Public Transportation Accessibility Impacts of the Tucson Modern Streetcar

by

Benjamin Arthur Suber

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DEDICATION

During the final preparation of this thesis in November 2016, Pamela Kieran Hesselbacher was killed by a driver who ran a red light while making sure her young children safely crossed a major Chandler, Arizona road. Pamela and I both joined the Theta Iota Chapter of Alpha Phi Omega in 2006, and she graduated from the University of Arizona in 2007. Pamela's strong, upbeat and positive character provided a great sense of relief in situations of uncertainty, stress, and sorrow. It is sad to consider that her children will not be able to benefit from her great character and strength while they grow up.

This thesis is dedicated to Pamela's memory.

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List of Acronyms

GIS	Geographic Information Systems
GTFS	General Transit Feed Specification
LUPTAI	Land Use Transportation Accessibility Index
MATAS	Master Transportation Accessibility Score
MAUP	Modifiable Areal Unit Problem
MSA	Metropolitan Statistical Area
NAICS	North American Industrial Classification System
O-D	Origin-to-Destinations
TMSA	Tucson Metropolitan Statistical Area

Abstract

The Sun Link Modern Streetcar route opened on July 25, 2014, in Downtown Tucson and on the University of Arizona campus. Even though the opening of this 3.9-mile route has been hailed as a success due to its role in revitalizing Downtown Tucson, there are still major issues with accessibility to mass transit in greater Tucson. In this study, mass transit accessibility in Tucson is measured using a GIS-based transit accessibility model before and after the opening of the Sun Link system to determine the effect the streetcar had on overall transit accessibility in the Tucson Metropolitan Area. The study is focused on the years 2009 and 2014 (i.e., two points in time, five years apart) to clearly identify accessibility differences before and after the Sun Link system began operation.

The analysis compares transit routes and resulting access for each residential parcel in Tucson to a diverse set of land uses based on the Land Use Public Transportation Accessibility Index (LUPTAI) during the study interval. The study finds that while residential parcel accessibility increased on average, accessibility to a diverse mix of land uses at transit stops themselves decreased on average within the study interval. Recommendations from this analysis are important in determining what areas of Tucson need improvement on mass transit accessibility. This thesis serves as a demonstration of the effects of a new rail transit system in medium-sized metropolitan areas and provides the first implementation of the LUPTAI GIS transit accessibility model in the U.S.

Chapter 1 Introduction

This thesis conducts a GIS-based transportation accessibility analysis with a focus on land use designations and residential parcels in Tucson, Arizona, and its surrounding suburbs. Transportation accessibility analyses are not new, and these analyses were completed as early as the 1920's with initial definitions provided in 1959 (Hansen 1959, 4). Multiple analyses were conducted since then, with studies using GIS accelerating in the 1990s (Allen 1992).

Transportation accessibility studies evolved in parallel with geographic information systems (GIS) and science, with accessibility equations edited and implemented into spatial analytic methods. GIS became more involved in these specific modeling techniques dating back as far as 1991 with space-time models (Liu 2004, 110). These space-time analyses built the backbone for modern day accessibility analyses through model edits and variable experiments. This thesis will add to the role of GIS in transportation accessibility analyses through a scale of analysis that assesses accessibility for individual parcels regardless of size.

Most transportation accessibility analyses focus on major metropolitan areas with well-established transportation systems, such as Boston, New York or San Francisco. Other large metropolitan areas with traffic congestion issues, such as Los Angeles, Phoenix or Tampa have also been a major focus of studies. Tucson is not the first city to come to mind for transportation accessibility analysis. It is a moderate-sized city that ranked below the top 50 in population in 2015 (U.S. Census Bureau 2015) and has regional influence through the presence of the University of Arizona. It also does not have as many employment or service clusters as larger metropolitan areas in the United States. However, a moderate-sized metropolitan area is a good place to complete a transportation accessibility analysis based on detailed land use designations because the data is more easily managed. Also, to realize the promise of increasing public transit to meet environmental and economic goals, planners must understand how to measure accessibility both in major cities and in smaller metropolitan areas.

Land use and parcel boundaries are at the heart of this assessment. In 2005, three professors and a Queensland, Australia land use planner developed a model for the assessment of transportation accessibility based on land use designations and activity centers called the Land Use Public Transportation Accessibility Index (LUPTAI). LUPTAI examines five different land use destination categories but omits residential land uses, which it treats as points of origination in the model (Pitot 2006, 9-11). This study draws heavily on LUPTAI to examine land use designation and transit route changes in Tucson between 2009 and 2014 with a process similar to the LUPTAI modeling process.

