity and is a multiuse mix of dense development that generates significant levels of transit riders." (CTA, 2009) These two cases suggest that while the relationship between transit and development is well established, the pedestrian friendly concept is considered to be a designed for approach, but not a natural linkage between the transit and the development. Failure to place stations where walking and dense infrastructure is already a feasible option affects the station typology and suggests that the area is un-compatible for TOD, by prematurely designating it to have a high catchment of walk and ride users when the built environment is not conducive to encouraging such mode choice.

Historically around the early 1900's, LRT known as "street-cars" developed in the downtowns and the fringe of central business districts (CBD) where all stations produced about the same densities and mixed uses that were pedestrian friendly. (Kuby, 2004) In 1996, a study by Parsons and Brinckherhoff (P&B) attempted to predict the factors that impacted Light Rail Ridership boarding's in U.S. cities, not considering that LRT systems that started to develop in the Post World-War II era were found to be a lot more expansive than older systems and reach past the urban fringe into what is referred to as the modernized suburban community. (Baldassare, 1992; TCRP, 1996) Kuby's findings suggest that P&B mistakes light rail systems as commuter rail systems, designed in the latter half of the 20th century as a way to preserve suburban development while facilitating access to the urban core by connecting non-CBD residential districts to jobs in the CBD in places like New York and Boston. (Transit Capacity and Quality of Service Manual – 2nd Edition, TCRP Report 100, 2003) However in accordance with the Transportation Research Board, LRT behaves differently than heavy or commuter rail because it was designed to blend in with the urban fabric, " *along exclusive right of ways at* *ground level, in streets and to board and discharge passengers at track or car floor level*", providing greater access within the CBD and less impedance on the surrounding environment. (Grey, 1989) Kuby's correction of failing to distinguish CBD vs. non-CBD stations, built upon a significantly improved model towards predicting ridership for LRT by considering that transit ridership should account for multiple uses and multiple typologies.



TOD Typology	Desired Land Use Mix	Desired Housing Types	Commercial/ Employment Types	Proposed Scale	Transit System Function
Downtown	Office, retail, residential, entertainment, and civic uses	Multi-family and loft	Prime office and shopping location	5 stories and above	Intermodal facility/transit hub. Major regional destination with high quality feeder bus/streetcar connections.
Major Urban Center	Office, retail, residential, entertainment	Multi-family and townhome	Employment emphasis, with more than 250,000 office & 50,000 sf retail	5 stories and above	Sub-Regional destination. Some Park-n-ride. Linked with district circulator transit and express feeder bus.
Urban Center	Office, retail, residential	Multi-family and townhome	Limited office. Less than 25,000 sf office. More than 50,000 sf retail	3 stories and above	Sub-Regional destination. Some Park-n-ride. Linked with district circulator transit and express feeder bus.
Urban Neighborhood	Residential, neighborhood retail	Multi-family townhome, small lot single-family	Local-serving retail. No more than 50,000 sf	2-7 stories	Neighborhood walk-up station. Very small Park-n-ride, if any. Local bus connections.
Commuter Town Center	Office, retail, residential	Multi-family townhome, small lot single-family	Local and commuter-serving. No more than 25,000 sf	2-7 stories	Capture station for in-bound commuters. Large Park-n-ride with local and express bus connections.
Main Street	Residential, neighborhood retail	Multi-family	Main street retail infill	2-7 stories	Bus or streetcar corridors. District circulator or feeder transit service. Walk-up stops. No transit parking.
Campus/	University	Limited			Large Commuter

Figure 1: TOD Typologies from the Denver Strategic Plan Manual for 2006.

In light of researchers showing that LRT can produce multiple TOD typologies that work well with each other, certain regional planners that have pushed towards transit implementation have applied forecasting of what kind of variations are expected in future years. DRCOG produced The Denver Strategic Plan Manual in 2006, and analyzed the existing conditions of all its current and proposed station corridors to assess what kind of TOD outcomes they would expect the system to produce by 2030. They revealed 7 different typologies that could characterize the built environments of all the existing and proposed stations in the system to validate the idea that multiple TOD outcomes would produce the best system ridership. Typologies showed a variety of details ranging from desired land use mix and housing types, to proposed scale and system function including amount of park and ride spacing. Figure 1 shows all these details.

Forecasting future typologies may be effective for planners, yet it can't be assumed that a station can transition easily into desired typologies without looking into what the current composition of the built environment is comprised of. One study found that ten new light rail systems found ridership to be 15-75% below forecasted levels, which suggests that planners overlook the existing capacity of transit feasibility. (Pickrell, 1992) Phoenix, Arizona tried to avoid this error using a concept called advanced TOD to zone for Light rail ahead of implementation in operations. (Atkinson-Palombo, 2010) A 2010 study used typology analysis to provide an inventory of what kind of station typologies existed on the system to predict which built environments had the best capacity to support the envisioned changes that overlay zoning was trying to achieve. The results of this study presents a methodology that could be applied to other systems to address the question of what types of stations exist on a system and what function they will serve. These can be compared to future desired typologies to better address which places can support place making that can fully transition to a pedestrian friendly environment.

The advanced TOD methodology looks at identifying if TOD characteristics can fit easily at any station while understanding that certain elements are permanent in nature. Overlaying transit onto an urban fabric is not always effective in producing the desired TOD outcomes, which leads planners to become naïve in believing they have developed a true TOD corridor. (Atkinson-Palombo and Kuby, 2010; Cervero and Kockelman, 1997) Recent studies suggest that in many cases, the preservation of the automobile in these corridors has created what many look to as Transit Adjacent Development (TAD) that identify transit modes as no more than an option of travel in an auto-oriented street network known as joint development. (Renne, 2009) Streets have been referred to as bones of a city in that they are merely permanent in nature and strongly impact the development that is supported by it, to the extent that converting an entire corridor from a non-TOD compatible built environment to one that is TOD compatible could be infeasible. (Garrick and Marshall, 2009)

Studies have produced limited evidence of how TOD compatibility affects the composition of walk and ride versus park and ride users at a station, although obtaining this ratio is difficult to obtain with useful accuracy. One study found that mixed-use suburban centers have been successful in attaining high transit-use, concluding that areas that are prone to walking given the dense mixed-use environment, reduces long trips and thus discourages auto-use. (Filion, 2000). If a station has low or no park and ride spots with high ridership, it can be hypothesized that a majority of transit users are not driving to the station, meaning they are likely finding walking to other parts of the corridor at their origin and destination stations as an accessible means. Given this literature, it’s important to further assess if whether there is a significant relationship between built environment and ridership of a station corridor.

The validation of the relationship between the built environment and ridership may also come from understanding the socioeconomic profiles of riders that are attracted to LRT systems in various typologies. Kuby’s methodology produced a statistically significant model with a sample size of 9 LRT systems that potentially predicts ridership for any LRT system in a corridor while taking into consideration multiple factors of the built environment. Improving upon the P&B analysis, he considered that there were 17 different possible factors that prior research found to be significant towards ridership, yet only the P&B analysis had aggregated all of them in a single model. Improving on the CBD factor as mentioned earlier, a multi-regression analysis was performed with 9 different rail systems comprising 268 stations given their measured ridership for all stations as a dependent, and was able to quantify to what extent certain factors encouraged and discouraged ridership. Kuby looked at factors involving traffic generation, intermodal connections, citywide variables, network structure, and socioeconomic data. The statistical significance of the model fabricates a potential baseline analysis for future research towards the prediction of LRT ridership for any LRT system.

If it is proven that there is a significant relationship between ridership and the built environment, Kuby's quantitative model could compliment a typology analysis to show which variable factors of the station area are significant with ridership and which typologies presented such factors. Even if it was found that the relationship between the built environments and ridership was not significant, the model could still validate assumptions that there is a relationship between built environments and ridership, by pointing out what factors of the station area environment work for or against ridership in the station area. The main issue with the Kuby model is the ignorance towards factoring the built environment. Its failure to consider factors such as building density, street network characteristics, or mixes in land use ignores the foundation of concepts in TOD design. Factoring these variables into the analysis would provide conclusive evidence on how the physical built environment plays a role in accounting for ridership trends at a station corridor, by identifying negative coefficients on a binary variable system for the built environment that suggest a typology works against promoting transit ridership.

With the degree of pedestrian friendliness evident as a primary indicator of TOD success by promoting walk and ride users, the street network design is one of the many features of the built environment that are permanent in nature and provide an indicator of TOD compatibility. The built environment calculation includes Intersection Density and Link to Node Ratio as predicators of the street network design to detect how the roads of the city structure the development patterns. Link to Node ratios however have discrepancy when providing indication of the street network connectivity and the walkability standards that have been joined to it. The degree of confusion is comprised from cases where cities exclude heavy arterials or freeways in the link to node calculation, which questions its ability to universally compare the degree of walkability. (Garrick and Marshall, 2009)

Because freeways have limited connectivity and divide a corridor because of the physical impedance in width, it questions whether freeways should be considered a part of the street network, considering the studies that link walkability to the parameter. In the city of Denver along with many other cities, LRT expansion has developed adjacent to freeways while placing stations near freeway interchanges, such as the Louisiana Pearl station just outside the CBD. Louisiana Pearl has an intersection density of 146 intersections/sq mile and 1.72 Link to Node Ratio within a ½ mile Euclidian buffer distance and no park and ride spots at the station, suggesting a highly walk-able corridor. However out of 36 stations, the RTD ridership count in August 2010 revealed that the station ranked 26th out of 36 stations on the line in total weekly boarding's. (RTD, 2010) Even if the area was considered pedestrian friendly, this is suggestive that a pedestrian friendly network does not promote high ridership when the freeway divides a corridor and preserves auto-accessibility, proposing that freeways should not be considered as a component of the street network.

It is hypothesized that freeways impact the walk-able capacity of a station corridor mainly because of its size. As part of the Hierarchical Network that was established by the Federal Highway Administration, they are best explained as the thoroughfares that are exclusively designed towards safe mobility with limited accessibility. (Federal Highway Administration, 1989) Thus in cities where they connect neighborhoods, they are the most frequently used thoroughfares within the network and thus require the greatest capacity, meaning a span of 2-5 lanes each way, with a required width of 12 feet per lane. (HCM, 2010) Freeway developments potentially contain easements, which can help expand the resulting non-TOD compatible corridor in some areas as much as 200 feet by 1 mile, a linear widespread of dead space in a station corridor that can never transition to dense mixed use development, and likely deter pedestrian use, that local newspapers in Denver and Seattle suggested to be the case. (Moler 2001; Freemark, 2010)

The city of Denver is the most compelling site to look at as the city itself has experienced rapid changes in population growth and environmental improvements over the last few decades. Its light rail system has been promoted towards helping reduce air pollutants and promoting sustainable growth in its rail corridors, which has helped it garnish funding for rail expansion. The region itself has faced huge population expansion which led to the opening of the Southeast Corridor which consisted of 13 new stations that were all placed adjacent to a freeway corridor.

Since it's evident that the freeway should be excluded from the street network, then we must also ask how the freeway itself affects ridership in a TOD framework. On the same system as Louisiana-Pearl, there is also a station called Colfax at Auraria, on the main terminal just outside of the CBD. Colfax has a nearly similar Intersection Density of 143 intersections per square mile and a Link to Node Ratio of 1.46. However Colfax is ranked 1st out of the 36 stations in ridership, despite having a significantly lower Link to Node ratio and a slightly lower Intersection Density.

The main difference between these two stations is that Louisiana-Pearl has a freeway run through its station buffer zone while Colfax does not. One can argue that Colfax is in the CBD, however Kuby provided evidence that this relationship was not significant. Another argument could be that because it's an education center, trips are naturally elevated, however education trips only make up on average about 14% of total system ridership on average. (Fielding, 1995) Therefore it begs to ask the question whether or not the presence of freeways is one of the variables significant with ridership?

Understanding the relationships between freeway and walk-ability can help answer this question. The Hierarchical Network is explained by the FHWA as a method of improving street classification systems over AASHTO to better define the relationship between mobility and accessibility in street networks. Figure 2 shows this relationship that streets that want to maximize mobility need to limit the access it provides in order to limit number of stop points such as with a highway or parkway. Streets that want to maximize accessibility need to sacrifice mobility in order to properly facilitate the efficiency in reaching desired goods and services. When analyzing the application of this theory at the neighborhood or city scale, these streets typically branch out from arterials to local roads.

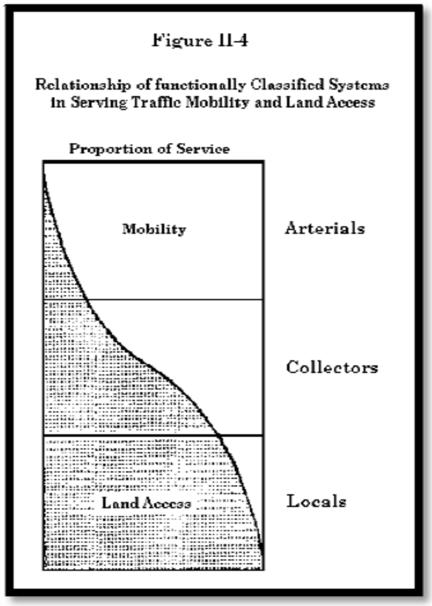


Figure 2: Pedshed.net

Some of the varying factors designed for on these roads include number of lanes, 12 foot minimum lane width, speed limits in excess of 50 miles per hour, pedestrian facilities, and intersection traffic control. (American Association of State Highway and Transportation Officials, 2001) It is expected that walk-able streets fall under local and collectors, which would minimize number of lanes and widths and speed limits, while containing sufficient pedestrian facilities such as wide sidewalks, benches, on-street parking, and bike-lanes. Streets that maximize mobility for cars would likely see the opposite of these features, in order to maintain proper flow and safety between auto and non-auto users. Therefore in order to prevent grid-lock and safety issues, streets near freeways must have a limit on walk-ability if it assumed these features measured as the primary contributors to a walk-able street network reduce traffic flow and speed.

Using the relationship between transportation and land use defined earlier, it can be expected that the types of building infrastructure that exists at a station corridor is reflective upon the supporting street network, or the bones of the city that has been referred to thus far. Streets that are more conducive towards the automobile see businesses that recognize the need to provide parking to attract auto-users. The result is that places like strip malls, box-retails, and single family residential, must facilitate for the auto-user by designing parking lots that facilitate the desired capacity of these places, which in part consume space. The County Line station on the RTD light rail comprises of mainly box-retail and a shopping mall that finds that nearly 11% of its land is dedicated to parking spaces, along with 5% of vacant space and nearly 38% of space for road/rail corridors. Excluding extra space the freeway would consume, land used for building infrastructure or recreation would be less than half of the ½ mile Euclidian corridor.

Additionally, the County Line station has an Intersection Density of 12 intersection/square mile and a Link to Node Ratio of 1.3, well below pedestrian friendly standards. (Garrick and Marshall, 2009) Removing and replacing roads is a costly process and even funding for pedestrian features like sidewalks can even become highly challenging. It is expected that areas such as County Line does not support any capacity to transform into a pedestrian friendly TOD, but rather provide no dynamic in land use change while sustaining itself as a feeder station to park and ride users, falling short of attracting a higher capacity of walk and ride users. Thus it is believed that the placement of transit systems near freeways is not conducive to the best potential ridership by failing to promote walk-able places. A loosely based methodology replicating the Advanced TOD typology analysis will be used to identify built environments, and a multivariate regression analysis is then used to quantify the effects of ridership, to derive conclusions based from this section.

Description of Study Area

For this analysis, we will use the city of Denver, Colorado as a case study, given the Light Rail's maturity within the city as well as the huge growth the area has incurred within the last few decades according to the U.S. Census. Denver, Colorado is the 20th largest city in the United States, which includes 9 counties in the metropolitan area as defined by DRCOG. The major freeway's in Denver are comprised of Interstate 70 going West to East passing just north of the city boundary, and Interstate 25 going North to South passing just to the west of the city boundary. Other major routes include Interstate 225 as a partial beltway on the Southeast side of the city in Aurora, as well as U.S. Route 6 that goes east to west through the Denver Metropolitan area. Amongst the major cities that are recognized as part of the Denver Metropolitan area include Boulder to the northwest, Centennial and Littleton to the South, and Aurora to the east.

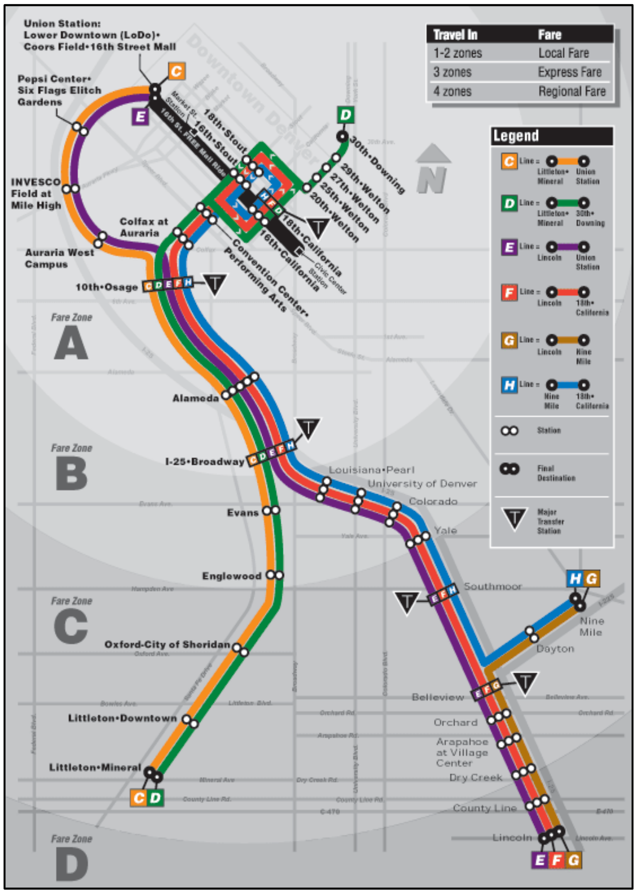


Figure 3: RTD-Light Rail Map

The RTD Light rail (Figure 3) has

been in place since 1994, with a series of city stops from as far north as 30th and Downing, to the 16th street mall stations and the Pepsi Center and Invesco Field sporting facilities. The system also is connected to Union Station as a terminal stop where Amtrak formally made stops, and follows south to 10th and Osage, Alameda, and I-25 and Broadway stations. In the CBD including the Welton St, 16th and 18th street, the Convention Center and Auraria stops, the LRT is a shared rail system within the road. The rest of the system includes the 2 southern lines are designed like a commuter rail with a travel speed of around 50 mph with a right of way rail corridor. The initial line installed which is now referred to as the Southwest Line, follows parallel along a freight route, going into the villages of Englewood, Evans, and the city of Sheridan, containing upscale walk-able town centers. The line ends in the city of Littleton, stopping at the downtown village before ending at Littleton Mineral, a rural/suburbanized stop with less walk-ability.

In 2006, The T-REX program in designing an extension to the light rail system completed what is now referred to as the Southeast corridor, branching off from the original southwest line right after the I-25 Broadway station. The majority of the southeast corridor runs parallel along the southbound side of Interstate 25, passing the stations of Louisiana-Pearl, Yale, Colorado, University of Denver, and Southmoor. After Southmoor, another fork was designed where the I-225 interchange begins off of Interstate 25, where the light rail's H-line goes to Dayton before ending at Nine-Mile Station. The remainder of the southeast corridor includes Belleview, Orchard, Arapahoe at Center Village, Dry Creek, County Line (where a shopping mall is) and the Terminal station of Lincoln.

Data

The data used in this analysis was to be the most detailed and up to date information that was available to the Denver region. The time-range of the data collected varies from 2000 to 2011, and may not fully reflect the system in its entirety. All data collected in this analysis was collected within a ½ Euclidian buffer of a Light Rail station, as a standard for the maximum distance people are usually willing to walk to a station as mentioned earlier. In cases where there was overlap in station corridors, spatial characteristics were applied to the nearest station, which was determined using the “Near” Arc Toolbox function in ArcGIS. The process includes a collection of 23 independent variables and 1 dependent variable that comprise of data gathered from multiple sources. The data can be defined into 3 categories: 1) Built Environment Variables; 2) Regression Variables 3) Dependent Variables. Figure 4 shows all the variable data collected and brief explanations.

Built Environment Variables

The first part of the analysis as mentioned was to define the built environments that reflect the 3 main characteristics to support what creates a pedestrian friendly TOD in accordance with Dittmar and Ohland.