The first section of this chapter describes the motivation behind this thesis and the analyses that have been completed on transportation accessibility in the past. The second section introduces the Tucson Metropolitan Statistical Area (TMSA) and a background on the issues its citizens have faced. The third section introduces the research questions and provides an overview of complementary questions to be addressed in this assessment. The fourth section provides an overview of all aspects to be covered in the study and also the contents of the thesis paper.

1.1 Motivation

Transportation accessibility has been a major topic of research because the focus on decreasing urban sprawl emerged as a strong topic in urban planning and urban studies discussions in the 20th century. Hansen (1959) first defined transportation accessibility as, “potential of opportunities for interaction” (4). Definitions have evolved over the years to include various land uses (e.g., employment) and walking accessibilities. The prevailing accessibility measures may not adequately capture the impact of projects like the Tucson Modern Streetcar, or

Sun Link system, due to the nature of the area defined by urban sprawl and poor mass transit connections. Metropolitan areas of similar size and history to Tucson have only added light rail or modern streetcar systems since about 2000. Like Tucson, these systems connect major activity centers within a relatively short distance. The Sun Link system in Tucson connects Downtown Tucson with the University of Arizona and the proposed Mercado neighborhood (See Figure 2).

The Tucson Metropolitan Area covers a large area (See Figure 1), and the Sun Link system does not serve the periphery. How can we best measure how deeply, if at all, the Sun Link system has changed transit access for the citizens of the Tucson Metropolitan Statistical Area (TMSA)? This study seeks to answer this question by applying a GIS-based accessibility model called Land Use Public Transportation Accessibility Index, or LUPTAI, to the Sun Tran network. This study is the first known implementation of LUPTAI in the U.S., and it provides transit planners an intimate perspective where they can assess specific land uses and whether specific properties lack access to one or more land uses through public transportation.

This assessment may impact the ways public transportation agencies and urban transportation researchers evaluate transportation accessibility. Assessments based on a diverse set of land uses may give U.S. public transportation agencies a stronger means to assess bus and rail routes. Parcel boundaries provide specific locations and may be associated with specific data on land uses. However, this approach is also difficult because many jurisdictions define land use differently. In some jurisdictions, it may be best to approximate land uses through the general use plans while in other jurisdictions, it may be best to use cadastral data. Once such challenges are overcome, the parcel scale of analysis provides an individualized accessibility assessment for categories of land uses.

Ridership is a typical focus on many public transit assessments, especially in the years immediately after major projects, like the Sun Link system, are completed. Demographics and ridership numbers play a role in determining whether a route should be continued or discontinued, but overall accessibility to the route is not always considered, especially in the years after a project is finished (Polzin 1999, 150). Transit-oriented development is a major movement in urban planning, and if practiced, it may influence land use changes along a new route. Measuring such evolution of land uses around transit infrastructure requires a land use-based accessibility model.

With the right kinds of spatial data and GIS-modeling, public transportation and land use planning agencies can factor accessibility to the route to support a variety of decisions about continued building, scheduling, and zoning. One objective of this case study of Tucson is to demonstrate ways that planners can derive an increasingly sophisticated measurement of transit accessibility that that could in turn influence the operation of a bus, streetcar or even a light rail route.

As will be seen below, this study is focused particularly on comparing transit accessibility in the TMSA before and after the Sun Link streetcar system is implemented. Therefore, the study may also benefit planners in metropolitan areas who are considering to add a light rail or modern streetcar system. As of 2016, five moderate-sized metropolitan areas are planning to add a light rail system, eight moderate-sized metropolitan areas are planning to add a modern streetcar system, and seven moderate-sized metropolitan areas are planning to add a bus rapid-transit system (See Table 1).

Table 1 Planned Mass Transit Projects in Moderate-Sized Metropolitan Areas in the United States (Transport Politic 2016)

PROPOSED LIGHT RAIL	PROPOSED MODERN STREETCAR	PROPOSED BUS RAPID TRANSIT
Hamilton, ON (Canada)	Austin, TX	Austin, TX
Hampton Roads, VA	Boise, ID	Fort Collins, CO
Honolulu, HI	Fort Lauderdale, FL	Fresno, CA
Jacksonville, NC	Hampton Roads, VA	Grand Rapids, MI
Monterey, CA	New Haven, CT	Hartford, CT
Raleigh, NC	Providence, RI	Jacksonville, FL
	Reno, NV	Roaring Fork, CO
	Stamford, CT	

The modern streetcar is not the most expansive mass transit rail network type. Light rail systems have stronger capacities to cover more distance and increase the potential of a mass transit network (Furmaniak 2014, 16-17). This study explores whether the modern streetcar system built in Tucson plays a significant role in positively impacting a mass transit network in spite of its size and limitations.

1.2 The Tucson Metropolitan Area

Before reviewing LUPTAI and prior accessibility analyses, it is important to consider the trends of the Tucson Metropolitan Statistical Area (TMSA). The TMSA consists of all cities within Pima County boundaries, including Ajo, Three Points, and Why (See Figure 1).

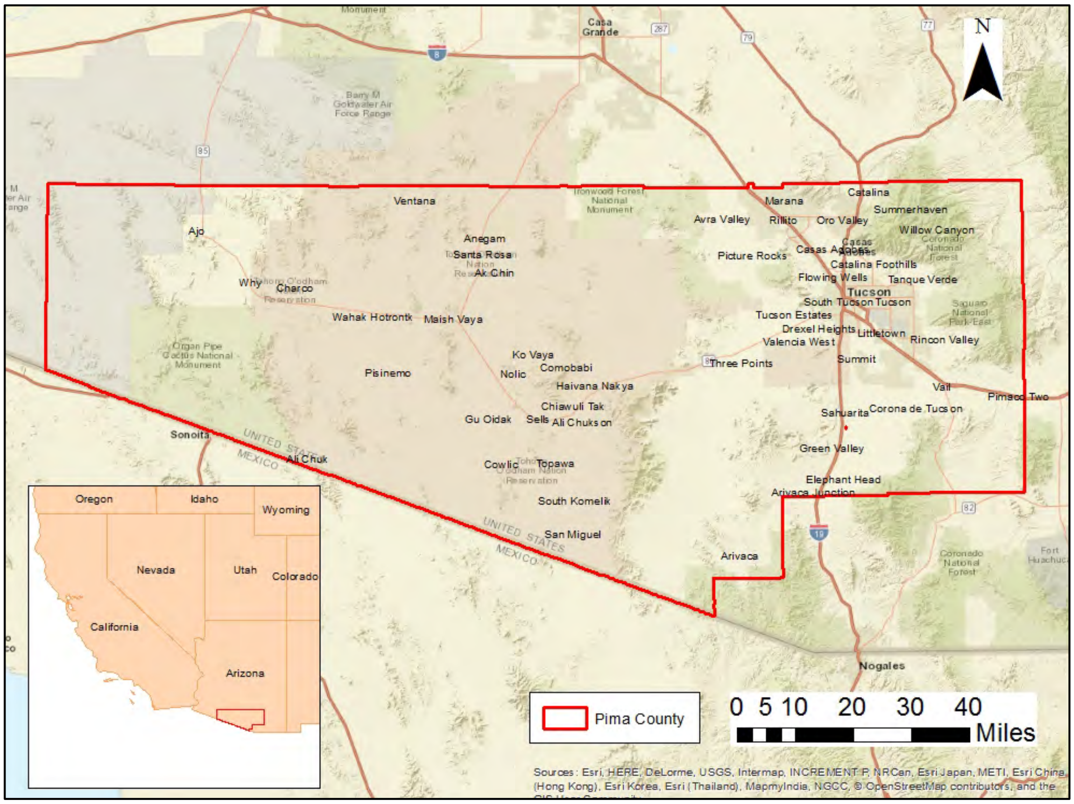


Figure 1 Tucson Metropolitan Statistical Area & Pima County

Tucson lacked growth controls when it witnessed a significant expansion during the 1960's and 1970's, which cleared agricultural land and open space for single-family residences (Al-Shammari 2011, 44). With this type of growth, Pima County proposed many transportation initiatives, but transportation planners focused on private transportation as opposed to public transportation. Multiple freeways were proposed throughout the Tucson area to fortify a two-freeway network in response to large population growth trends. Pima County voters rejected these freeway plans throughout the 1960's, 1970's, and 1980's as a result of heavy public participation and an anti-freeway stance from residents (Logan 1995, 90).

After the failures of the freeway initiatives of the 1960's through the early-1980's, there have been additional transportation initiatives throughout the Tucson area. Two of the three major initiatives failed when they focused on roadway improvements, including a 1984 plan to construct a parkway on the outskirts of Tucson and a 1986 plan to institute a half-cent tax to overhaul the transportation system for roadways instead of mass transit (LaFleur 2002).

Even initiatives in the 1990’s that included mass transit failed to win voter support. A 1990 half-cent tax proposition was proposed to split funding between road and mass transit projects, which provided promise for mass transit proponents, but failed at the polls (LaFleur 2002). One more initiative was proposed thirteen years later, but unlike previous initiatives, this initiative focused on light rail. The initiative to implement a plan to construct a light rail system in Tucson had a lot of promise, but just like the additional initiatives, it received mixed reactions and was defeated at the polls (Herr-Cardillo 2014).