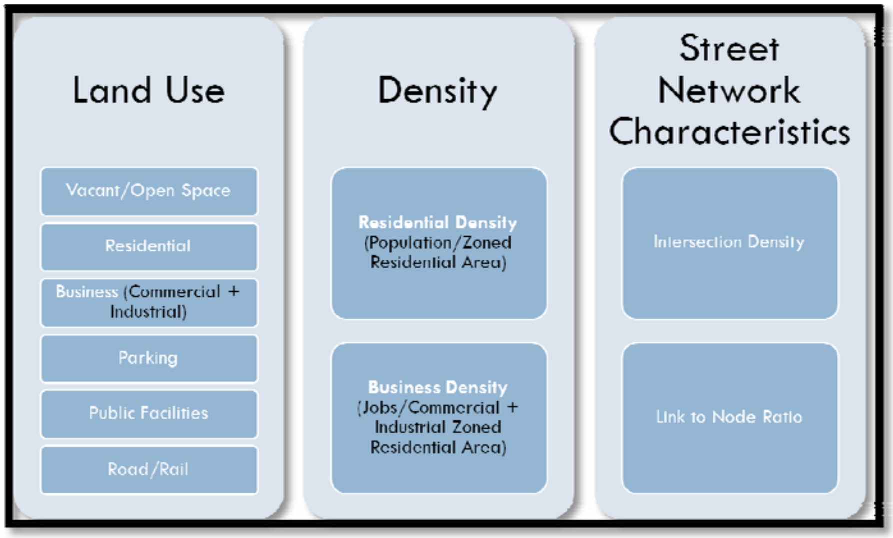


Figure 4: The 3 Categories that explicitly define a TOD Typology: Mixed Land Use, Dense Development, Location Efficient Street Network Design

Therefore a total of 10 variables were collected to reflect the built environment that is able to measure mixed land use, density, and pedestrian friendly street network. Land use data was collected by collecting zoning information for the 3 counties that have stations, and classifying zoning into several categories. Density is described as building density, by looking at residential and business density involving dividing the number of residents and jobs by the square mileage of the residential and commercial land use. Finally the street network data includes intersection density and link to node ratios of the station corridors as used by Garrick and Marshall that can illustrate pedestrian friendly street networks.

Land use data was collected from parcel maps from the three county government websites (Denver, Arapahoe, and Douglas) GIS database. Parcel data was used for Denver and Arapahoe counties to aggregate a zoning map for the entire region in ArcGIS, along with Douglas counties regular zoning map since they did not have parcel information available. Using the three data maps, a set of zoning types were composed to define the land use into a set of several land use types. The land use types include vacant/open space, residential, commercial, industrial/agricultural, parking, public facilities, mixed land use, and road/rail land use. For simplicity in the analysis, commercial and industrial/agricultural land uses were combined to create a business land use, while mixed land use was excluded because it was highly negligible in zoning.

Regression Variables

The output from the typology analysis is expected to produce a set number of typologies that will be used as independent variables in a regression analysis that is similar to the one performed by Kuby. These variables will be a binary set to indicate which stations of the system fit into each typology. Kuby's original analysis contained 5 categories that tested 17 different variables expected to impact ridership. Understanding Kuby's reductions as well as excluding variables that are city-wide that don't vary across one system, 12 variables were collected for 5 different categories for this analysis.

Traffic Generation

1) **Employment** – This counts the total number of jobs whose main offices are located within the Euclidian buffer of the system. Employment hypothesized by Kuby to be the most important factor in work trips. This data was collected through the department of Labor, which contained a dataset full of addresses that were geocoded to form a point shapefile in ArcGIS for the year 2010. Using ArcGIS, the businesses within the Euclidian distance were extracted and then assigned to the station they were found in. Employment counts from all the jobs were summed together to determine total station employment
2) **Population** – The counts the total number of people who live in housing within a half mile Euclidian buffer of the system. It is expected that higher population of an area potential draws higher ridership. This data was collected through block data for 2010 on the census website. The data was joined to a block shapefile for Denver, and then used spatial analysis to determine what percentage of the block was within the Euclidian buffer. This percentage was applied to the total population count and all adjusted block populations within the Euclidian buffer were summed together.
3) **College Enrollments** – Educational trips on average make up 14% of transit trips (Pickrell, 1992) This counts the total number of enrollments at colleges that are within the Euclidian Buffer. College enrollments were determined by google imagery

identifying all the colleges that existed within Euclidian station buffers, and accessing website data to find total students that attended all secondary schools.

Intermodal Access Variables

1) **Park and Ride Spots** – RTD had GIS data that indicated coordinate locations of light rail stations as well as the total number of park and ride spots for each station. Kuby's regression model found that .774 park and ride spots generate one rider, or 1000 riders for every 774 park and ride spots.
2) **Bus Connections** – The RTD website has data that shows how many total bus routes stop at each light rail station. More bus connections suggest higher regional connectivity and likely higher ridership.

Network Structure Variables

1) **Terminal Station** – A dummy variable indicating whether a station was a terminal was hypothesized by Kuby to produce significant additional ridership.
2) **Transfer Station** – Ideally many stations on the Denver line can be used for transfers as there are 5 routes, however Kuby suggests restriction to designated transfer stations as the dummy variable. The Denver system in this case has 4 designated transfer stations also as a dummy variable
3) **Centrality** – Kuby describes Centrality as the relative accessibility of each station to all other stations, measuring the average travel time one station has to all other stations. This number is then divided by the highest average travel time for the entire system, usually a value from terminal to terminal. Values can range from 0 to 1, 1 meaning the station has

the worst centrality. Station near the middle of the system will typically have the lowest centrality value.

Citywide Variables

1) **Degree Days** – This is a meteorological measure of extreme temperatures in a city, and was expected by Kuby to strongly impact the number of users who could not bear a waiting time in extreme weather. This is a citywide variable which is constant across the entire system.

Socioeconomic Variables

1) **Percent Renters** – Given the number of households in the station corridor that is occupied, this takes the percentage that is found to be rented by the tenants. This is calculated by using census data at the block group level for 2010, and uses spatial analysis in Arc Toolbox in GIS to spatially calculate the percentage of renters in the Euclidian buffer. Kuby's model found that in a corridor completely occupied by renters, the station would generate 624 boardings.

The regression analysis also includes a freeway variable that is a dummy variable to identify if whether a freeway runs parallel with the Light Rail system. Freeways aren't considered in cases where they just intersect the buffer, but rather be within approximately ¼ mile of the station to be considered running parallel with the system.

Dependent Variable

Ridership - The dependent variable for this analysis is ridership for each light rail station, measuring total daily weekday ridership on average for August of 2011. This data is available at the RTD Light Rail website. Ridership is the most simplistic indicator of system wide VMT reduction as a majority of people who board rail are replacing auto trips with LRT.

Methodology

The software used for the typology and regression analysis is an International Business Machines Corporation (IBM) product called Statistical Package for the Social Sciences (SPSS) that can be used for a wide variety of statistical analyses including cluster analysis and multi-regression. All data collected for each station in the previous section is copied and pasted from an excel spreadsheet into a table on the user interface which is then saved by the program that can be called to run any series of statistical tests. The rows represent each station, while columns represent all the variable data collected.

The objective of the typology analysis is to establish a set of station typologies for the light rail system that are defined by a set of independent variables that define each station from a built environment perspective measuring levels of mixed land use, building density, and pedestrian friendly street networks. These results were conducted by performing a factor analysis and cluster analysis as a statistical method used to best categorize a set of observations into smaller classifications for comparison. Factor analysis is sometimes performed prior to the cluster analysis to reduce multicollinearity in the variables by creating an uncorrelated set of factor variables, which is useful when dealing with a large number of independent variables that are considered in a cluster analysis. (Lawley, 1971)

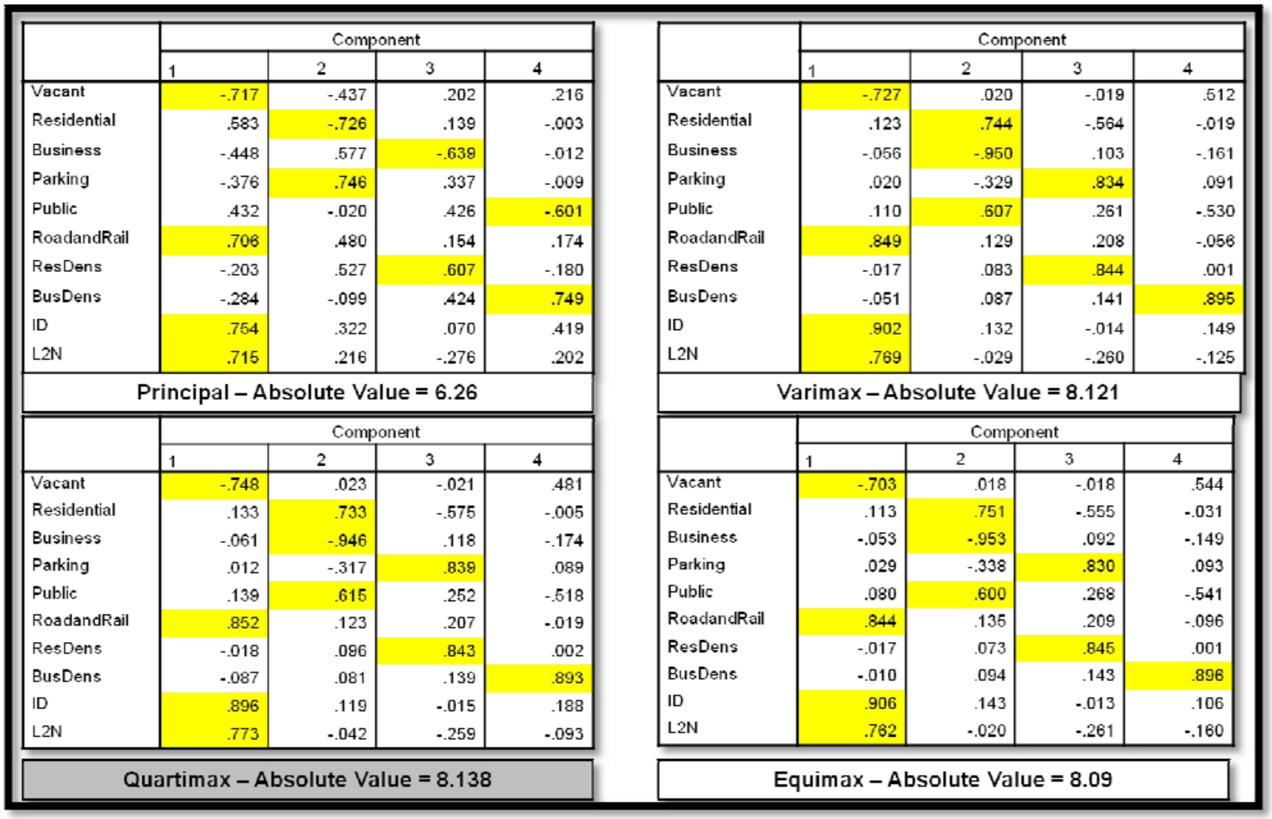
When running factor analysis, it is necessary to select which variables from the data spreadsheet are to be considered for factoring. This involves selecting 10 total variables including the 6 land use types, Residential and Business Density, and Intersection Density and Link to Node Ratio. When running factor analysis, there are several possible methods to consider, which are rotations of the correlation matrix that are derived from different statistical algorithms. The possible rotations considered are as follows: (Abdi, 2003)

1) ***Principal (Un-Rotated)** – Maximizes the variance accounted for by the first and subsequent factors, forcing factors to be orthogonal*
2) ***Varimax** – Maximizes the factor axes to maximize the variance of the squared loadings of a factor on all the variables in the factor matrix, differentiating the original variables by extracted factor. Most common rotation option*
3) ***Quartimax** – Minimizes number of factors needed to explain each variable. The rotation often generates a general factor on which most variables are loaded to a high or medium degree.*
4) ***Equimax** – a compromise between the Varimax and Quartimax*

The other 2 possible rotations are a Direct Oblimin and Promax rotation however these are non-orthogonal solutions that make some variables irrelevant, which should not be considered for this analysis.

Choosing the best rotation involves looking at the factor matrix, and analyzing the highest loadings (positive and negative) on each of the factors for each independent variable a shown in Figure 5. The higher the degrees on the loadings, the more uncorrelated the factors become. These factors can also suggest how different cluster groups will form based on which high loadings are within each factor variable.

Choosing the rotation with the highest loadings overall is the best statistical fit for this factor analysis. Once it is determined which rotation is best, the program must be instructed to save variables. This will output on the data spreadsheet a new set of columns after all the independent variables, which are the factor variables that are to be used for the cluster analysis.



	Component			
	1	2	3	4
Vacant	-.717	-.437	.202	.216
Residential	.583	-.726	.139	-.003
Business	-.448	.577	-.639	-.012
Parking	-.376	.746	.337	-.009
Public	.432	-.020	.426	-.601
RoadandRail	.706	.480	.154	.174
ResDens	-.203	.527	.607	-.180
BusDens	-.284	-.099	.424	.749
ID	.754	.322	.070	.419
L2N	.715	.216	-.276	.202

Principal – Absolute Value = 6.26

	Component			
	1	2	3	4
Vacant	-.727	.020	-.019	.512
Residential	.123	.744	-.564	-.019
Business	-.056	-.950	.103	-.161
Parking	.020	-.329	.834	.091
Public	.110	.607	.261	-.530
RoadandRail	.849	.129	.208	-.056
ResDens	-.017	.083	.844	.001
BusDens	-.051	.087	.141	.895
ID	.902	.132	-.014	.149
L2N	.769	-.029	-.260	-.125

Varimax – Absolute Value = 8.121

	Component			
	1	2	3	4
Vacant	-.748	.023	-.021	.481
Residential	.133	.733	-.575	-.005
Business	-.061	-.946	.118	-.174
Parking	.012	-.317	.839	.089
Public	.139	.615	.252	-.518
RoadandRail	.852	.123	.207	-.019
ResDens	-.018	.096	.843	.002
BusDens	-.087	.081	.139	.893
ID	.896	.119	-.015	.188
L2N	.773	-.042	-.259	-.093

Quartimax – Absolute Value = 8.138

	Component			
	1	2	3	4
Vacant	-.703	.018	-.018	.544
Residential	.113	.751	-.555	-.031
Business	-.053	-.953	.092	-.149
Parking	.029	-.338	.830	.093
Public	.080	.600	.268	-.541
RoadandRail	.844	.135	.209	-.096
ResDens	-.017	.073	.845	.001
BusDens	-.010	.094	.143	.896
ID	.906	.143	-.013	.106
L2N	.762	-.020	-.261	-.160

Equimax – Absolute Value = 8.09

Figure 5: The 4 Rotations that are considered for a factor analysis. A shortcut method for choosing the best rotation is to sum the absolute value of the max coefficient from each set of components and determine which value is greatest, since having values closest to one shows better non-correlation amongst the variables.

The cluster analysis is performed by using only the saved factor variables from the factor analysis and using a Hierarchical method, which is based on the idea of objects being more related to near-by objects than objects farther away. This uses a distance function called linkages to form clusters, by constantly grouping observations together into like sets until all the observations are said to be in one cluster alike. This uses a squared-linked distance to categorize stations. Clustering is also performed using Ward's method, which uses a sum of squares criteria to maximize differences and minimize within-group differences. (Atkinson-Palombo 2007) K-means cluster was also considered which allows clusters to be represented by a central vector and creates an optimization problem by finding the k cluster centers and assigning the observations to the nearest cluster center so that squared distances are minimized. This process however was excluded because the number of clusters needs to be specified in advance.

Using the Hierarchical Cluster analysis method has the ability to produce a dendrogram that illustrates the clustering of stations into groups over linkage distance. Figure 6 shows how this process works, which involves making an imaginary cut along the dendrogram to determine how many clusters should be used. 3 to 5 clusters should be chosen, and the remainder of the methodology can involve repetitions from different cluster amounts to produce best fit results. When it is determined how many clusters will be used, the stations must be manually identified by group number in a separate column on the data spreadsheet. The dendrogram will identify stations with a group number that matches the row number in the spreadsheet.

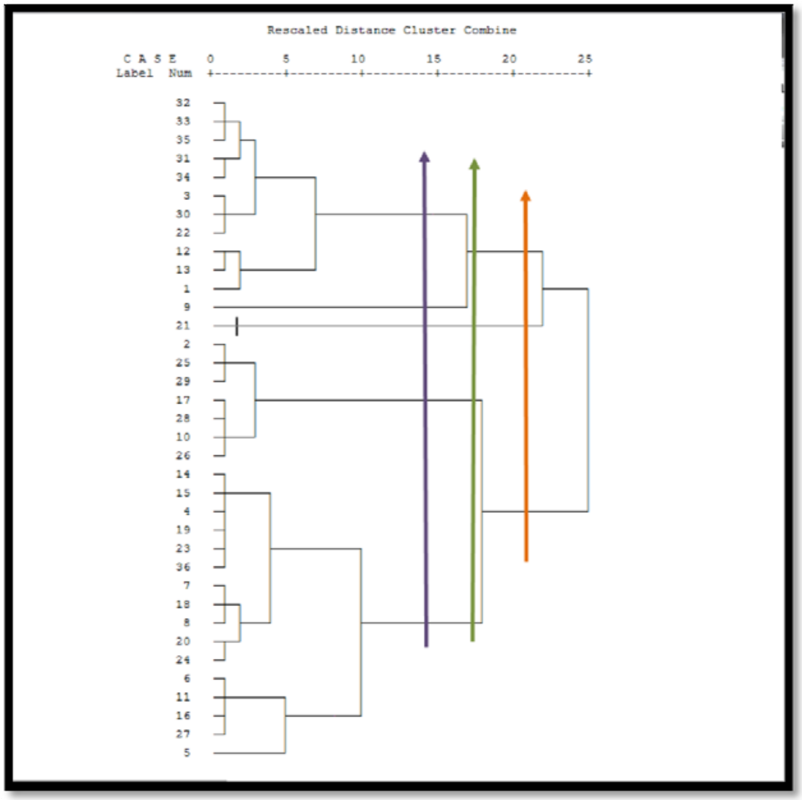
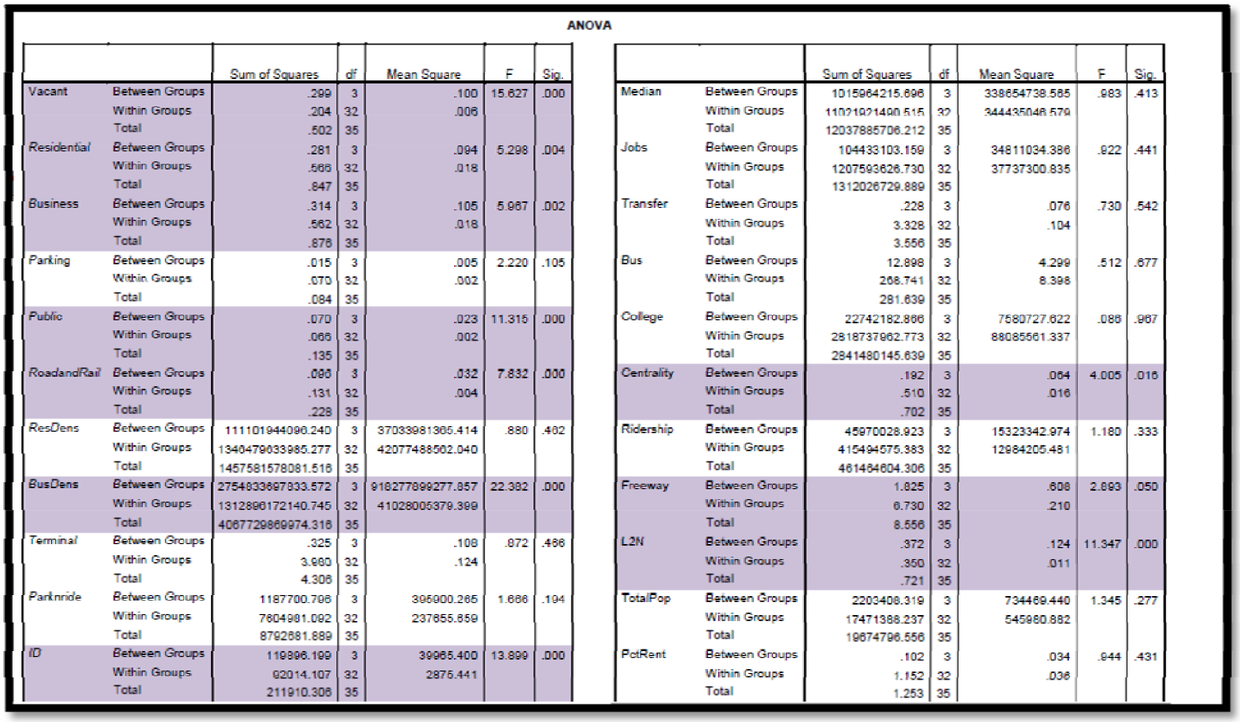


Figure 6: Dendrogram for Visual Illustration of a Cluster Analysis - Using Ward's Method. User can define how many observed clusters they want (Vertical Arrows show the divides which determine which observations go in which group by tracing the branches to the left to trace back to the observations.)

Using these results, it must be determined how the final output is significant statistically. ANOVA tests are run on the cluster results, by looking at all the 18 independent variables and Ridership variable collected and analyzing their significance by group number. Figure 7 shows the SPSS output, which includes the significance factor. Using a 95% confidence interval, values of this factor that are less than .05 are variables that are significant by group and can be used to explain variances for different typologies. Ridership significance by group is important to identify if there is a significant relationship between ridership and the built environment. Descriptive statistics are also produced which identify averages by group for each independent variable, including mean, standard deviation, minimum/maximum, and upper and lower bounds. The mean values by group are to be used to describe typologies using only the variables that were found to be significant by group in the ANOVA results.