Pima County and the City of Tucson regrouped and came up with a new idea for their residents three years later. Pima County realized that they would need a stronger transportation network to combat negative urban sprawl effects that came to light in the early 2000’s. In 2006, Pima County residents approved the Regional Transportation Authority plan with comprehensive objectives over a wide scale. As part of this 20-year regional transportation plan, Pima County proposed a four-mile streetcar system to link relatively densely populated areas, such as Downtown Tucson and the University of Arizona (Pima County Regional Transportation Authority 2006, 55). This streetcar system was expected to open during the second period of the implementation schedule between 2012 and 2016 (Pima County Regional Transportation Authority 2006, 55). Sun Link opened in the middle of this period in July 2014 in accordance with this schedule. The Sun Link system is a good candidate for a before and after accessibility study in the TMSA due to its connectivity between Downtown Tucson, the University of Arizona, and Fourth Avenue (See Figure 2).

Figure 2 Sun Link Modern Streetcar Route (Source: City of Tucson, 2014)

1.3 Research Objective and Questions

The purpose of this thesis is to assess changes and trends in mass transit accessibility as a result of the opening of the Sun Link system. Sun Link opened to the public on July 25, 2014, and served as a catalyst for development and business improvements along the route, even while it was still under construction (City of Tucson 2014). The objective of this study is to determine accessibility impacts to mass transit resulting from the opening of the Sun Link system. This objective requires not only an assessment of the accessibility along this Sun Link system, but also an assessment of the bus routes around the TMSA, which includes the suburbs of South

Tucson, Marana, Oro Valley, Vail, and Sahuarita (See Figure 3). The analysis results determine how the Sun Link system has influenced accessibility overall in the TMSA.

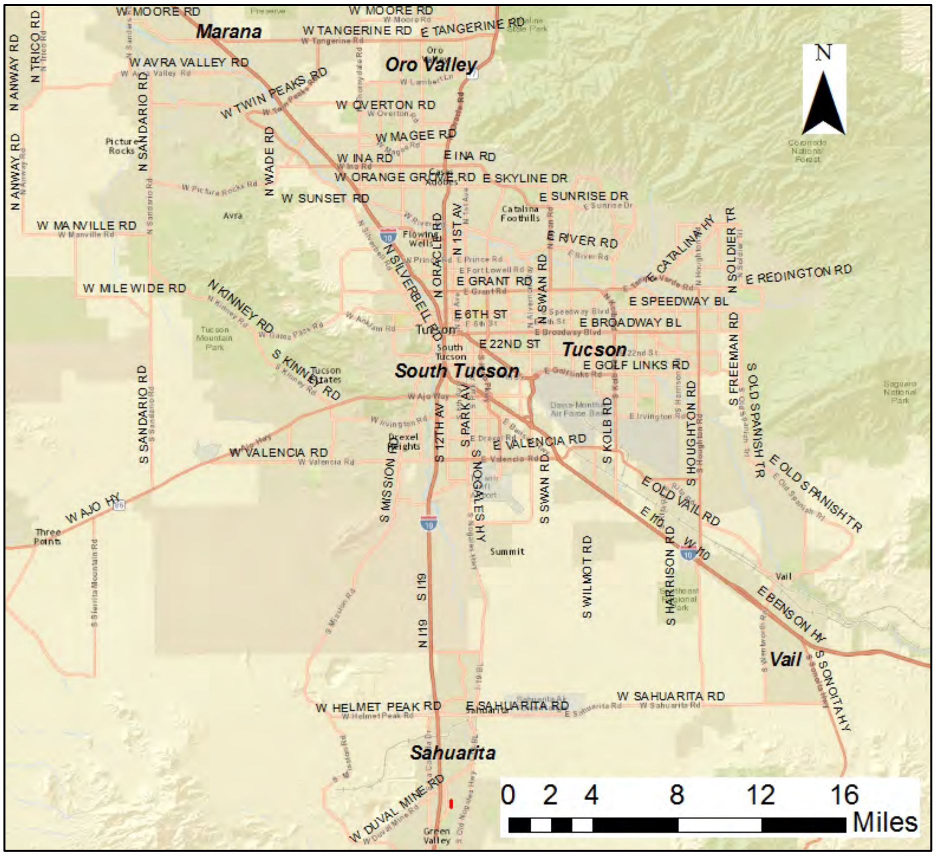


Figure 3 Greater Tucson Area Streetmap

This assessment focuses on the following question: To what extent can a regional transportation plan, a newly implemented mass transit system or a new mass transit mode impact transportation accessibility in a moderately-sized metropolitan statistical area (MSA) characterized by urban sprawl? This is a vital question for examining and perhaps eventually reversing the trends of 20th-century urban sprawl communities in the U.S. Such communities have poor public transportation networks and are characterized by large distances between destinations, automobile dependency, and little motivation to walk. New rail lines are catalysts for reversing this trend because they promote economic growth, increase employment demand,

and make land more readily available for development (Higgins 2014, 100-101). The answer to this question will provide new insight for urban planners who hope to reverse this trend.