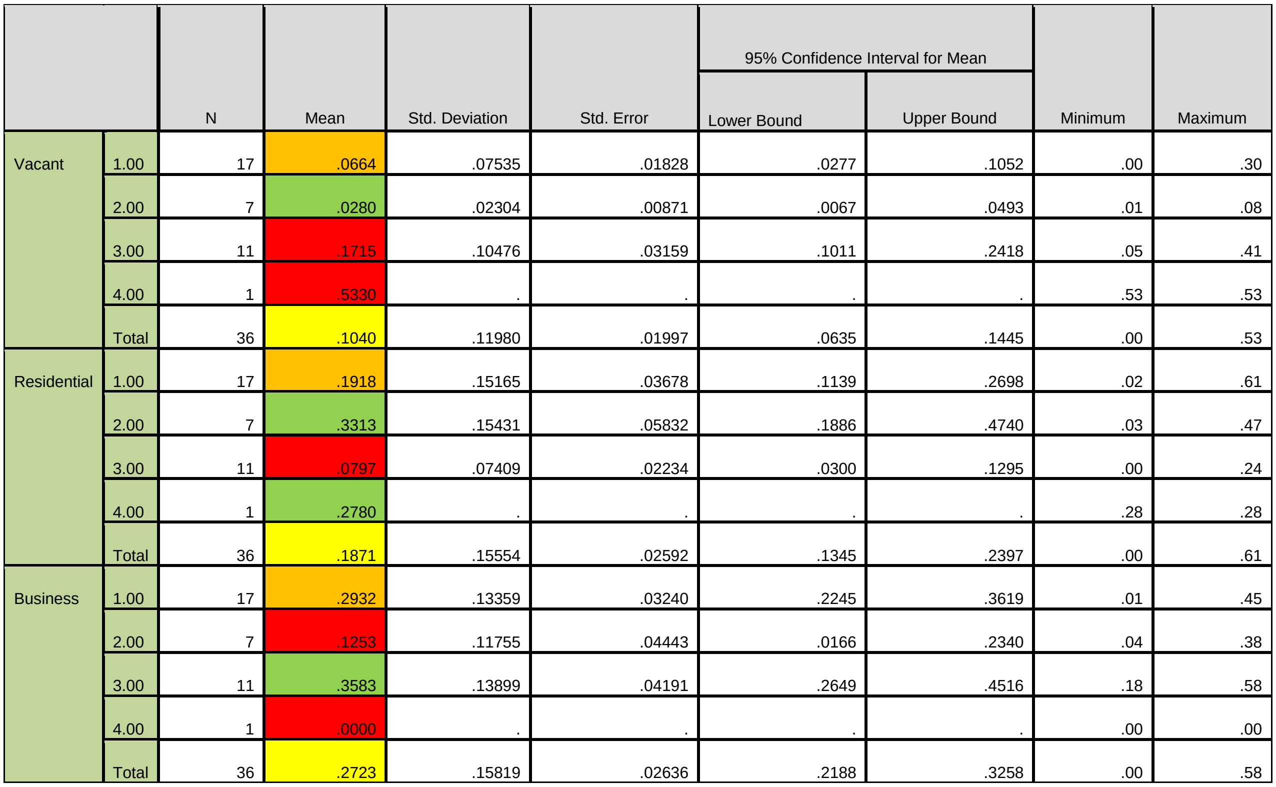
ANOVA

		Sum of Squares	df	Mean Square	F	Sig.
Vacant	Between Groups	.299	3	.100	15.627	.000
	Within Groups	.204	32	.006		
	Total	.502	35			
Residential	Between Groups	.281	3	.094	5.298	.004
	Within Groups	.566	32	.018		
	Total	.847	35			
Business	Between Groups	.314	3	.105	5.967	.002
	Within Groups	.562	32	.018		
	Total	.876	35			
Parking	Between Groups	.015	3	.005	2.220	.105
	Within Groups	.070	32	.002		
	Total	.084	35			
Public	Between Groups	.070	3	.023	11.315	.000
	Within Groups	.066	32	.002		
	Total	.135	35			
RoadandRail	Between Groups	.096	3	.032	7.832	.000
	Within Groups	.131	32	.004		
	Total	.228	35			
ResDens	Between Groups	111101944096.240	3	37033981365.414	.880	.462
	Within Groups	1346479633985.277	32	42077488562.040		
	Total	1457581578081.516	35			
BusDens	Between Groups	2754833697833.572	3	918277899277.857	22.382	.000
	Within Groups	1312896172140.745	32	41028005379.399		
	Total	4067729869974.316	35			
Terminal	Between Groups	.325	3	.108	.872	.466
	Within Groups	3.980	32	.124		
	Total	4.306	35			
Parknride	Between Groups	1187700.796	3	395900.265	1.666	.194
	Within Groups	7604981.092	32	237655.659		
	Total	8792681.889	35			
ID	Between Groups	119896.199	3	39965.400	13.899	.000
	Within Groups	92014.107	32	2875.441		
	Total	211910.306	35			
Median	Between Groups	1015964215.696	3	338654738.565	.983	.413
	Within Groups	11021921490.515	32	344435046.579		
	Total	12037885706.212	35			
Jobs	Between Groups	104433103.159	3	34811034.386	.922	.441
	Within Groups	1207593626.730	32	37737300.835		
	Total	1312026729.889	35			
Transfer	Between Groups	.228	3	.076	.730	.542
	Within Groups	3.328	32	.104		
	Total	3.556	35			
Bus	Between Groups	12.898	3	4.299	.512	.677
	Within Groups	268.741	32	8.398		
	Total	281.639	35			
College	Between Groups	22742182.866	3	7580727.622	.086	.967
	Within Groups	2818737962.773	32	88085561.337		
	Total	2841480145.639	35			
Centrality	Between Groups	.192	3	.064	4.005	.016
	Within Groups	.510	32	.016		
	Total	.702	35			
Ridership	Between Groups	45970028.923	3	15323342.974	1.180	.333
	Within Groups	415494575.383	32	12984205.481		
	Total	461464604.306	35			
Freeway	Between Groups	1.825	3	.608	2.893	.050
	Within Groups	6.730	32	.210		
	Total	8.556	35			
L2N	Between Groups	.372	3	.124	11.347	.000
	Within Groups	.350	32	.011		
	Total	.721	35			
TotalPop	Between Groups	2203408.319	3	734469.440	1.345	.277
	Within Groups	17471388.237	32	545980.882		
	Total	19674796.556	35			
PctRent	Between Groups	.102	3	.034	.944	.431
	Within Groups	1.152	32	.036		
	Total	1.253	35			

Figure 7: One Way ANOVA results - Highlighted Variables are found to be significant meaning that the relationship between the typology number and variable is not by accident within a 95% confidence interval. Significance is the last value in the table.

The typology labels are user-defined in ways that are clear to interpret and can help clearly distinguish the group types. Features of the build environment that were commented on include density levels in development, zoning compositions, street network types, and whether a significant number of stations in the group include adjacent freeways. Mean values quantify the presence of such features and can be defined as high, average, or low values. Using all the information gathered about the comments, a general typology label can be formed to associate with what type of classification is appropriate. An example is shown in Figure 8.

The average ridership of each group should also be noted and ranked for each typology in the label. Regardless of ridership significance with group, it is likely that different ridership levels of the group reflect the typology of the built environment. Things to observe are if there



		N	Mean	Std. Deviation	Std. Error	95% Confidence Interval for Mean		Minimum	Maximum
						Lower Bound	Upper Bound		
Vacant	1.00	17	🟧 .0664	.07535	.01828	.0277	.1052	.00	.30
	2.00	7	🟩 .0280	.02304	.00871	.0067	.0493	.01	.08
	3.00	11	🟥 .1715	.10476	.03159	.1011	.2418	.05	.41
	4.00	1	🟥 .5330	.	.	.	.	.53	.53
	Total	36	🟨 .1040	.11980	.01997	.0635	.1445	.00	.53
Residential	1.00	17	🟧 .1918	.15165	.03678	.1139	.2698	.02	.61
	2.00	7	🟩 .3313	.15431	.05832	.1886	.4740	.03	.47
	3.00	11	🟥 .0797	.07409	.02234	.0300	.1295	.00	.24
	4.00	1	🟩 .2780	.	.	.	.	.28	.28
	Total	36	🟨 .1871	.15554	.02592	.1345	.2397	.00	.61
Business	1.00	17	🟧 .2932	.13359	.03240	.2245	.3619	.01	.45
	2.00	7	🟥 .1253	.11755	.04443	.0166	.2340	.04	.38
	3.00	11	🟩 .3583	.13899	.04191	.2649	.4516	.18	.58
	4.00	1	🟥 .0000	.	.	.	.	.00	.00
	Total	36	🟨 .2723	.15819	.02636	.2188	.3258	.00	.58

Figure 8: Descriptive Statistics are also produced during a One-Way ANOVA showing mean values, standard deviations, and minimum/maximum values. The mean values are used in labeling presence of levels of features in the built environment. (Red-Worst Values, Orange-Average Values, Green – Best Values, Yellow – System Average)

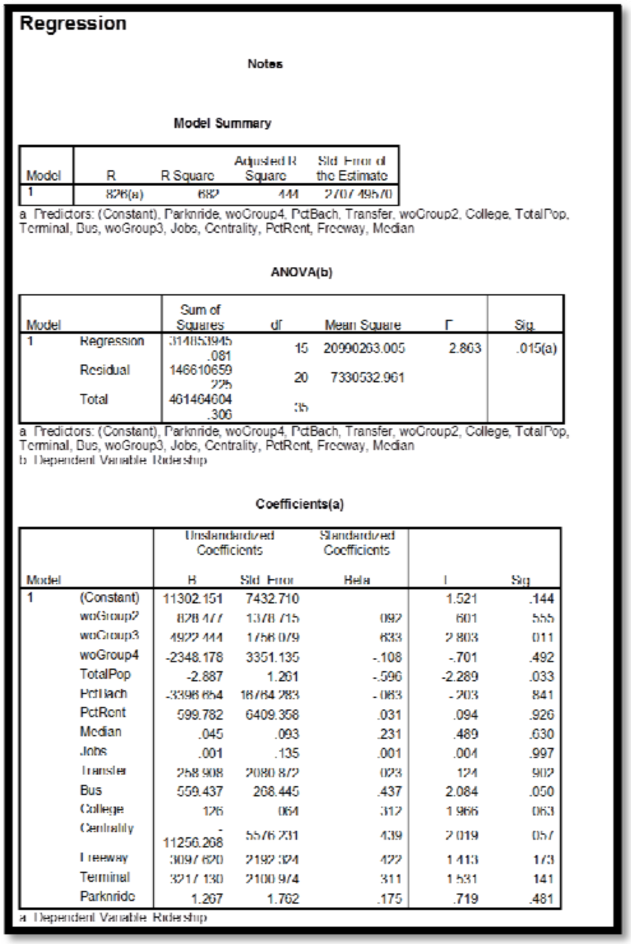
are typologies that contain a majority of the freeway stations and what those stations ridership levels are. This can help establish important relationships between the freeway and built environment. The freeway was not included in the built environment as it's a dummy variable whose presence is absolute and not graded, which does not help define the built environment quantitatively.

The main question that needs to be answered from the typology analysis is whether there is a significant relationship between the built environment and ridership. If it is found there was significance, the analysis needs to continue to determine what variables contribute to ridership and determine if this significance can be measured quantitatively. If the typology analysis did not find this relationship significant, than the hope is that there is another model that can validate the assumptions that there is a relationship between the built environment and ridership.

Existing research found that Kuby's multiple regression model is the most effective method in predicting light rail ridership. Predicting factors in a multiple regression analysis can conclude through statistical processes the extent that certain factors of a station environment impact ridership. Kuby tested 17 hypothesized variables that was researched to have an impact on light rail boardings and placed them into OLS regression. 5 variables were found to be non-significant while 12 were significant. His final model was produced based on data for 9 light rail systems that he anticipated could be used universally for other light rail systems, such as the Denver system.

The data for the 12 variables was collected as noted in the data section for each station. Then using excel spreadsheet, a formula imitating Kuby's model was placed in to a column recalling data for the 11 variables. The resulting output of measured ridership was compared with the actual ridership reflective of the RTD counts from August 2011, and looked at percent error between the values. In the case of their being significant error between the two values, Kuby's model was not considered a best fit approach for predicting the factors influencing ridership. Errors can be found in the appendix.

Errors in Kuby's model can be suggestive of comments made earlier that he fails to account for the built environment. If Dittmar's approach supports that TOD should represent a mixed use, dense, pedestrian friendly street network, than Kuby fell short of this by not including any measures that were used in the typology. Rather than just putting in the same 8 variables for the built environment, the typology analysis assisted this process by clustering classifications of built environments that are distinguishable in nature. Relationships between built environments and ridership are easier to interpret than relationships between ridership and all of the elements separately.



Regression

Notes

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.826(a)	.682	.444	2707.49570

a Predictors: (Constant), Parknride, woGroup4, PctBach, Transfer, woGroup2, College, TotalPop, Terminal, Bus, woGroup3, Jobs, Centrality, PctRent, Freeway, Median

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	314853945.081	15	20990263.005	2.863	.015(a)
	Residual	146610659.225	20	7330532.961		
	Total	461464604.306	35			

a Predictors: (Constant), Parknride, woGroup4, PctBach, Transfer, woGroup2, College, TotalPop, Terminal, Bus, woGroup3, Jobs, Centrality, PctRent, Freeway, Median
b Dependent Variable: Ridership

Coefficients(a)

		Unstandardized Coefficients		Standardized Coefficients		
Model		B	Std. Error	Beta	t	Sig.
1	(Constant)	11302.151	7432.710		1.521	.144
	woGroup2	828.477	1378.715	.092	.601	.555
	woGroup3	4922.444	1756.079	.633	2.803	.011
	woGroup4	-2348.178	3351.135	-.108	-.701	.492
	TotalPop	-2.887	1.261	-.596	-2.289	.033
	PctBach	-3398.654	16784.283	-.063	-.203	.841
	PctRent	599.782	6409.358	.031	.094	.926
	Median	.045	.093	.231	.489	.630
	Jobs	.001	.135	.001	.004	.997
	Transfer	258.908	2080.872	.023	.124	.902
	Bus	559.437	268.445	.437	2.084	.050
	College	.126	.064	.312	1.966	.063
	Centrality	-11256.268	5576.231	.439	2.019	.057
	Freeway	3097.620	2192.324	.422	1.413	.173
	Terminal	3217.130	2100.974	.311	1.531	.141
	Parknride	1.267	1.762	.175	.719	.481

a Dependent Variable: Ridership

Figure 9: Illustration of SPSS - Multiple Regression Output Screen. The Main Focuses are the Model (R, R2, and Adjusted R2), the model ANOVA (F-test and Significance, and the variable coefficient significance. The unstandardized B-value is the resulting coefficients to be used for the final model.

After the typology analysis is complete, the stations must be placed into a binary set that can be used for a regression analysis. In this case 4 typologies were formed so four variables were created in the data spreadsheet in SPSS, indicating if a station was in a certain typology or not. A few variables used in Kuby's model had to be excluded from the Denver model as they were either non-existent or constant amongst the entire system. The airport and border variables were excluded since LRT does not connect to either feature, while degree_days and employee coverage were also excluded since they were constants amongst the system. College Enrollments was originally removed from Kuby's analysis however this will also be reinstated for the equation. The freeway variable as mentioned earlier is also used as a dummy variable for this analysis, to analyze if the model can predict the freeway as a significant factor for ridership on the entire system.

The regression analysis involves selecting all the above variables to be considered into the regression equation as independent variables, with ridership being the dependent variable. The software does not produce automatically a best fit model as there are many statistical parameters to consider. The main model parameters to focus on are highlighted in Figure 9, focusing on R, R2, Adjusted R2. ANOVA parameters to consider are F-statistics and model significance, while the main parameter to focus on for the coefficients is there overall significance in the model. Significant values should all be under .05 to fit in place with a 95% confidence interval, while all other parameters should be as high as possible. R2 values should be at least .6 with an adjusted R2 of at least .5.

When running the regression the first time with all the variables included, it is highly likely there will be variables whose coefficients exceed the .05 level. The adding and removal of variables are what will make the model likely to fit the statistical parameters of the regression equation and therefore they must be removed strategically. The approach used in this analysis was to remove one variable at a time, always removing the variable that was least significant, and running the analysis repeated doing this until all variables were significant at the .05 level and the model was statistically valid and significant as well. Depending on the number of clusters chosen or the variable data used, the model may or may not be valid. This is important to note when drawing conclusions.

Once the model fits the mentioned parameters, the output produced a set of unstandardized coefficients. It is highly likely there is a constant variable that is used to help fit the model for all stations in the system given the remaining variable data that is being used for the final equation. The coefficients that are produced can be interpreted differently based on the range of values that the independent variables contain. Figure 10 can explain how to interpret these variables.

The final step was to run the regression results produced from the model and compare ridership explained by the model with the RTD measured ridership. It was expected that this model would produce significantly less percent errors than the Kuby model runs. It was predicted some stations may not fit well depending on the Standard Error of the final model, but there should be overall improvements from the Kuby model.

Variable Type	**Description**	**Variables**
Binary Variables – 1 or 0 entries only	Represents number of estimated riders attracted or un-attracted to a station based on the existence of such feature	Terminal, Transfer, Freeway, Typology Variables
Percentage Variables – 0 to 1 only (Decimal)	Number of riders attracted or un-attracted to the system if the feature is absolute (100%), Linear relation between feature and ridership factored from variable	Centrality, % Renters
Numerical Variables – Any Real Number <0	Either a percentage or a multiplier of observed value in station corridor that translate to number of attracted or un-attracted riders to a system per unit of the feature	Population, Employment, Park and Ride, Bus
Constant	Ridership Threshold at Stations (Balance Point)	

Figure 10: How to Interpret Coefficient's in Multi-Regression Analysis

Results

All data and results from this analysis can be referenced in the appendix of this paper, starting with the factor matrix results for the four possible rotations. Looking at the total values of all loadings, it was found that the Quartimax rotation was the best produced rotation. Although studies suggest this is the least useful for research, the analysis found that there were no significant differences between the varimax, quartimax, and equimax rotations.

Using the quartimax rotation to produce factor variables, the hierarchical cluster

Typology: Group 1	**Mixed Use Urban Centers**
Details	Low Vacant LU, Average Residential LU, Average Business LU, Average Public LU, High Road/Rail LU, High Business Density, High ID, High L2N, Lowest Centrality, Low number of Freeway Stations
Ridership	1st
Typology: Group 2	**High Density Residential Centers**
Details	Lowest Vacant LU, Highest Residential LU, Lowest Business LU, High Public LU, High Road/Rail LU, Med-Low Business Density, Highest ID, Highest L2N, Average Centrality, Some Freeway Stations
Ridership	2nd
Typology: Group 3	**Low Density Business Park Centers**
Details	High Vacant LU, Low Residential LU, High Business LU, Average Public LU, Low Road/Rail LU, Lowest Business Density, Lowest ID, Low L2N, Highest Centrality, High Number of Freeway Stations
Ridership	3rd
Typology: Group 4	**Dayton Station: Undeveloped**
Details	Mostly Vacant LU , Some Residential LU, No Commercial LU, No Public LU, Low Road/Rail LU, Extremely High Building Density, Low ID, Lowest L2N, High Centrality, Freeway Station
Ridership	4th

Figure 11: Typology Results from Cluster Analysis

analysis was then run and divided into 4 clusters, which produced clusters that were made up of 17, 7, 11, and 1 station for the 4 clusters. The 4th cluster was only the Dayton station, a unique output from the cluster analysis which will be further explained in the next section.

The ANOVA tests from Figure 7 found that all the variables of the built environment were significant in the analysis with the exception of parking land use and residential density. While the freeway variable was also significant, centrality was the only other regression variable that was within the 95% confidence interval for the 4 groups. Ridership was found to not be significant at a level of .333.

Figure 11 shows the final typology output, which includes the details of the descriptive statistics by mean values, as well as the group average of station ridership ranking and the typology formed. The four typologies formed were Mixed Use Urban Centers, High Density Residential Centers, Low Density Business Park Centers, and the Dayton Station: Undeveloped. Typology explanations are as follows ranked from highest to lowest ridership:

Mixed Use Urban Centers – **Ridership Rank: 1st -** (4789 Daily Average Riders)

17 of the 36 stations fit into this typology, nearly half the system as station corridors that strongly reflect Dittmar's three TOD characteristics. These stations saw low amounts of vacant/open space land use, a balanced mixture between residential, business, and public land uses, as well as a street network that was dense and highly connected. Most of these stations were near or part of the CBD, and only the Colorado and Yale stations were the only stations with adjacent freeways to be placed into this group. Other stations that fit into this group include the 16th and 18th street stations, the Welton street stations, as well as the Colfax at Auraria station, the highest ridership for the system.

High Density Residential Centers – **Ridership Rank: 2nd** – (3965 Daily Average Riders)

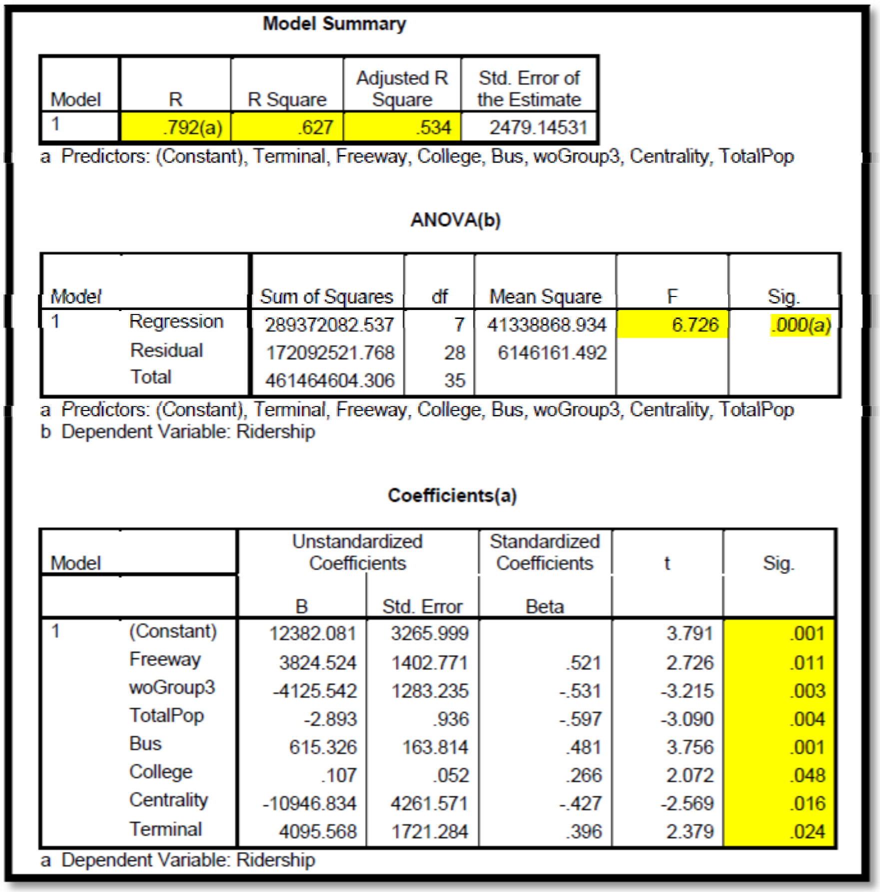
7 stations fit into this typology, where even though there was a poor mix of land use that leaned heavily towards residential, they were densely developed corridors that contained pedestrian friendly street networks. Businesses were sparse yet densely developed infrastructure, while public facilities consumed much land along with residential. These were mostly communities that were not in the CBD but just outside the fringe of it, commonly referred to as the modern suburban communities. 3 of the 7 stations were freeway stations, including Louisiana Pearl, Southmoor, and University of Denver. Other stations include Littleton-Downtown, the terminal station of 30th and Downing, and the 16th and Stout station in the CBD.

Low Density Business Park Centers – **Ridership Rank: 3rd** – (2398 Daily Average Riders)

This group is the focal point of the typology analysis, as the majority of freeway stations fit into this group. 7 of the total 13 freeway stations were placed into this typology which had 11 total stations, the 4 of which that were not freeway being the Littleton-Mineral terminal station, the sporting arena stations, and the Auraria West Campus station which unlike Colfax at Auraria captures significantly low ridership. The freeway stations in this case were all the furthest from the system reflective of highest centrality values, high vacant/open space land uses, and a non-pedestrian friendly street network. The stations show a high amount of land use catered towards business in these station corridors, however they are mostly low density developments. These stations fail to cater to Dittmar's 3 TOD principles. Notable stations include the Terminal station Lincoln, the Belleview station that includes a technology park, and the County Line station that contains a shopping mall and numerous strip malls with large quantities of parking.

Dayton Station – Undeveloped – **Ridership Rank: 4th** – (1059)

The typology analysis identified one station that possesses characteristics that are extremely unique in comparison to other stations on the system in the Dayton station. As a freeway station, it is the second to last station from the Nine mile terminal station, and was unique in that it is mostly undeveloped. It is expected that this station should most likely fit into the Business park typology, however despite essentially no business land use, there were a few buildings near the corridor that were dense enough to produce a high number of jobs, which explains why despite a highly undeveloped corridor, it is not the lowest ridership total on the system being ranked 30th out of 36 stations. A further analysis about this station will be explained in the next section about why this may be a positive sign for the system.



Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate
1	.792(a)	.627	.534	2479.14531

a Predictors: (Constant), Terminal, Freeway, College, Bus, woGroup3, Centrality, TotalPop

ANOVA(b)

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	289372082.537	7	41338868.934	6.726	.000(a)
	Residual	172092521.768	28	6146161.492		
	Total	461464604.306	35			

a Predictors: (Constant), Terminal, Freeway, College, Bus, woGroup3, Centrality, TotalPop
b Dependent Variable: Ridership

Coefficients(a)

Model		Unstandardized Coefficients		Standardized Coefficients	t	Sig.
		B	Std. Error	Beta		
1	(Constant)	12382.081	3265.999		3.791	.001
	Freeway	3824.524	1402.771	.521	2.726	.011
	woGroup3	-4125.542	1283.235	-.531	-3.215	.003
	TotalPop	-2.893	.936	-.597	-3.090	.004
	Bus	615.326	163.814	.481	3.756	.001
	College	.107	.052	.266	2.072	.048
	Centrality	-10946.834	4261.571	-.427	-2.569	.016
	Terminal	4095.568	1721.284	.396	2.379	.024

a Dependent Variable: Ridership

Figure 12: Final Regression Model

Kuby's regression model was expected to not produce extremely useful results, however it was not expected that the degree of error would be as high as produced. Kuby's model required a measure of data to be within a walk-able buffer along the road network as opposed to a Euclidian buffer, so the data was adjusted in all cases to reflect this. However, out of the 36 stations, the station that produced the least error between the model's estimation and the actual ridership was the Pepsi Center station at 13%. The 10th and Osage and 18th and California stations contained percent errors that were over 100% and in most cases, the measured ridership was well below the actual ridership. Therefore it was evident that the model needed to be adjusted to better reflect the questions mentioned in the literature review section about Kuby's analysis regarding non-significant values like college enrollments as well as the lack of taking into consideration of the built environment.

The final produced model is shown in Figure 12, which contained 7 variables and a constant. The variables put into the model are mentioned in the methodology section, which resulted in the exclusion of the percent renter, transfer, jobs, and median income variables. The remaining variables included the freeway, low density business park center typology, total population, bus routes, college enrollments, centrality, and transfer variables. The constant and bus route variables were the most significant at .001, while the college enrollment variable was least significant at .048, but still within the 95% confidence interval. The model itself was significant at <.001 with an F-test of 6.726, while the R, R2, and adjusted R2 values were at .792, .627, and .534 respectively. The final equation for the regression model is as follows:

$$Y_r = 12382.081 + 3824.524 * X_f - 4125.542 * X_3 - 2.893 * X_p + 615.326 * X_b + .107 * X_e - 10946.834 * X_c + 4095.568 * X_t \qquad (1)$$

Where:
Y_r = *Total Daily Boarding's at Station*
X_f = *Freeway Binary Variable*
X_3 = *Low Density Business Park Center Typology Binary Variable*
X_p = *Total Population within Station Euclidian Buffer*
X_b = *Total Number of Bus Route Connections at Station*
X_e = *Total Number of College Enrollments at Secondary Schools in Station Euclidian Buffer*
X_c = *Centrality Variable*
X_t = *Terminal Station Binary Variable*

The model can be interpreted by variable to explain what deters and encourages ridership. 12382 riders is a balance point which is ridership that is not easily explained by factors. 0 values from all independent variables used in this analysis would project 12382 riders based on factors other than described by what was used in this analysis. The presence of a freeway generates 3825 riders on average at each station based on the theories of congestion relief. A station whose built environment can be described as a low density business park would lose 4126 riders on average possibly explained by issues such as poor walk-ability or accessibility to parking provided by local businesses. For every 10 people that live in the corridor, the station loses 29 riders, possibly because these riders are accounted for in other variables including the constant variable, but this cannot be proven. For every bus that connects to a transit station an extra 615 riders are produced based on the improved regional connectivity the station provides. 11% of all college students are expected to use transit to any university within walking distance of a transit stop. The station that is farthest away from the system being Lincoln loses 10,947 riders because of its poor proximity to the CBD resulting in poor travel time. Any terminal station however will gain back on average 4097 riders because it's the most accessible station for those farthest out, where park and ride garages can attract many commuters and city visitors.

The appendix includes a section that compares the actual ridership measured by RTD to the measured ridership by Kuby's model as well as the updated model, as well as percent errors. It is evident that this model did a more sufficient job in accurately predicting station ridership data. The main issues with the new model are that a high constant value is rendered useless because it does explain significant amounts of ridership for certain stations. While it behaves as a balance point for the model, it can be misleading in the conclusions that it draws about the factors that encourage ridership on LRT.

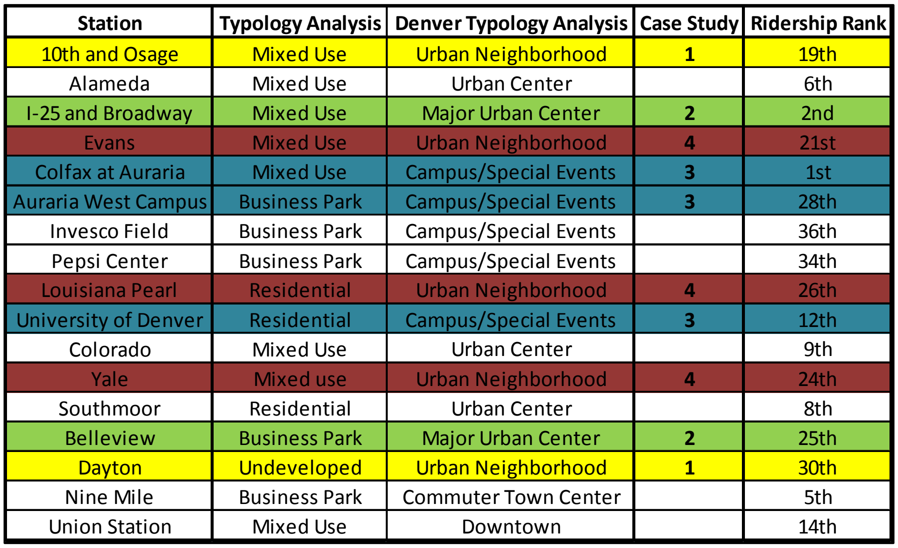
Discussion of Results

The typology analysis found that from a built environment perspective, there are 3 main categories of built environments and 1 station that can be classified as other that does not fit into any typology category. Mixed Use Urban Centers is a typology that can classify nearly half of the stations on the system (17 of 36). These areas were typically found in the CBD, however the Colorado and Yale stations which are freeway stations fit into this category as well. Other communities worth mentioning are Alameda and Englewood, which are not freeway stations but do produce walk-able corridors.

Group 2 consisted of 7 stations that were categorized to be High Density residential centers, which might be why ridership was not found to be significant in this analysis, however this cannot be proven. 16th and Stout had the second highest ridership of the system in the CBD however the Louisiana Pearl station was also in this category as 1 of 3 freeway stations who has experienced ridership levels near the bottom of the system ranks. Littleton-Downtown was also in this category which can be described as a walk-able urban center with a University as well as many shops. 30th and Downing is a terminal station but exists in a densely gridded street network that is still pedestrian friendly and does not have a lot of parking.

Groups 3 and 4 are the most important to look at as 8 of the 13 freeway stations on the southeast corridor make up the 12 stations that fit into these categories. Group 4 as mentioned was the Dayton station, however it is believed that statistically building density was so extreme compared to rest of the stations that it could not be coded into any of the typologies. Yet when comparing Dayton's station characteristics to group 3 stations, it fits in well excluding business density, by having large levels of vacant/open space, and low levels of Intersection Density and Link to Node Ratios, along with being a poor proximity to the system center. Group 3 stations were characterized as Low Density Business Park Centers. Most of these stations contain mainly commercial features, as it is believed that wealthy residents who live outside the city may not want to live near the highway due to air and noise pollution. While it's not conclusive to refer to these places as Suburban, they support many of the characterizations of suburban life. Evidence to suggest this include low density residential land use in the form of single family homes, low ID and L2N to provide curvilinear street networks, and having higher centrality on the system which is evident of it being far away from the CBD. These are features of the built environment that have been suggestive to not support pedestrian friendly areas that encourage the best transit ridership, as they deter from Dittmar's TOD principles.

It was mentioned earlier that a motivation behind a typology analysis was to analyze the accuracy of the Denver Strategic Manual to assess how future typologies compare with the existing corridors. Figure 13 shows some of the stations and compares our results with the manuals characterizations of the existing stations. To draw some conclusions from the typology analysis, several case study comparisons will be made.



Station	Typology Analysis	Denver Typology Analysis	Case Study	Ridership Rank
10th and Osage	Mixed Use	Urban Neighborhood	1	19th
Alameda	Mixed Use	Urban Center		6th
I-25 and Broadway	Mixed Use	Major Urban Center	2	2nd
Evans	Mixed Use	Urban Neighborhood	4	21st
Colfax at Auraria	Mixed Use	Campus/Special Events	3	1st
Auraria West Campus	Business Park	Campus/Special Events	3	28th
Invesco Field	Business Park	Campus/Special Events		36th
Pepsi Center	Business Park	Campus/Special Events		34th
Louisiana Pearl	Residential	Urban Neighborhood	4	26th
University of Denver	Residential	Campus/Special Events	3	12th
Colorado	Mixed Use	Urban Center		9th
Yale	Mixed use	Urban Neighborhood	4	24th
Southmoor	Residential	Urban Center		8th
Belleview	Business Park	Major Urban Center	2	25th
Dayton	Undeveloped	Urban Neighborhood	1	30th
Nine Mile	Business Park	Commuter Town Center		5th
Union Station	Mixed Use	Downtown		14th

Figure 13: Typology Comparisons between Analysis and Denver Strategic Manual. Case Studies are highlighted.

Case Study 1: *10th and Osage vs. Dayton Stations*

Both these stations were categorized to have future typologies reflective of Urban Neighborhoods, having a desired land use mix of multifamily townhome and small lot single family residential with neighborhood retail not in excess of 50,000 square feet. These stations were designated to contain building densities of 2 to 7 stories with a walk up station that has very low park and ride. The 2011 ridership trends showed that both stations were in the bottom of ridership ranks however 10th and Osage which is just outside the CBD ranks 19th while Dayton is ranked 30th. Our results found that 10th and Osage behaved like a mixed use station while Dayton was too undeveloped despite having an extremely high business density. From a pedestrian perspective, Dayton had an intersection density of 33 and a link to node ratio of 1.19 which are well below Garrick's standards for pedestrian friendliness, while 10th and Osage had an intersection density and link to node ratio of 1.06 and 1.52 respectively. The poor proximity Dayton has to the station along with the street network is a reflection of the unique differences in the built environment that place Dayton in a far different typology than 10th and Osage, which leaves little expectation that Dayton can transition similarly to 10th and Osage.

Case Study 2: ***Belleview and I-25 Broadway Stations***

The strategic plan manual believed these stations can transition into Major Urban Centers, providing a complete mix of office, retail, entertainment, and multi-family and townhome residential. There is a large emphasis on employment with more than 250,000 square

Figure 14: Comparitive Aerial Views between I-25 and Belleview Stations

feet in office and 50,000 square feet in retail with at least 5 story developments. These stations however were projected to be designed as feeder stations with circulator transit and express feeder bus systems as well as some park and ride.

The typology analysis found that regardless of the freeway, the I-25 Broadway station typology could be classified as mixed use with a good mix of dense land uses. The ridership at the station ranks 2nd on the system partially because it has over 1200 parking spots, compared to the Belleview Station. The Belleview station ranks 25th and like Dayton has a poor proximity to the CBD. The station only has 59 park and ride spots as well as much vacant land even though there exists many nice apartments and the technology business park. The relationship between these stations is embedded in the street network versus park and ride spots. Both these stations despite good levels of activity and housing have low levels of Intersection Density even though they both have a Link to Node Ratio of around 1.5 that can suggest the area is pedestrian friendly. However it is found that when it comes to stations like these ones, the amount of park and ride is proportional to ridership when the street network characteristics are considered subpar for pedestrian activity.

Case Study 3: *Colfax at Auraria, Auraria at West Campus, and University of Denver*

The Denver Strategic Manual produced a set of typologies strictly on function of the station corridor, which is suggestive in this case study, when 3 stations next to Education centers were placed in the same typology regardless of the built environment. While considering this to be a TOD typology, it was described as areas that have limited residential, office, and retail, varied scale, and a function of being a large commuter destination with large parking lots, not necessarily for transit. These stations were placed in the same category as Invesco Field and

Pepsi Center, which are stations only used for events and thus have the lowest ridership ranks on the system.

The ridership counts of all 3 stations are at all spectrums of the ridership rank. Colfax at Auraria ranks 1st on the system, mainly because it's an education center, however this is not the only reason, as Auraria at West Campus is next to the education center as well and yet ranks 28th. The major difference between these stations is that the street network in both corridors are completely different in addition to the measured building densities and land use mixes, all important identifiers of TOD effectiveness. Figure 15 shows that when quantitatively comparing some of these measures, Colfax at Auraria illustrates a better pedestrian friendly network which is why it captures a better ridership threshold.

Category	**Auraria at West Campus**	**Colfax at Auraria**	**University of Denver**
Vacant/Open Space	8.6%	3.0%	0.9%
Residential	0%	22.4%	37.8%
Commercial	31.1%	15.4%	4.9%
Residential Density	0 people/mi^2	11073 people/mi^2	8703 people/mi^2
Business Density	9009 jobs/mi^2	30810 jobs/mi^2	14095 jobs/mi^2
Intersection Density	47 Intersects/mi^2	143 Intersects/mi^2	108 Intersects/mi^2
Link to Node Ratio	1.29	1.46	1.54
Park and Ride Spots	0	0	540
Freeway (Y/N)	No	No	Yes
Ridership Rank	28th	1st	12th

Figure 15: Campus Special Events stations from Denver Strategic Manual.

The University of Denver is also a station with an education center, and despite having good levels of walk-ability and mixes in dense land use, the station only ranks 12th compared with Colfax. Again this is tribute to the fact that while education does capture a significant portion of riders, it is not the only relevant feature in these environments. A case can be made that the freeway does impede ridership at University of Denver by providing competition in travel times and cost however there is no gathered evidence to support this claim.

Case Study 4: *Evans, Louisiana Pearl, Yale*

It was determined that the Denver Strategic Manual was able to match some stations properly in comparison with the typology results from this analysis. Urban Neighborhoods which were described in case study 1 also consisted of the Evans, Louisiana Pearl, and Yale Stations, which like 10th and Osage were found to be in the Mixed Land Use typology results with Louisiana Pearl being placed in the Residential Center Typology which is not far off from group 1. While these neighborhoods were described as typologies with a good use of mixes and low amounts of park and ride spots, the results show that they all have low levels of ridership.

Figure 16: Louisiana Pearl provides a pedestrian friendly network, yet low ridership levels.

Figure 15 shows that while stations produce a strong gridded network with a good use of mixes, the relationship between density and freeway exists in this group as well. Even though Evans station does not have a freeway through its corridor the lack of density suggests that it cannot attract high levels of ridership. This still supports that freeways do impede ridership, as it ranks 21st, while Louisiana Pearl and Yale rank 26th and 24th respectively.

Category	**Evans**	**Yale**	**Louisiana Pearl**
Vacant/Open Space	6.0%	1.0%	1.9%
Residential	27.3%	61.0%	46.8%
Commercial	27.0%	1.0%	3.5%
Residential Density	6460 people/mi^2	4540 people/mi^2	8131 people/mi^2
Business Density	17244 jobs/mi^2	96197 jobs/mi^2	40206 jobs/mi^2
Intersection Density	126 Intersects/mi^2	115 Intersects/mi^2	146 Intersects/mi^2
Link to Node Ratio	1.67	1.35	1.72
Park and Ride Spots	99	129	0
Freeway (Y/N)	No	Yes	Yes
Ridership Rank	21st	24th	26th

Figure 17: Case Study 4 Comparisons

The relationship between freeway and the built environment is evident between Yale and Evans which were both considered to be mixed use centers. However the presence of freeways provides a much lower Link to Node Ratio and a low amount of Commercial Land Use even though it has a much higher Business Density. Alternatively, Yale and Louisiana Pearl are both Freeway stations, and even though Louisiana Pearl has better land use mixes, building densities, and pedestrian friendly environments, the lack of any park and ride spots leaves it at a lower ridership level than Yale.