This assessment will also address a number of supplemental questions that cover multiple topics. These questions include the following:

- What are the impacts to accessibility resulting from the opening of the Sun Link system?
- To what extent can a short modern streetcar line provide a change in accessibility throughout a sprawling region?
- Have different areas of the Tucson, AZ Metropolitan Statistical Area seen improvements or declines in accessibility as a result of this new implementation?

1.4 Assessment Overview

The overall assessment of the Sun Link system involved measures of overall accessibility to mass transit based on the Land Use Public Transportation Accessibility Index (LUPTAI). To complete the assessment, an analysis of accessibility before and after the opening of the Sun Link system and the Sun Tran network was conducted to determine the impacts. Land use and transportation data was examined from 2009 and 2014, the year the Sun Link system opened, with the most applicable data to those time periods.

Pitot (2006) provides the indicator set that guided this analysis, though the set was adapted to match data availability in the U.S. context and particularly in the TMSA. LUPTAI was created with five major types of land uses as destination indicators. These destination indicators include employment, health, shopping, financial/postal, and education (Pitot 2006, 4). Non-residential parcels were measured as to whether they match these types, giving an indication of where land use clusters of respective sectors are present in sprawl communities, such as the

TMSA. Esri ArcGIS Business Analyst data is a key land use dataset for realizing these indicators.

The data from 2009 was critical because it was the first data available from the time before construction activities commenced on the Sun Link system. Construction on the Sun Link system started in 2012 (City of Tucson, 2015). The Sun Link's predecessor, the Old Pueblo Trolley, extended into Downtown Tucson in 2009 (Pantell 2009). However, the Old Pueblo Trolley, which was a historic streetcar system sharing some of the routes of the new system, operated for the final time in 2011 (Smartlak 2012a).

1.5 Outline of the Thesis Project

The analysis of changes in transit accessibility related to the opening of the Sun Link system is explained in four additional chapters. Chapter 2 addresses the accessibility analyses and spatial constructs of transit accessibility analyses while providing context for this analysis. The methods and research design in Chapter 3 provide urban planners, transportation planners, and spatial analysts insight into how to conduct an analysis of transit accessibility for residential parcels in a U.S. MSA. Chapter 4 provides the reader insight to the analysis results, including trends along the Sun Link system, trends outside the Central Business District and impacts to the TMSA. Chapter 5 presents recommendations for further accessibility improvements and implications for metropolitan areas with the same issues.

Chapter 2 Background and Literature Review

The Land Use Public Transportation Accessibility Index (LUPTAI) is not the only public transit accessibility model. Scholars have conducted transportation accessibility analyses in the past, and some of these analyses included system expansions and additions as factors in the analysis. There have been general analyses that have focused on different topics, such as ridership and mode comparisons, in larger metropolitan statistical areas. While there have been analyses on mass transit accessibility, few analyses incorporated a diverse set of land use designations as a primary focus like LUPTAI.

Also, most accessibility definitions have not focused solely on mass transit, but on overall transportation. The accessibility definition does not include detail on mass transit because it also includes the automobile. Consequently, the literature on this topic does not contain the most up-to-date information. The lack of detailed modeling on mass transit leads to a poor guide for cities and metropolitan areas like Tucson and Pima County to consider the areas where mass transit accessibility is poor and how to remedy issues surrounding these issues.

Accessibility studies completed before the implementation of the LUPTAI model is addressed first in this chapter. The LUPTAI model is introduced next with an overview of the model creation and implementation. Two different types of accessibility studies are examined next based on whether LUPTAI influenced these studies. LUPTAI’s impact is demonstrated next with all studies that followed. Tucson’s prior accessibility studies are then assessed before the impact of LUPTAI on the assessment is examined, and a conclusion is given on the related work.

2.1 Accessibility Studies Before LUPTAI

Transportation accessibility was a complementary topic in some studies prior to the creation of LUPTAI. Accessibility is broadly defined beyond the Hanson (1959) definition as, "the pattern of land use, the nature of the transportation system, and the characteristics of the traveler" (Liu 2004, 106). David Levinson conducted a mathematical and statistical analysis that focused on the time it takes to get to work in the Washington D.C. Metropolitan Area. In that study, the urban structure became a major transportation accessibility indicator defined by job location and housing accessibility (Levinson 1998, 20). Other studies took a more secondary look at mass transit accessibility. One such article identified transportation accessibility as a factor of urban sprawl without delving very much into the topic (Zhang 2001, 221).

Urban sprawl provides many negative consequences for cities and metropolitan areas of all sizes, including poor air quality, increased obesity rates, and car dependency (Frumpkin 2002). However, most analyses primarily focus on larger metropolitan statistical areas. Washington D.C. was the study area in one article covering the topic of accessibility and commute times (Levinson 1998, 11). Chicago was the study area for an article that examined accessibility as a factor of urban sprawl (Zhang 2001, 221). The Philadelphia Metropolitan Area, including Pennsylvania and New Jersey, was the major study area for an article about accessibility measures in metropolitan statistical areas in the United States (Allen 1992, 443). At the same time, the metropolitan areas mentioned in these studies already have existing mass transit systems that balance rail and bus transportation while seeking expansion destinations. This is an issue because these analyses omit study areas where a rail system does not exist.

The Levinson (1998), Zhang (2001) and Allen (1992) studies do not entirely take GIS into account. Researchers solely analyzed mathematical models that took different factors, such as distances and populations, in order to complete the objective assessment. The authors visually demonstrated these results without any strong geographical analyses to back up their conclusions. In the aforementioned analyses, GIS is used more for visual analyses as opposed to spatial analyses.

Accessibility was mathematically defined through a regression analysis with unspecified locations and relative accessibility (Allen 1992, 440). Indicators for this definition included activity locations, such as employment, household and retail locations, travel time, travel cost between locations and distances between these locations (Allen 1992, 440-443). Accessibility factors were calculated through mathematical means where GIS served to calculate the travel times and visualize the results (Allen 1992, 443). GIS did not serve any other spatial analysis purposes.

GIS played a role in analyses completed for more than 20 years. One such article examined the role of GIS in transportation accessibility analyses after new advances emerged in GIScience. The aforementioned article reviewed different articles released in the late-1990's and early-2000's that demonstrate how GIS can be used not only as a primary basis for completing transportation accessibility analyses, but also to find real world solutions to such issues (Kwan 2003, 2-3). There were algorithms created in GIS, but no models were demonstrated in this article.

One article covered the role of GIS in assessing transportation accessibility, yet it looks at space-time accessibility measures that can be conducted for the public and private transportation infrastructure of Salt Lake City without providing an emphasis on the public transportation network (Miller 2000, 11-14). Private transportation accessibility may be important, but it is irrelevant in measuring only mass transit accessibility within a network, as in this study of the Tucson system.

A similar model to what would become LUPTAI is the UrbanSim model. The UrbanSim model has the purpose of integrating land use information with transportation data to provide more informed decisions in urban growth patterns (Waddell 2002, 298). This model takes into account spatial patterns similar to LUPTAI because it used walking, land use, and parcel information to drive recommendations to policymakers (Waddell 2002, 307). Waddell, et al. (2007), also used grid cells to cross reference political and urban planning boundaries (300-301). GIS was also at the heart of the data creation to feed the simulation model where multiple layers were processed to complete the objective of the model. The UrbanSim model can be considered in some ways to be a predecessor of the LUPTAI model even though it is not primarily a GIS model.

However, the UrbanSim model has more indicators than LUPTAI. UrbanSim created five other models including mobility, location, land price, real estate development and demographic transition models (Waddell 2002, 305). The additional model indicators distinguish the UrbanSim model from LUPTAI. Where LUPTAI is a transportation accessibility model, UrbanSim does not model mass transit accessibility at the same level of detail as LUPTAI. UrbanSim focuses on depicting the interaction of planning policy and economic decisions in response to mass transit development and resulting general levels of mobility. The UrbanSim model depends more on the grid cells than individual parcel data for implementation.

Land use and transportation were analyzed together in the years before LUPTAI was created. One such analysis examined transportation accessibility in five neighborhoods within the San Francisco Bay Area. The San Francisco analysis took population density and general land use characteristics into account as well as transportation diversity and population sampling to examine land use designations and behavior impacts on travel trends (Kitamura et al. 1997, 126). The San Francisco analysis has a resemblance to LUPTAI, except for one limitation. Kitamura et al. (1997) completed the survey-based objective regression analysis in an unspecified statistical software program and visualized the objective regression analysis results in a GIS (131-132). This analysis would have been very similar to LUPTAI if the authors had implemented the mathematical models in a GIS.