The typology analysis did not find ridership levels to be significant amongst the groups, yet when dissected at a station by station comparison, there was evidence to support that the freeway has strongly impacted the existing built environments and the ridership levels that go with it. It was not evident to what extent the freeway impacted ridership, and the non-significance of ridership levels amongst the 4 groups only leaves it as a coincidence that the freeway and built environments affect ridership. The regression analysis was used in this case to quantify these effects and determine if ridership levels were impacted directly by these physical features, or if other station characteristics could explain ridership more accurately.

The final model found 7 factors that explained ridership; (Freeway, Low Density Business Park Center Typology Variable, Total Population, Bus Connections, College Enrollments, Centrality, and Terminal Station) Overall what this suggested is that the existence of the freeway contributes to ridership, yet in stations where the built environment was classified as a low density business park center, there was a negative ridership. As a result it was found that 7 of the 13 freeway stations fit into this description.

Because of the 6 of the 13 freeway stations do not fit into the group 3 typology, it is inconclusive as to whether freeways always produce a built environment that is conducive to lower ridership levels or even more so lower levels of pedestrian ridership. Louisiana Pearl is an example of a station that was found to be near a highway but at the same time produces a pedestrian friendly environment with good levels of mixed land use and a walk-able street network. The model shows in this case that building near freeways produce higher ridership levels possibly because it provides congestion relief, cheaper service when gas prices rise, and contain free advertisement for users. Identifying if these reasons are valid should be looked into for future studies.

More importantly, the built environments are important to consider when evaluating TOD in studies. The regression model does not comment on how all typologies impact ridership, but did show that auto-oriented corridors that go against Dittmar's TOD characteristics will deter ridership. As much as building near a freeway can produce ridership because of congestion and gas prices, the lack of a pedestrian friendly network may never attract permanent riders that would walk to the system. These low density centers that existed along freeway stations all contained park and ride spots that are for attracting users farthest from station as a catchment to generating more ridership. The auto-oriented environment deters the constructions of dense residential and commercial facilities that are pedestrian friendly in the station corridor and thus can't produce walk and ride transit users. Without good pedestrian facilities, the capacity of ridership at these stations is only as good as the number of park and ride spots it provides.

What can be said overall about ridership on the Denver system is that these park and ride stations may never transition into the urban neighborhoods that the Strategic manual predicted because of this conflict between auto and pedestrian in the built environment. Stations like Belleview, Lincoln, and County Line, will continue to behave as feeder stations because the built environment is non-TOD compatible with high volume roads and a non-pedestrian network design that would be too costly and timely to convert. These are examples of Transit Adjacent Development mentioned earlier, which provides a station corridor that does not connect land use and transportation in a way that promotes the best ridership, nor a pedestrian friendly built environment. Further studies however need to better identify this relationship by being able to separate walk and ride versus park and ride users in ridership counts.

The accuracy of these results can only be clarified by paying close attention to the transition of these built environments and their ridership levels over time. The TOD vision was designed for 2030 in the strategic manual, and therefore a study should be done in 2020 to compare with the findings in this report. It is the author's intent that this methodology can be used on other cities in the U.S. or internationally that have developed near Freeways to further identify if the relationships between the Freeway and Built Environment is significant and if it impacts ridership in a negative way.

Overall the results provided a baseline analysis to provide further evidence that TOD is not an easily applied concept. As Cervero mentioned earlier, TOD cannot be easily overlaid onto an urban fabric, because it thrives only in an environment that provides dense, mixed land use that is in a pedestrian friendly network. Our results showed that some of these non-TOD compatible areas are locations that are the furthest away from downtown, which in practicum has turned LRT into a commuter system rather than an urban redevelopment tool. Numerous cities have traditionally suggested better transit coverage could overall improve transit ridership in a corridor which while it has to an extent, it cannot fully transform into a pedestrian friendly network. The built environments in some areas are not conducive to the TOD concept, and should not be labeled as such to suggest that these systems will promote places that can eliminate auto usage.

Our evidence supports that transit will be used only if it's accessible, which in freeway corridors is for the most part by only automobiles. Light Rail was designed to be an urban concept and must remain in an urban environment that reflects Dittmar's concepts properly, to more effectively reduce VMT and promote the highest ridership. It is in the hands of policy makers to understand these concepts to provide the best investments possible in American transportation.

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APPENDIX B

M.A. THESIS FOR PATRICK GALLAGHER

Master's Theses
University of Connecticut Graduate School

5-5-2012

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

Patrick James Gallagher

B.A., State University of New York, College at Geneseo, 2010

A Thesis
Submitted in Partial Fulfillment of the
Requirements for the Degree of
Master of the Arts
At the
University of Connecticut
2012

APPROVAL PAGE

Master of Arts Thesis

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

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2012

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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.

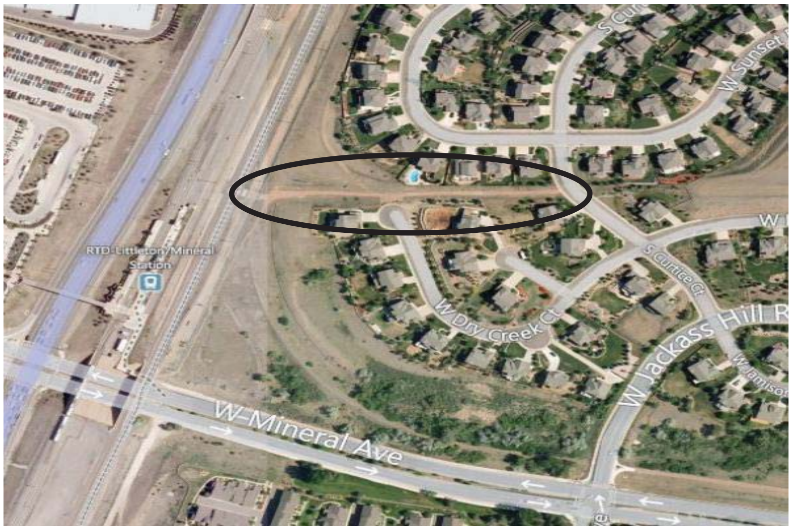
Several studies have introduced pedestrian level-of-service indexes for individual pedestrian links. Similar to road level-of-service indexes which focus on roadway characteristics, pedestrian indexes focus on characteristics of the pedestrian network. Pedestrian level-of-service analysis goes back to 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:

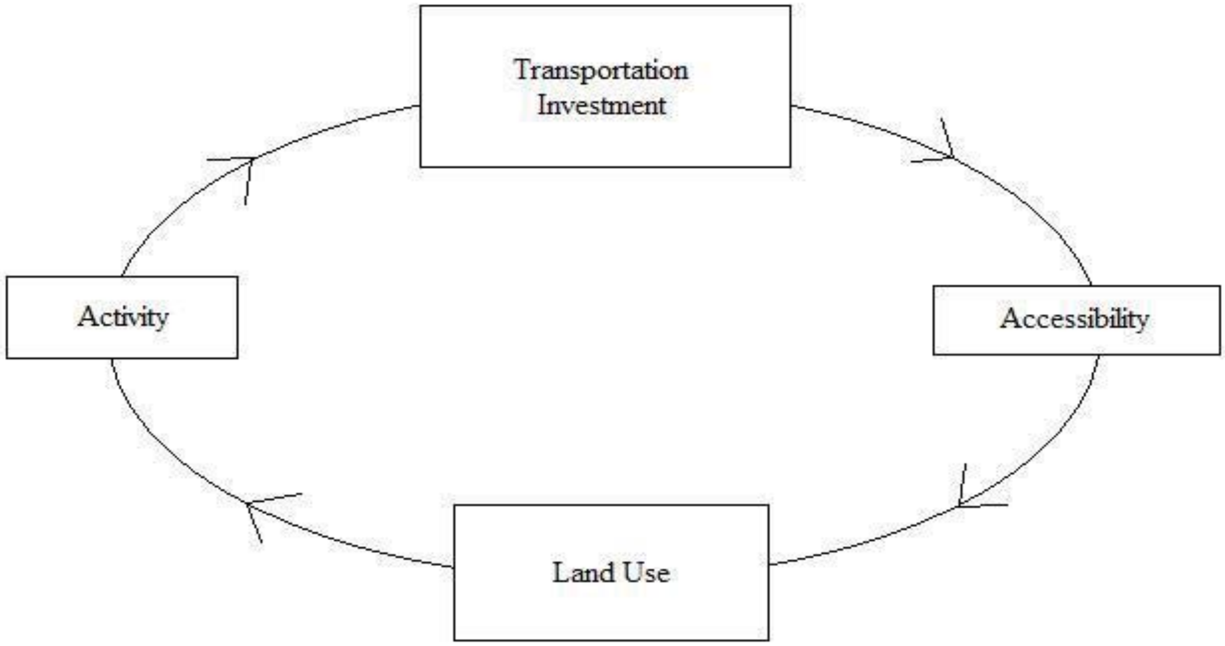
- Allows the basic access needs of individuals and societies to be met safely and in a manner consistent with human and ecosystem health, and with equity within and between generations.
- Is affordable, operates efficiently, offers choice of transport mode, and supports a vibrant economy.
- Limits emissions 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 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

Figure 3:1 The Transportation-Land Use Relationship

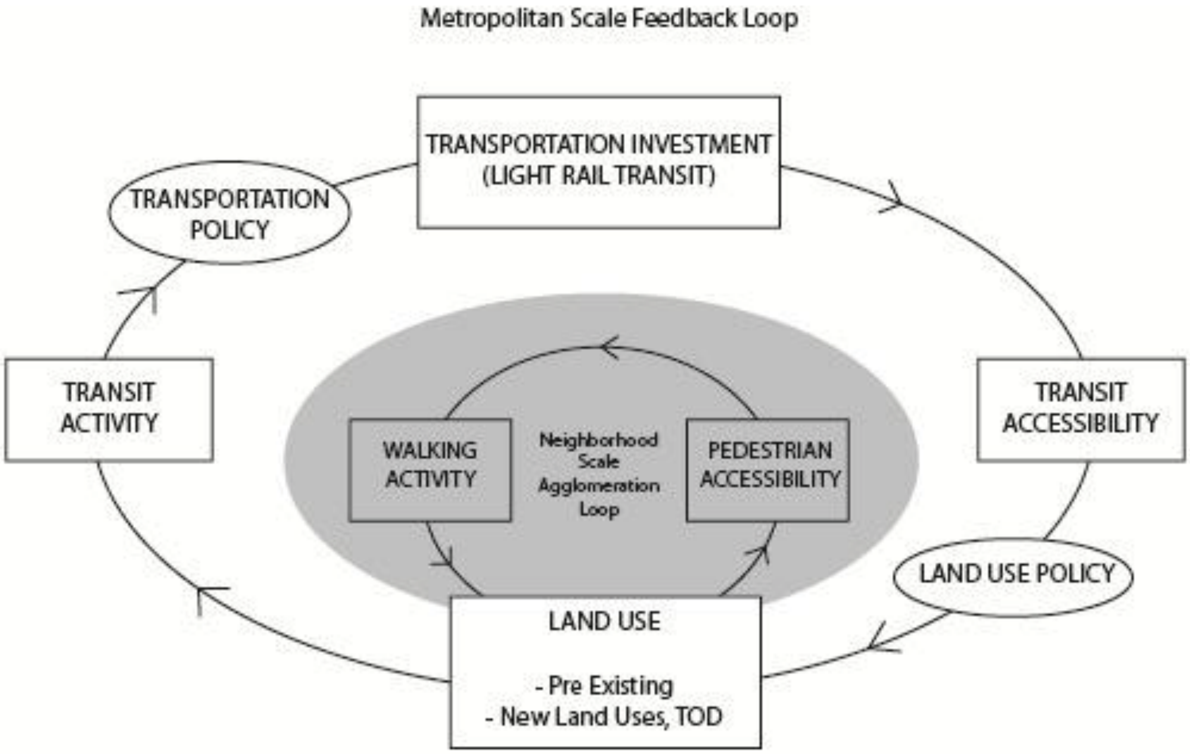


Source: Hanson and Giuliano (2004)

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

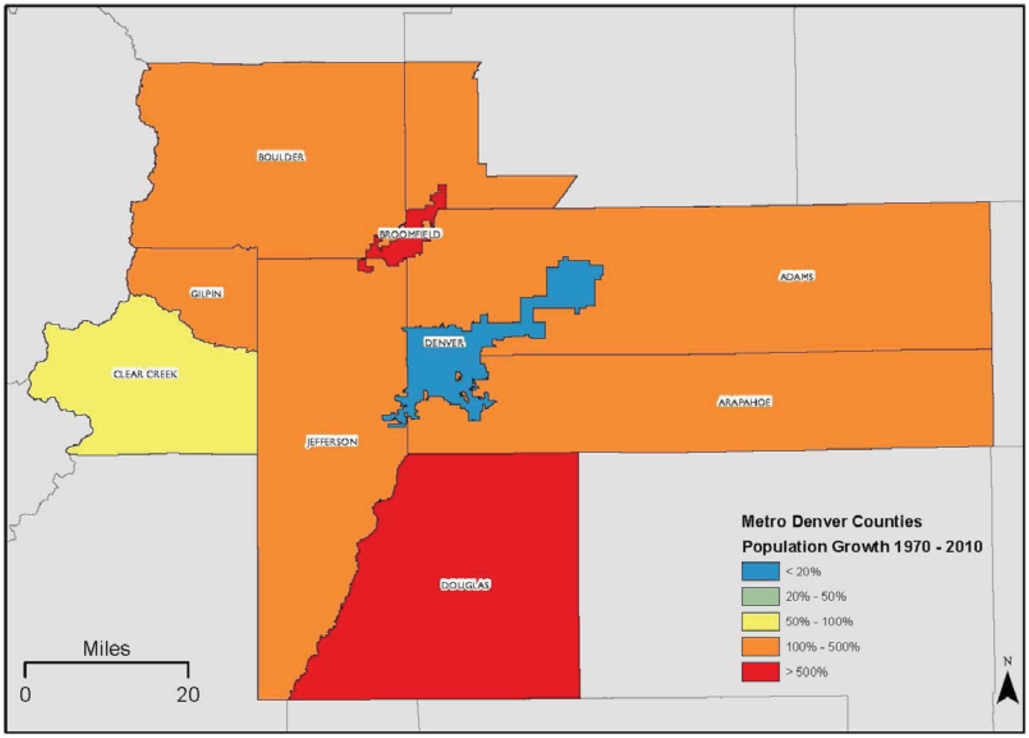
4.1 Introduction

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.



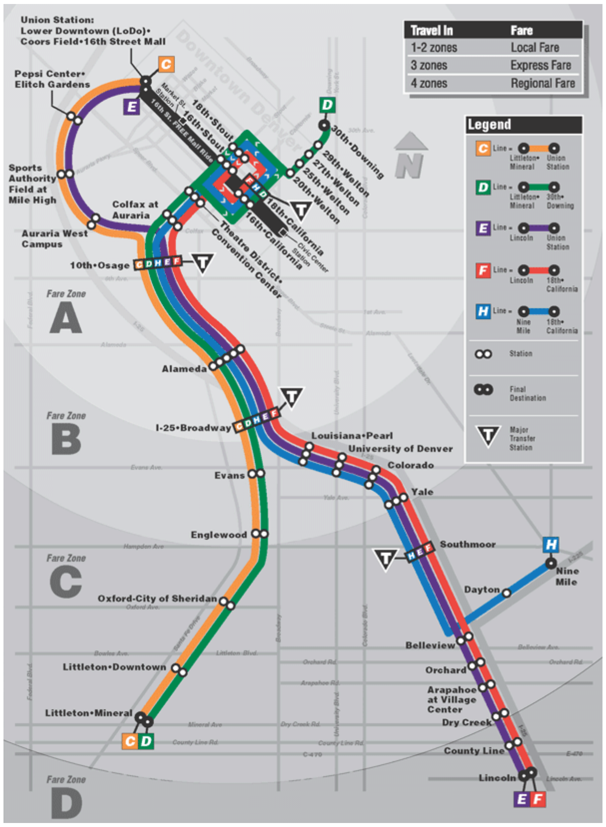
Source: US Census Bureau

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).

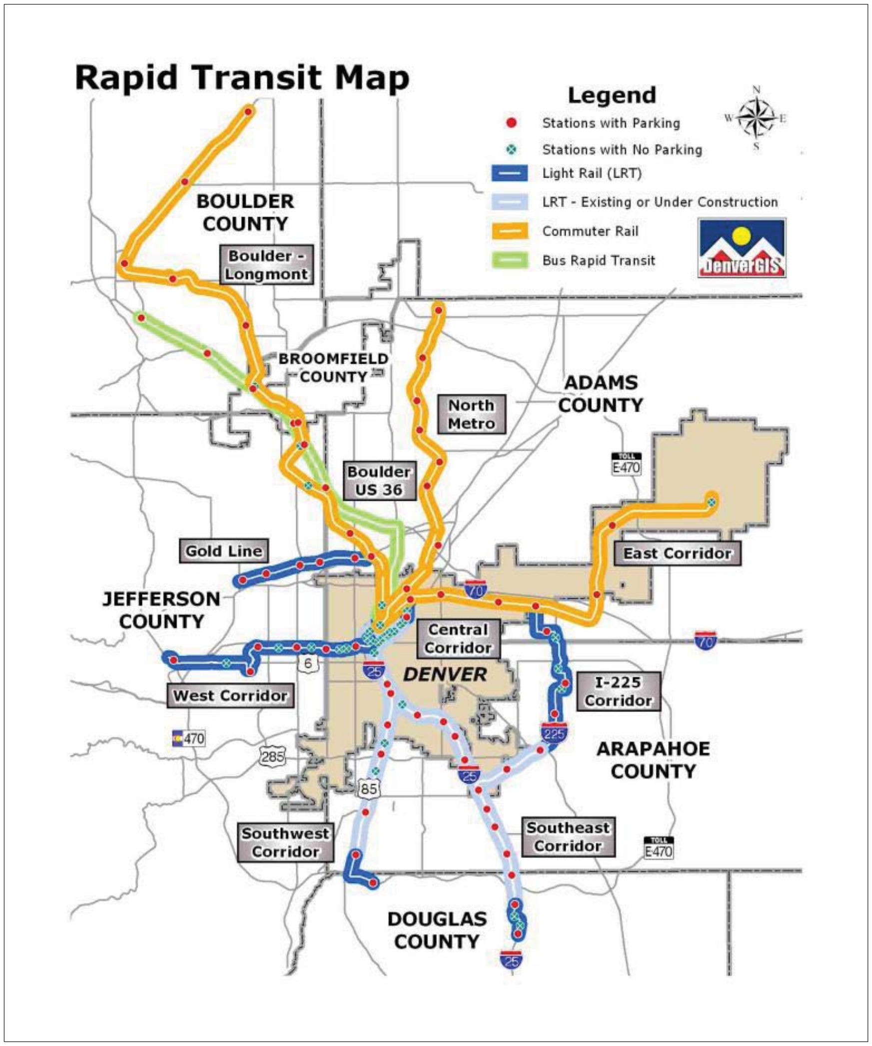
Figure 4:2 Current RTD Light Rail System



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

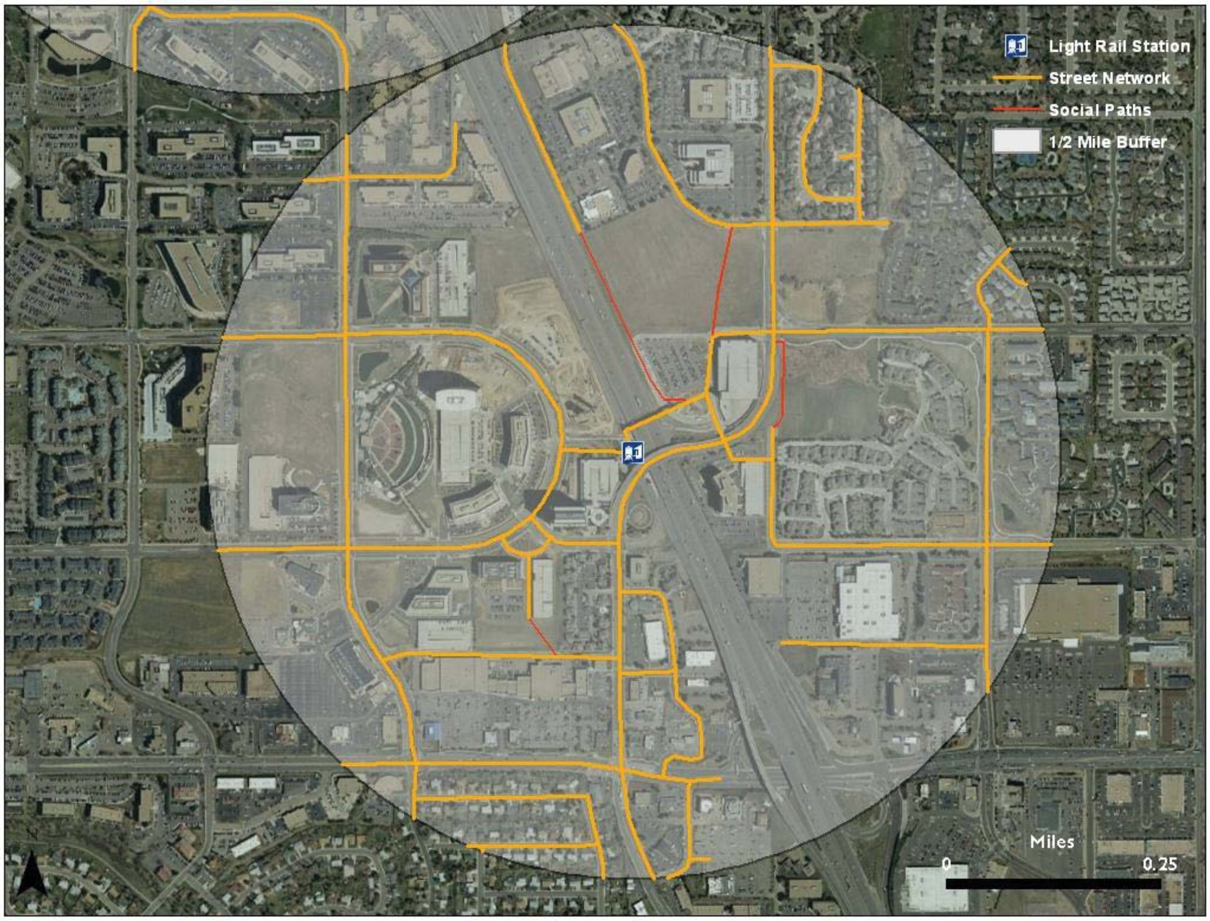
This thesis made use of a variety of geospatial data. Data could be broken up into two categories: (1) Network data, which were used to create transit service-areas; and (2) station area data which included of light rail stations, the density and diversity of land use, the number of station parking spaces 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, 16th Street and 18th 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

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

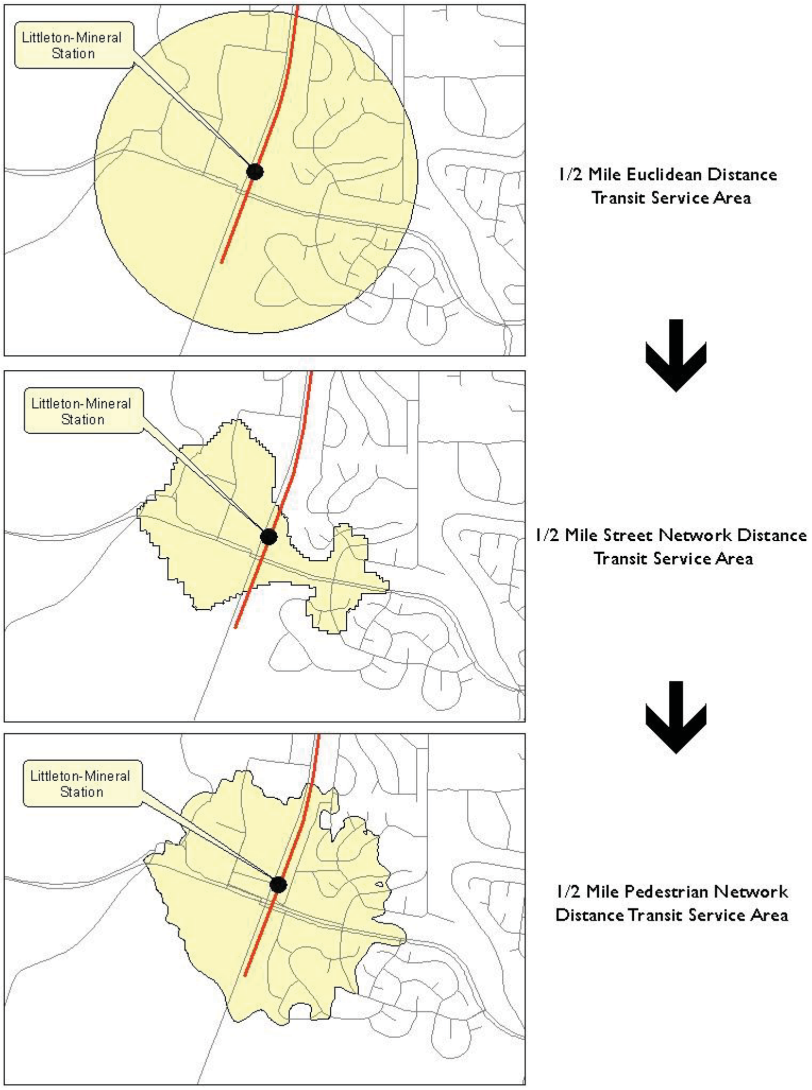
In equation 5:1, p represents the ratio of a particular land use while n represents the number of observations. For this analysis n = 4 and p was calculated for each of the four land use classes.

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

TRANSIT SERVICE-AREA CALCULATION

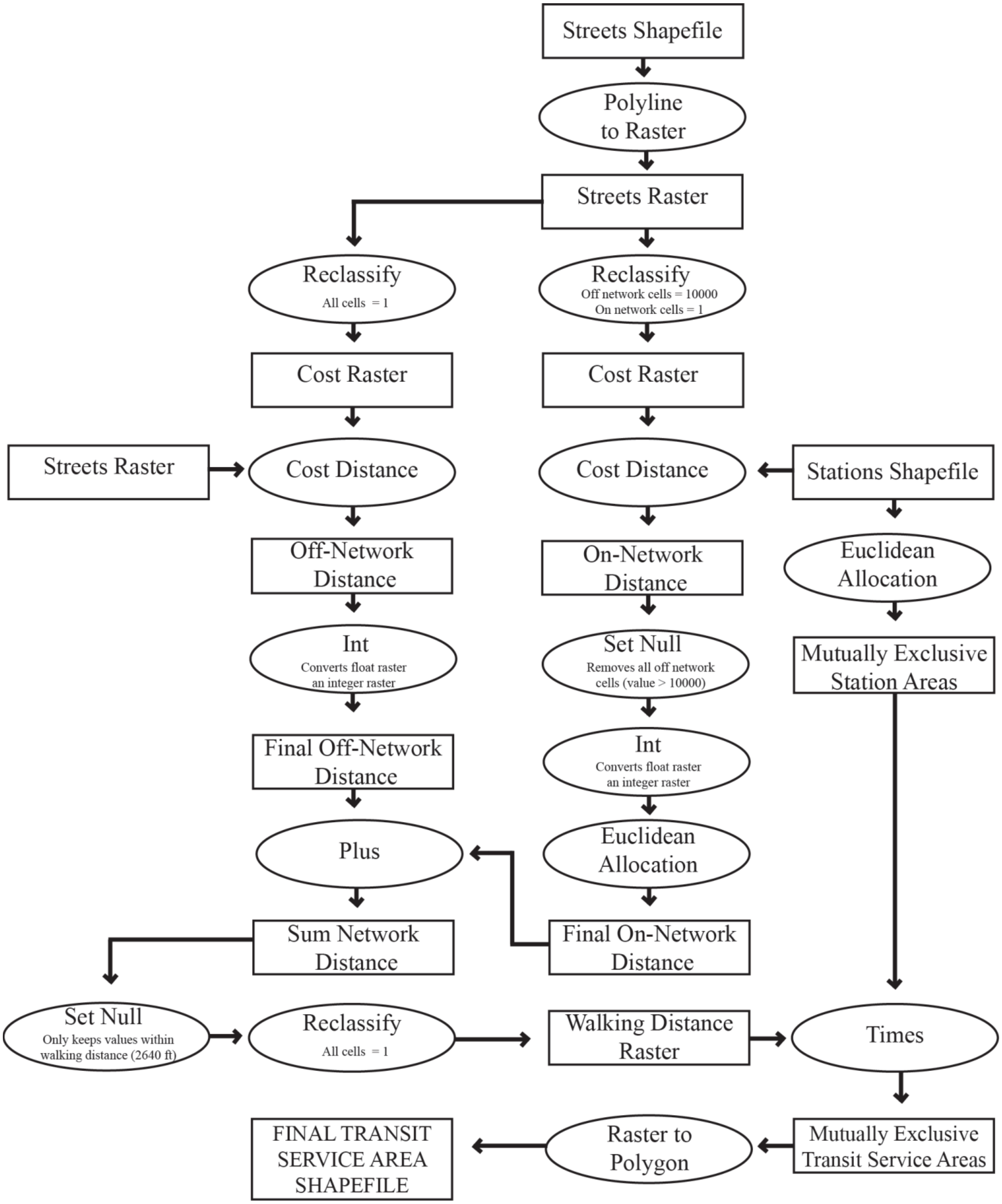
Transit service-areas were created using a python script in conjunction with ArcGIS 10. Python is a high level programming language that is incorporated into ArcGIS software. Python allowed GIS processes to be automated. This produced much faster results than manually performing operations. In addition 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.

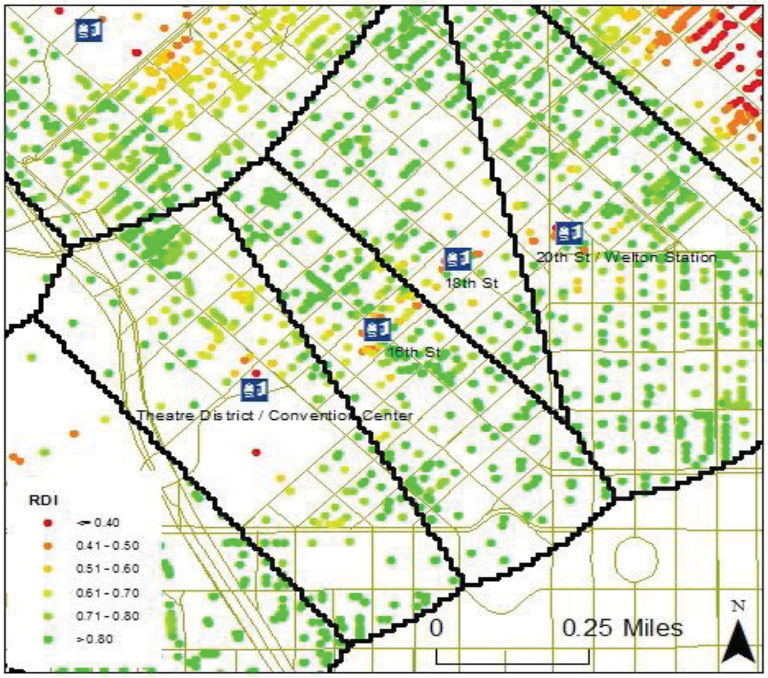
Equation 5:2 Pedestrian Catchment Ratio

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

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



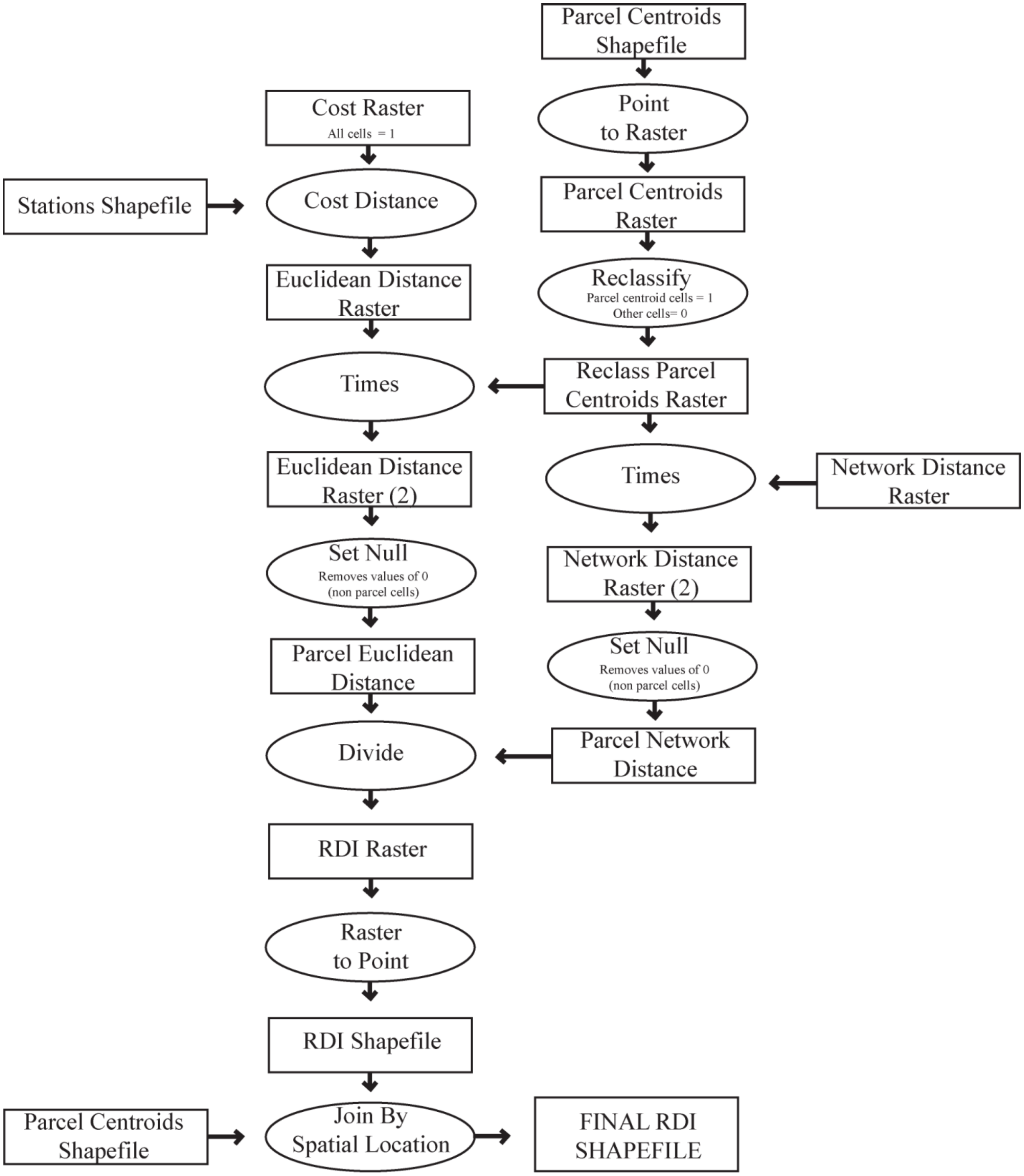
Only households within one half mile Euclidean distance of a transit stops were used. These households were examined using both the street network and the pedestrian network (street network, multi-use trails, bike paths and social paths). The equation for route directness index is shown below in Equation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

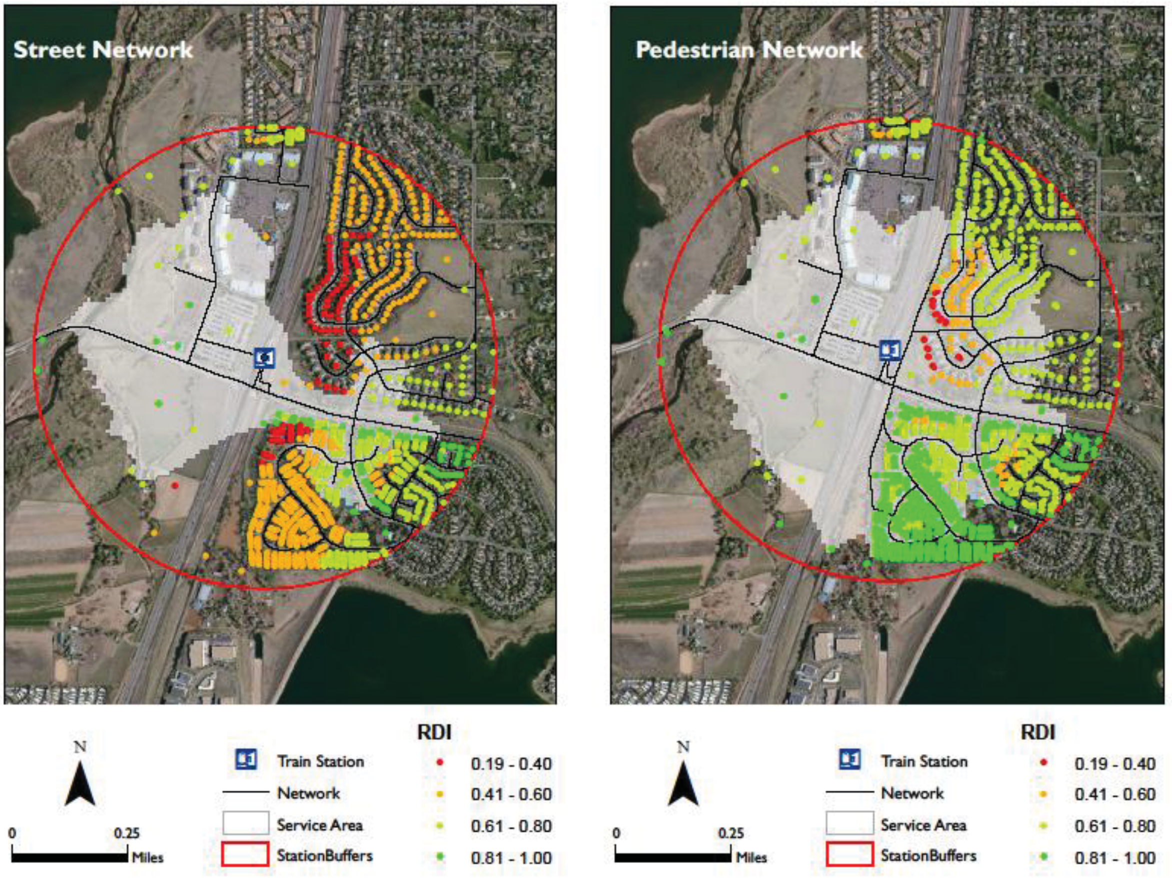
Table 6:1 Social Paths and Pedestrian Catchment (PC) Ratio

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 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

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

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 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

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

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 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

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

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, 16th Street, 18th 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.

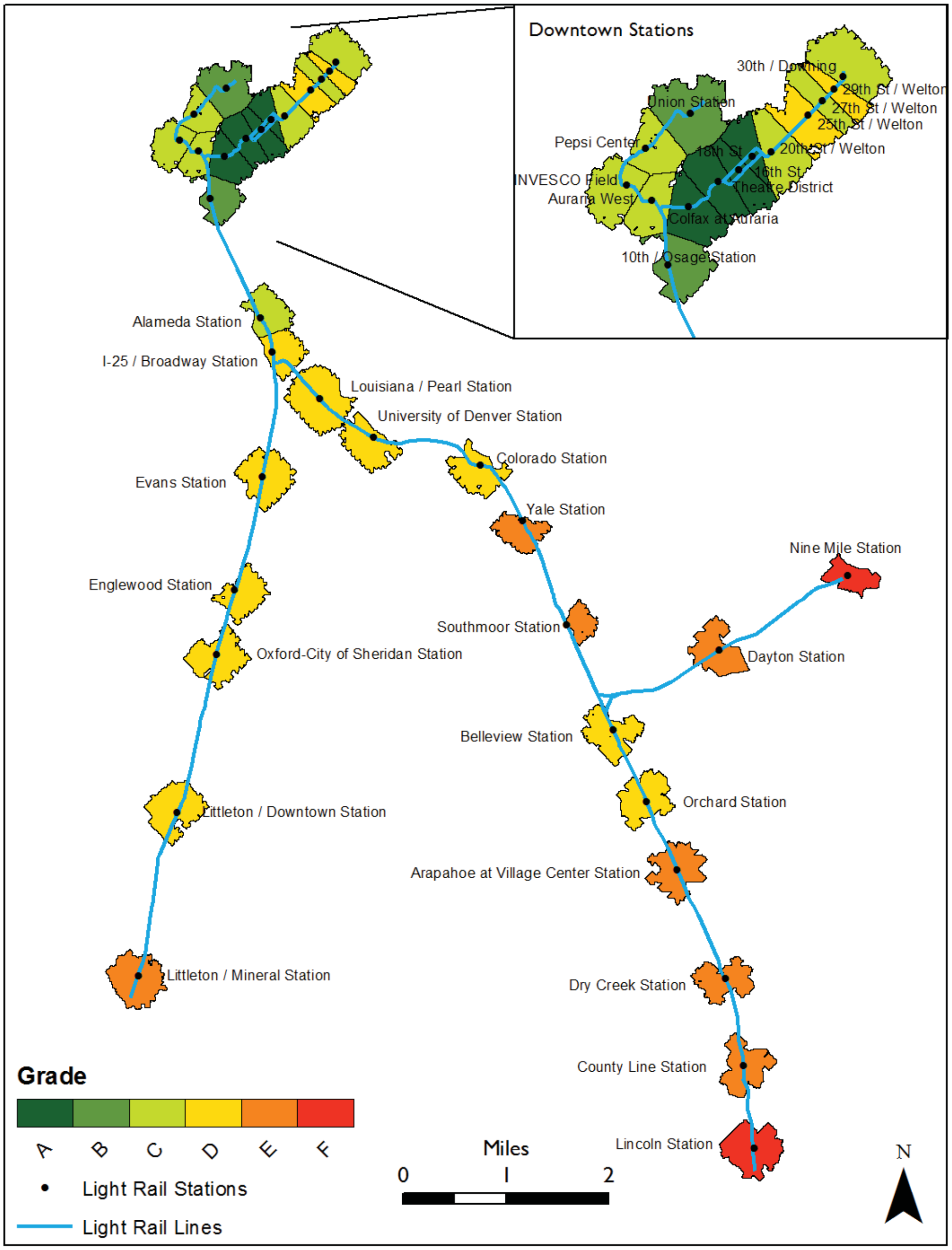
Seven stations received the second lowest grade of ‘E’ by scoring between 11 and 14 points. These stations were found to have inadequate pedestrian accessibility. All of these stations were located along limited access highways. Five were located along I-25, one along I-225 and one along Santa Fe Drive. 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.