Overall, each early article provided different indicators that could be used to conduct this assessment in a mathematical and statistical context. The biggest weakness of these assessments was the lack of emphasis towards spatial analysis methods in a GIS. Spatial considerations were present, but the mathematical and statistical considerations superseded the spatial considerations. Consideration of land use designations as a variable for these analyses was also rare. LUPTAI takes full advantage of the digital capabilities in a GIS with detailed land use data.

2.2 The Land Use Public Transportation Accessibility Index

The guiding force behind this thesis is the Land Use Public Transportation Accessibility Index (LUPTAI). LUPTAI was created in 2005 by three professors from Griffith University in Brisbane, Australia and a transportation planner in Queensland, Australia. The authors created LUPTAI with the purpose of "using a GIS-based methodology to quantify and map accessibility to common land use destinations by walking and/or public transport" (Pitot 2006, 1). LUPTAI offers a strong model used to assess transportation accessibility in ArcGIS using land use, transportation, and demographic data.

The LUPTAI authors created their data from multiple public and private datasets for land uses and the mass transit network. Land use data was derived from land use and zoning maps

(Yigitcanlar 2007, 8). This data source is challenging to translate into the U.S. context because the data schema for land use and zoning maps match each other, even within the United States. The network analysis consisted of transit routes, stop frequencies, road, and pedestrian networks (Yigitcanlar 2007, 8). The Queensland transportation network data is similar to American transportation network data and therefore, consistent. The land uses are not as consistent and different sources were explored for Tucson to maintain consistency. This study remedied the issue primarily by using the assessor's land use code tables.

The LUPTAI Model is founded on the destination-based approach, i.e., the accessibility of a diverse set of land uses from residences. The authors created specific buffers from bus and train stops (See Figure 4), selected roads within certain buffers, applied buffers around the roads and assigned an initial value to the adjacent land parcels based on the mix of destination indicators defined above (Pitot 2006, 4). Walking distances are also assessed in this model, but there is no consistent parameter to determine walkable distances. As specified in Figure 4, LUPTAI provides a highly accessible walking distance of 300 meters (Pitot 2006, 7) while the Walk Score web service defines 0.25 miles or 402 meters as highly walkable distances for the United States, Canada and Australia (Walk Score 2016).

Layer	Mode	High	Medium	Low	Poor
Public Transport	Bus	Up to 300m walk & up to 10 min service freq	Up to 400m walk & up to 30 min service freq	Up to 800m walk & up to 60 min service freq	Up to 1000m walk & all running bus services
	Train	Up to 600m walk & up to 15 min service freq	Up to 800m walk & up to 30 min service freq	Up to 1000m walk & up to 60 min service freq	Up to 1200m walk & all running train services

BUS	Service Frequency (min)				
Walking Distance (m)		≤10	30	60	>60
	>0	H	M	L	P
	100	H	M	L	P
	200	H	M	L	P
	300	H	M	L	P
	400	M	M	L	P
	500	L	L	L	P
	600	L	L	L	P
	700	L	L	L	P
	800	L	L	L	P
	900	P	P	P	P
	1000	P	P	P	P
	1100	N	N	N	N
	1200	N	N	N	N
	1300+	N	N	N	N

TRAIN	Service Frequency (min)				
Walking Distance (m)		≤15	30	60	>60
	>0	H	M	L	P
	100	H	M	L	P
	200	H	M	L	P
	300	H	M	L	P
	400	H	M	L	P
	500	H	M	L	P
	600	H	M	L	P
	700	M	M	L	P
	800	M	M	L	P
	900	L	L	L	P
	1000	L	L	L	P
	1100	P	P	P	P
	1200	P	P	P	P
	1300+	N	N	N	N

H: High M: Medium L: Low P: Poor N: None

Figure 4 LUPTAI Buffers by Transportation Mode with Walking Distance Assessment

The authors then proceeded to construct a methodology consisting of combined walking distances and public transit travel times between residential parcels and the various land use destinations to assign an index value to each residential parcel (Pitot 2006, 7). Each land use was assigned an equal weight value to balance the land use’s influence on the entire index and model (Pitot 2006, 7). An example of the LUPTAI methodology can be seen in Figure 5 below.

Figure 5 Results of Weighted Destination-Based Analysis (Pitot 2006, 8)

The LUPTAI authors created a raster with grid cells with equidistant 50-meter dimensions to analyze accessibility to all destinations (Pitot 2006, 7). The authors overlaid transit stop and line layers onto the raster to assess the walking accessibility and transit accessibility score results together. The LUPTAI approach provided a generalized transit accessibility to parcels with a special approach to assessing residential accessibility.