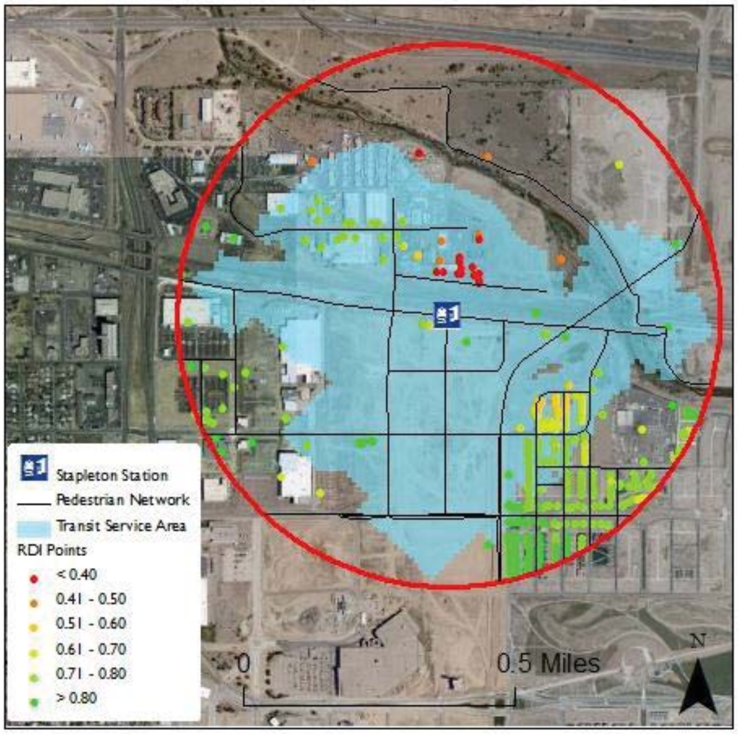
Overall, Stapleton station only scored 11 points resulting in a letter grade of ‘E’ corresponding to inadequate pedestrian accessibility. This is especially poor because of Stapleton’s commitment to new urbanist design. The final results for this analysis can be seen in

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

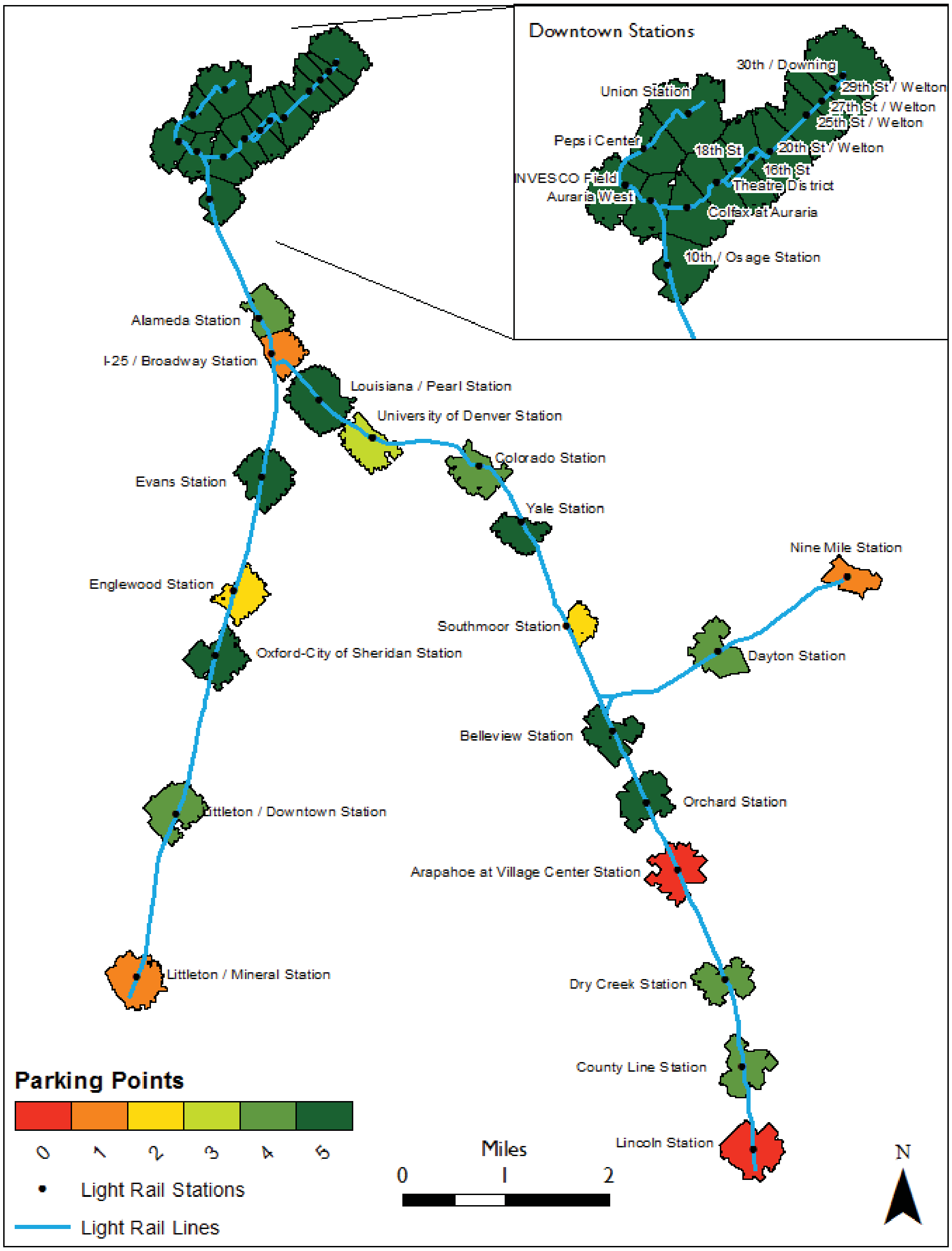


Figure A:2 Transit Connectivity Scoring

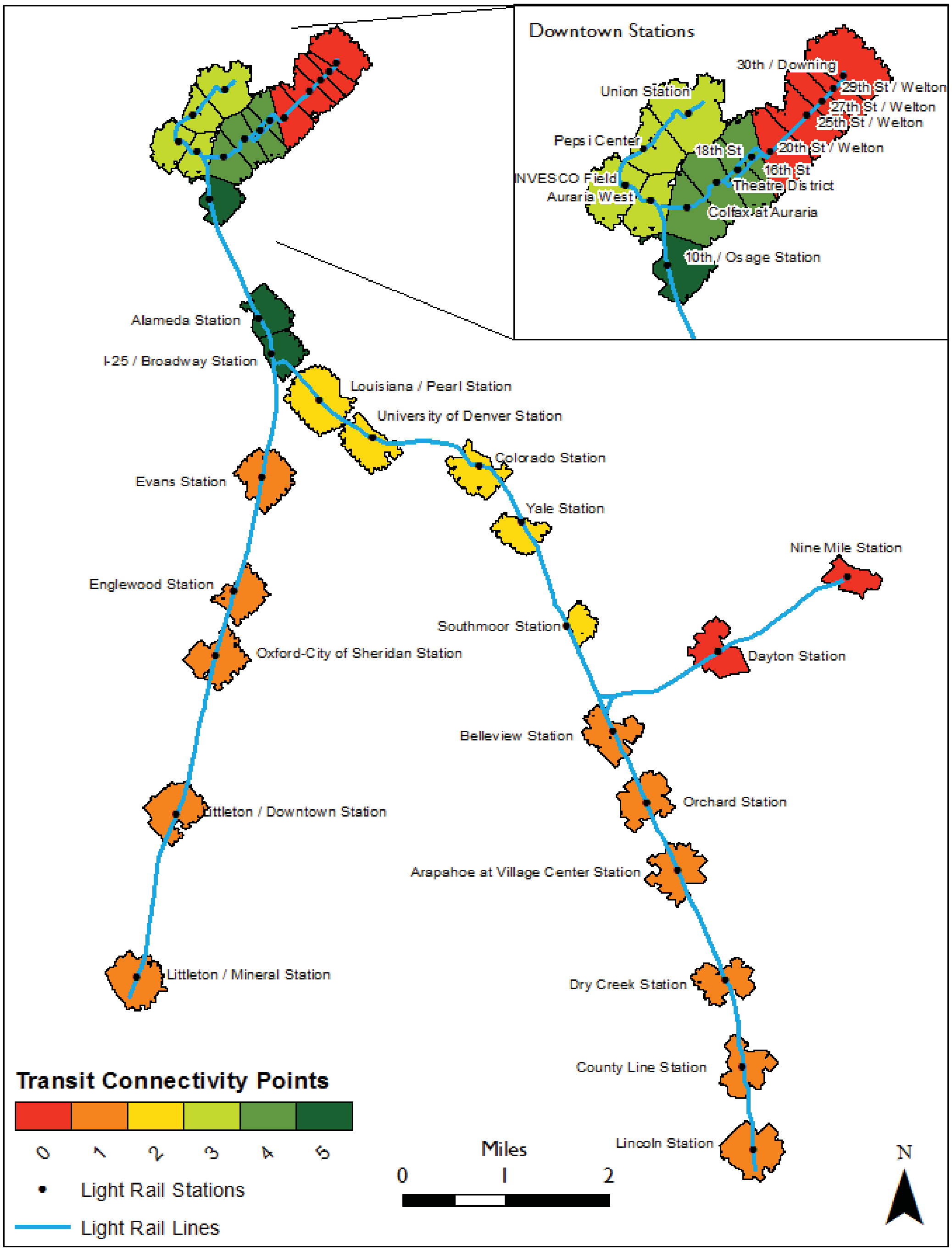


Figure A:3 Average RDI Scoring

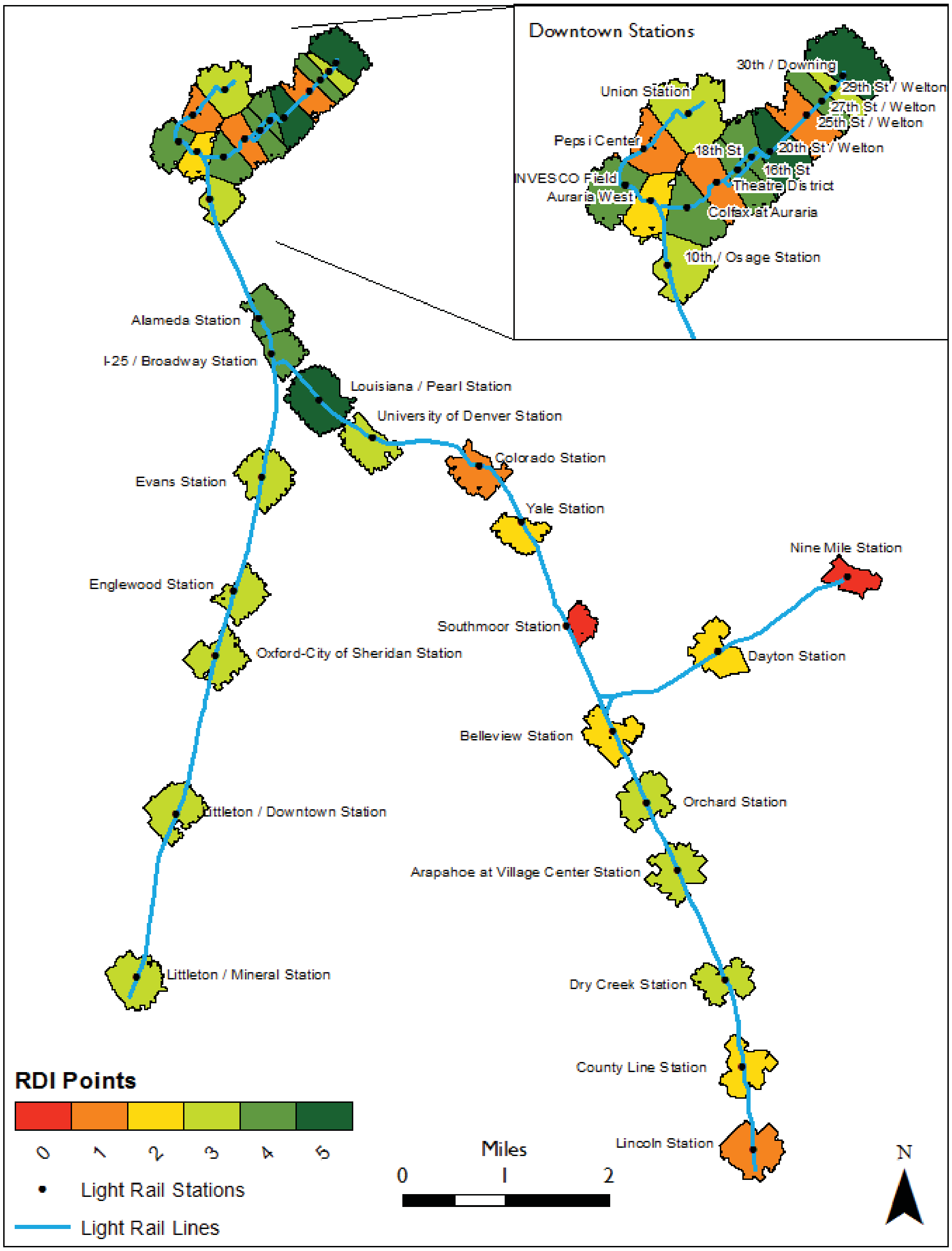


Figure A:4 PC Ratio Scoring

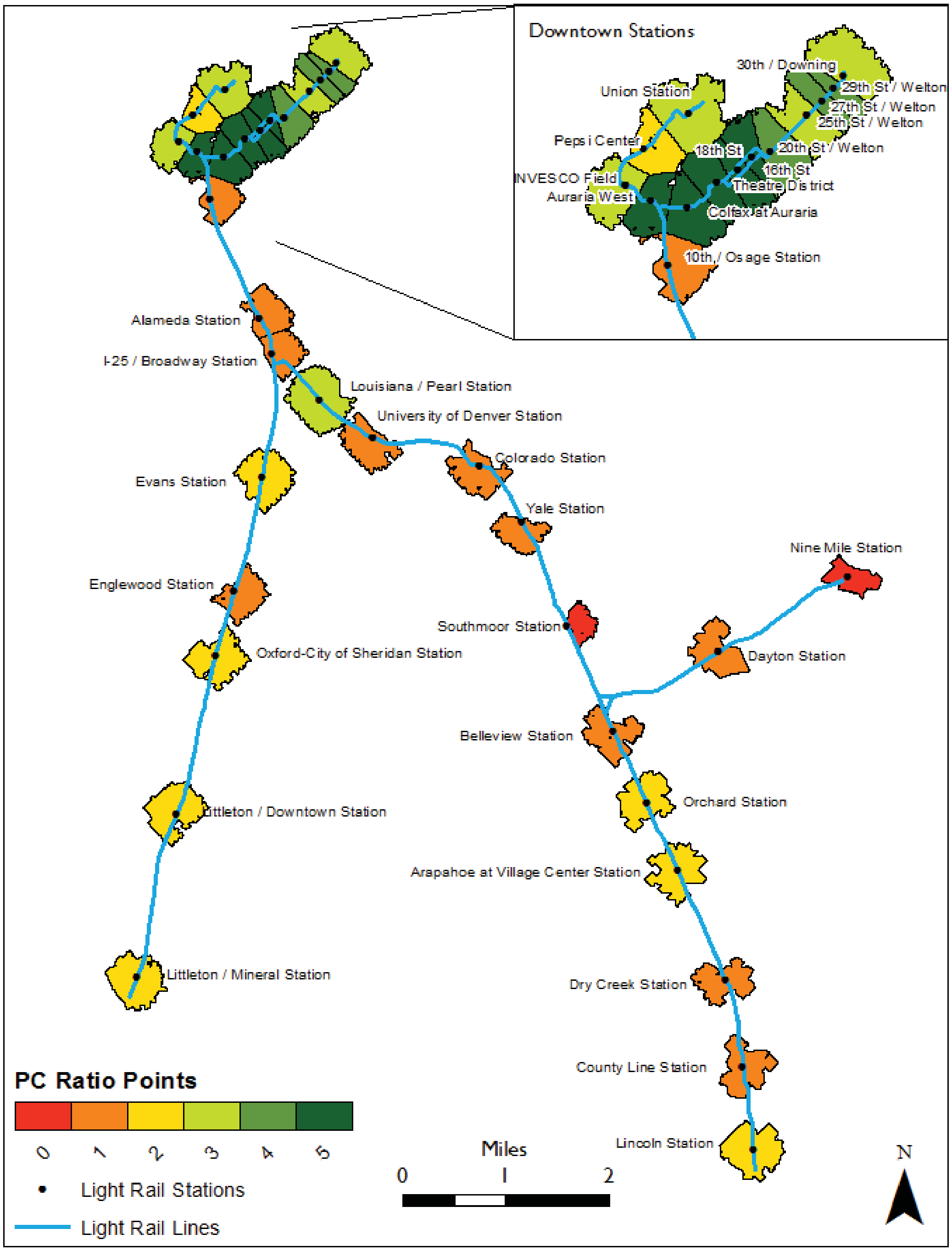


Figure A:5 Retail Density Scoring

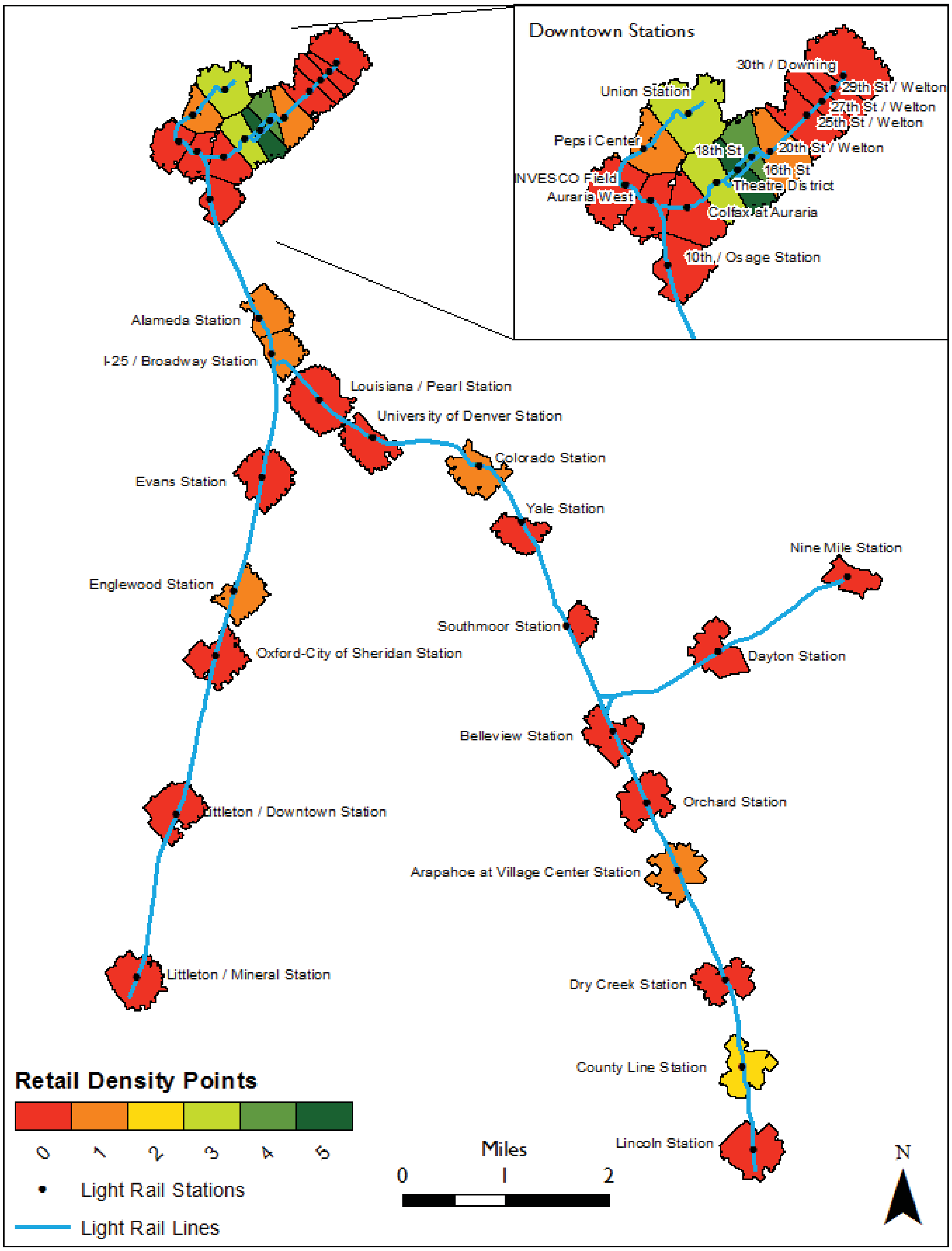


Figure A:6 Employment Density Scoring

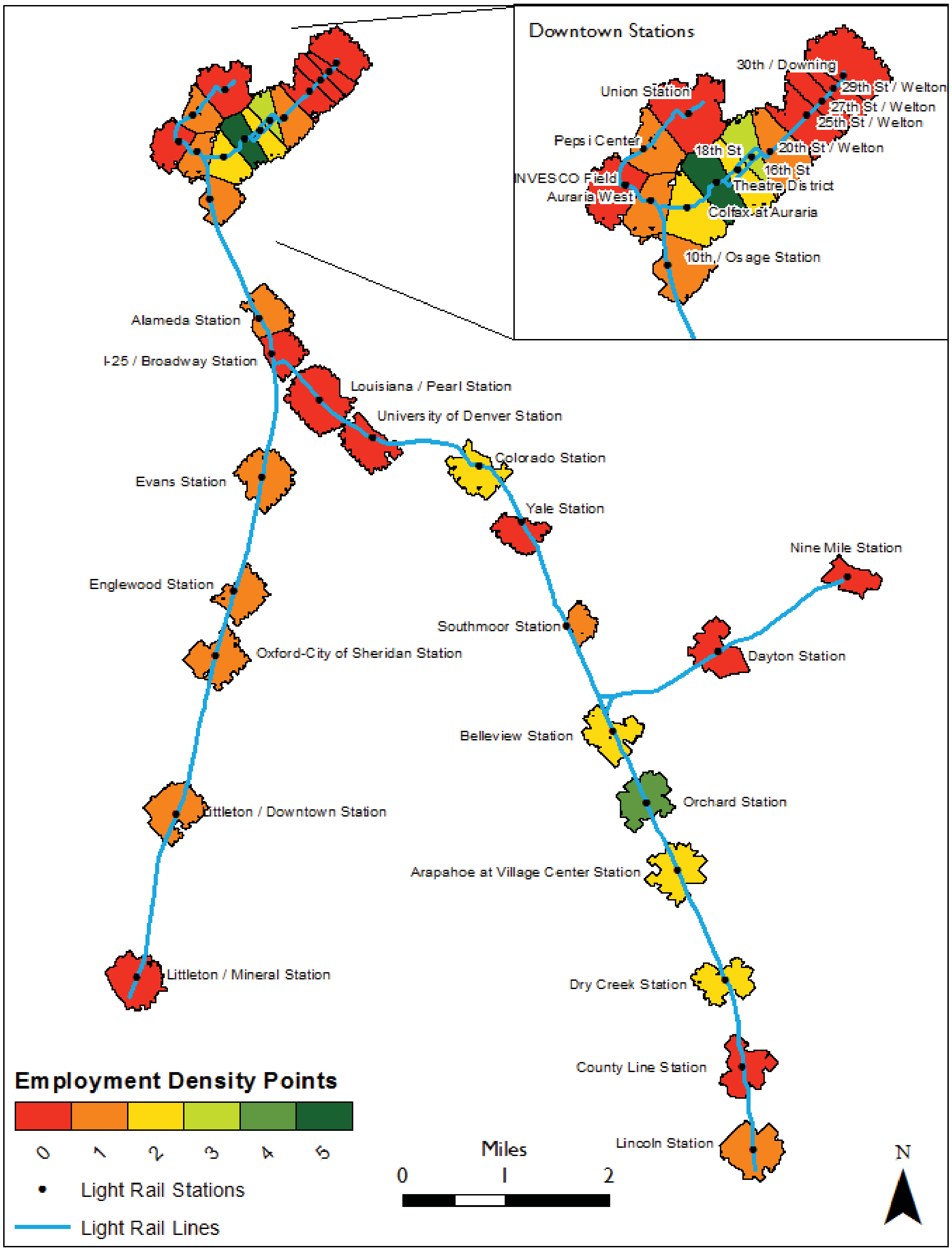


Figure A:7 Population Density Scoring

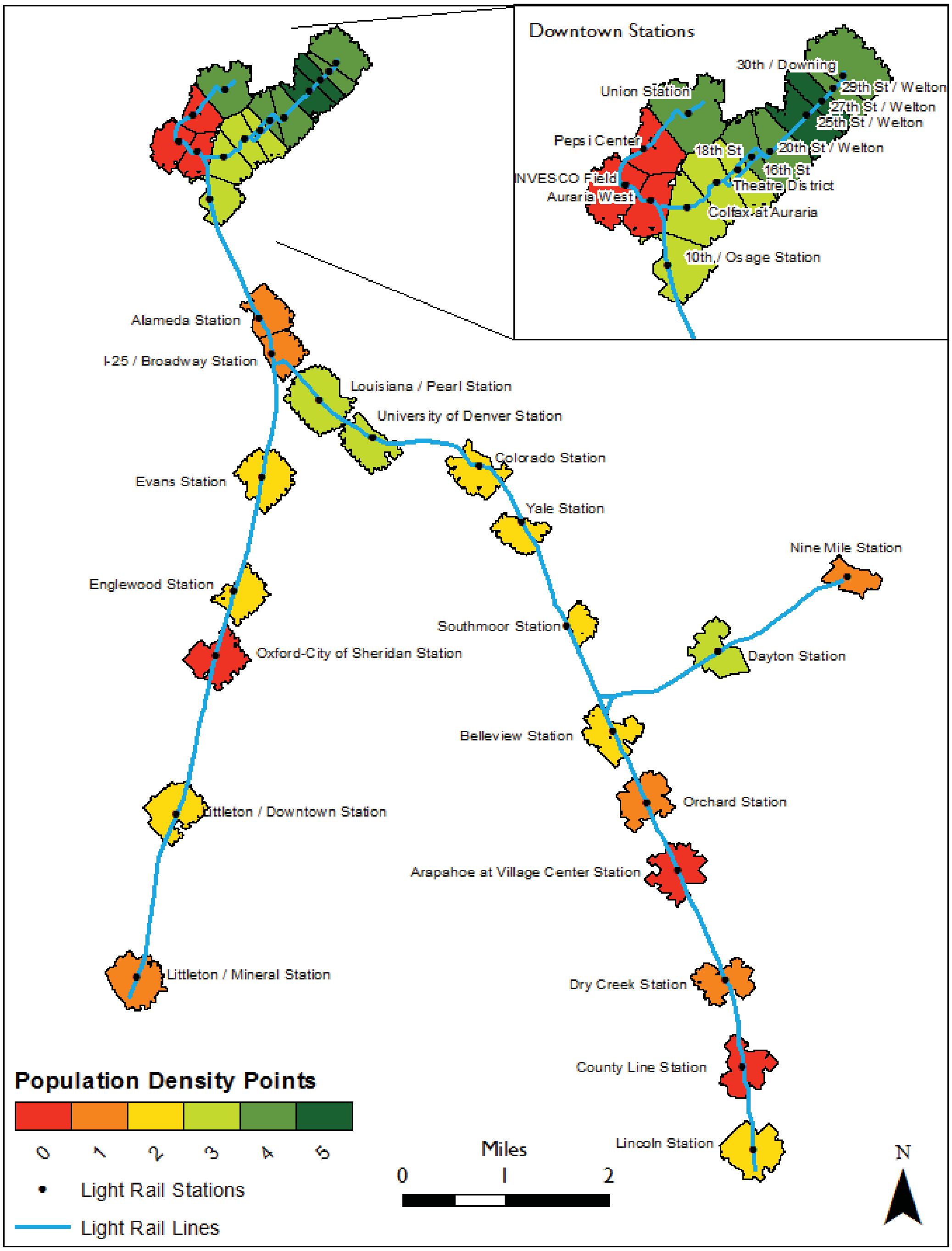


Figure A:8 Walking-Conducive Land Use Scoring

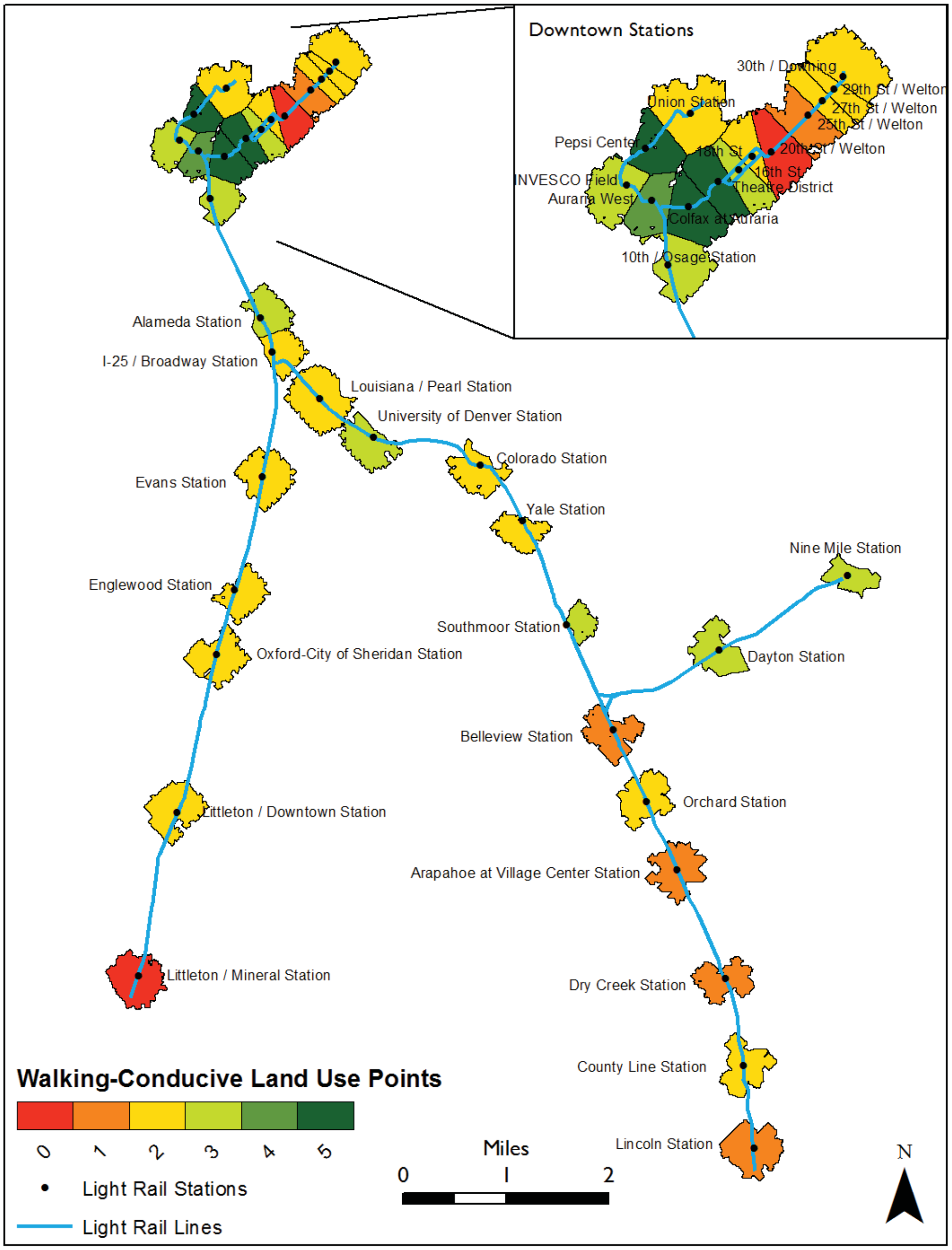
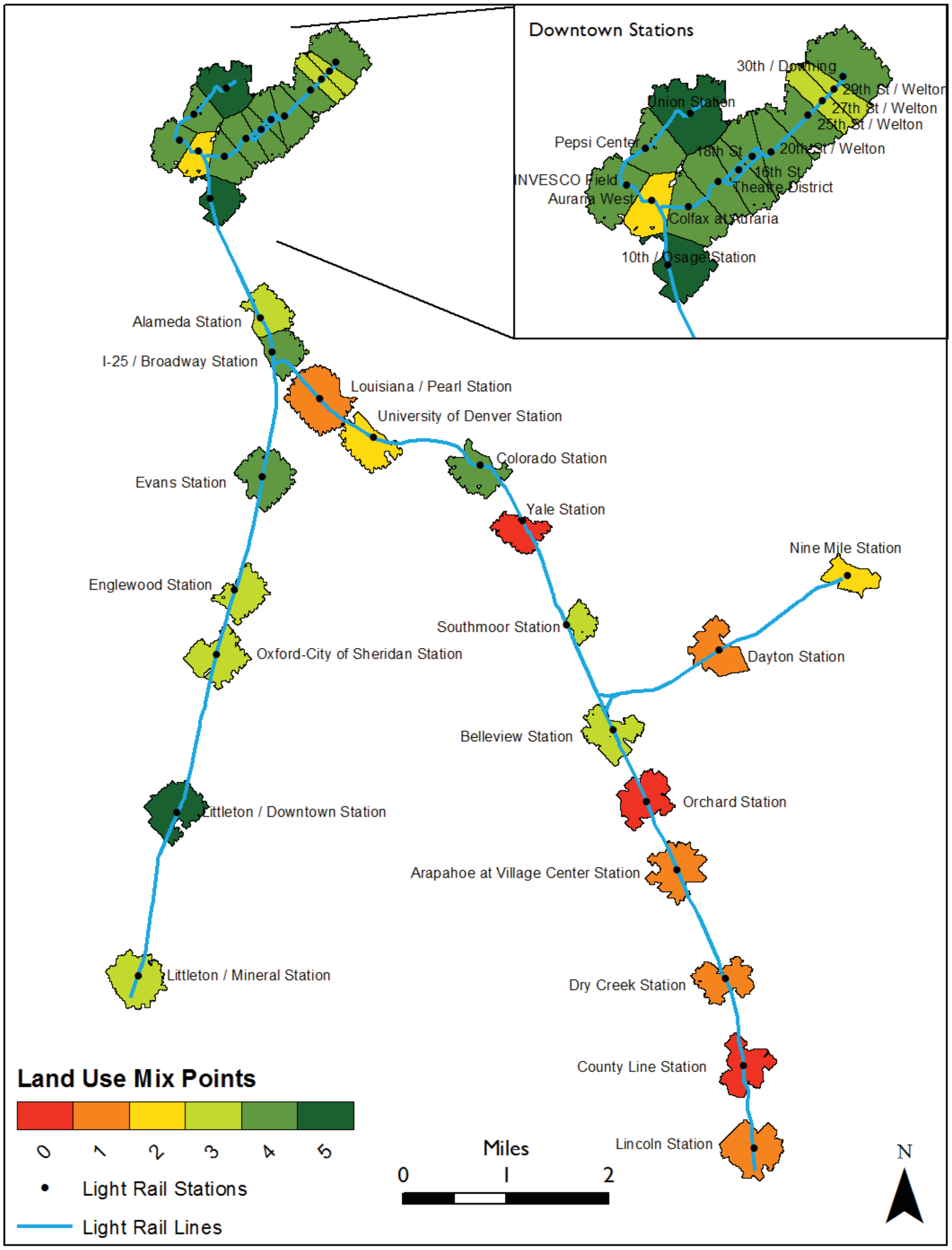


Figure A:9 Land Use Diversity Scoring



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)
```

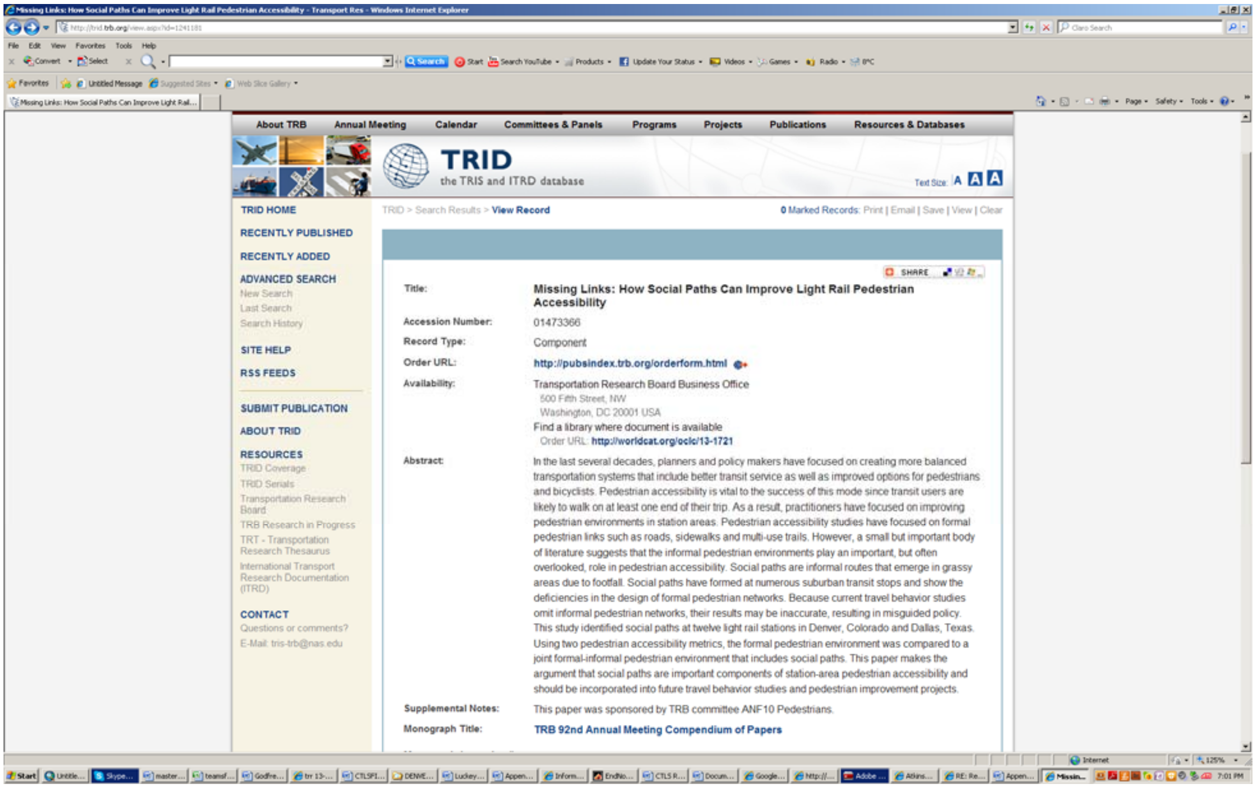
```
# Save the Set Null Raster
Null.save("HH_CFD_RC")


##______________________________________________________________________________
######## 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")
```

APPENDIX C

PUBLICATION IN THE TRANSPORTATION RESEARCH RECORD



Title: **Missing Links: How Social Paths Can Improve Light Rail Pedestrian Accessibility**

Accession Number: 01473366

Record Type: Component

Order URL: http://pubsindex.trb.org/orderform.html

Availability: Transportation Research Board Business Office
500 Fifth Street, NW
Washington, DC 20001 USA
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Order URL: http://worldcat.org/oclc/13-1721

Abstract: In the last several decades, planners and policy makers have focused on creating more balanced transportation systems that include better transit service as well as improved options for pedestrians and bicyclists. Pedestrian accessibility is vital to the success of this mode since transit users are likely to walk on at least one end of their trip. As a result, practitioners have focused on improving pedestrian environments in station areas. Pedestrian accessibility studies have focused on formal pedestrian links such as roads, sidewalks and multi-use trails. However, a small but important body of literature suggests that the informal pedestrian environments play an important, but often overlooked, role in pedestrian accessibility. Social paths are informal routes that emerge in grassy areas due to footfall. Social paths have formed at numerous suburban transit stops and show the deficiencies in the design of formal pedestrian networks. Because current travel behavior studies omit informal pedestrian networks, their results may be inaccurate, resulting in misguided policy. This study identified social paths at twelve light rail stations in Denver, Colorado and Dallas, Texas. Using two pedestrian accessibility metrics, the formal pedestrian environment was compared to a joint formal-informal pedestrian environment that includes social paths. This paper makes the argument that social paths are important components of station-area pedestrian accessibility and should be incorporated into future travel behavior studies and pedestrian improvement projects.

Supplemental Notes: This paper was sponsored by TRB committee ANF10 Pedestrians.

Monograph Title: TRB 92nd Annual Meeting Compendium of Papers