LUPTAI provides recommendations for the best locations to encourage population density and increase residential accessibilities. The authors created three classes that arrive at such recommendations, including two classes heavily weighted towards either density or accessibility values and a class that balanced the density and accessibility values (Pitot 2006, 11). The authors recommended specific density levels that corresponded to each different accessibility level. These densities ranged from 0 to more than 30 dwellings per hectare for a given parcel (See Figure 6). The recommended residential densities not only provide direction to planners on where to place new residences, but it also provides direction to transit planners on where new or realigned transit lines should be placed.

Accessibility Levels	Dwellings per Hectare (net)	
	Low	High
High	30	max
Medium	15	30
Low	10	15
Poor	5	10
None	0	5

Figure 6 Recommended Population Densities by Transportation Accessibility Level (Pitot 2006, 13)

The authors make additional recommendations based on the different issues transportation planners and urban planners face everyday. Such recommendations include transit-oriented development pinpointing, activity center identification and increased efficiency measures in implementing growth management strategy (Pitot 2006, 13-15). Transit-oriented development pinpointing could help Pima County and the City of Tucson identify the land uses that are lacking around the streetcar and nurture transit-oriented development policy creation and implementation.

The authors concluded with an observation that would provide ramifications for not only Australia but also the world. State and local governments would have the best tool to demonstrate the impact of projects on access to mass transit and individuals' travel choices (Pitot

2006, 17). Such a statement would ensure that transportation planners and urban planners would be willing to experiment with LUPTAI around the world.

2.3 Spatial Accessibility Studies Since 2005 with LUPTAI Influence

LUPTAI influenced many accessibility analyses routed in GIS and GIS-related platforms. One such research team used GIS in assessing accessibility in Auckland, New Zealand. The result was the identification of two indices that derived from a GIS analysis including an index measuring potential access to destinations through public transit and walking, and a transit frequency index measuring actual trips through an area (Mavoa 2012, 19-20). The Auckland indices derived from the creation of a multi-modal public transit network consisting of transit modes and walking paths (Mavoa 2012, 17).

Another study used LUPTAI to demonstrate accessibility trends years after LUPTAI was first developed (Kelly 2012, 50-51), but it was only used to make recommendations to planners, and no model was developed. Additional spatial indices did not assess public transportation accessibility, even though the indices were influenced by LUPTAI. The transportation accessibility topic was a subtopic in an analysis of transportation sustainability where the focus expanded beyond public transportation into private and commercial modes (Reisi 2014, 291). Many accessibility analyses were conducted on Australian Metropolitan Areas, New Zealand Metropolitan Areas as well as one Turkish Metropolitan Area (Gulhan 2013, Wang 2013, Reisi 2016), but until this thesis project LUPTAI had never been fully implemented outside of Australia.

Transportation accessibility did not have the only impact from LUPTAI. An unrelated spatial analysis built from LUPTAI's approach uses transportation as a factor to create a neighborhood destination accessibility index in order to address increases in obesity (Witten

2011, 205). Transportation accessibility was not the primary focus, but rather a complementary factor. LUPTAI's influence spreads beyond public transportation accessibility into private transportation and pedestrian accessibility spatial analyses.

2.4 Spatial Accessibility Studies Since 2005 not Influenced by LUPTAI

Other analyses have assessed transportation accessibility in U.S. metropolitan areas without LUPTAI influence. An index assessed walk scores and employment access scores in order to determine total transportation access within the Orlando MSA (Thompson 2012, 6-7). The Orlando model was calculated through the use of network analysis tools on feature classes representing the land use classifications and bus routes in the Orlando Metropolitan Area (Thompson 2012, 7). The Orlando model is similar to the Tucson model developed for this study because it assesses employment and walking accessibilities, but it did not contain the LUPTAI influence and the diversity of land uses in the LUPTAI index.

Another accessibility analysis was conducted nearly a decade after LUPTAI was created without its influence. Ford et al. (2015) created a GIS-based accessibility index that assessed public transportation in London, England, a city with densely developed mass transit. While this index was very similar to LUPTAI, it includes an additional variable. Bicycle lanes and paths became a major variable in this analysis (Ford 2015, 135), which provided a stronger emphasis on transportation sustainability as opposed to just accessibility.

While the Ford et al. (2015) analysis provides a strong assessment of the Transport for London network, LUPTAI has more strengths in assessing accessibility from land uses to mass transit. The land use assessment is stronger because it allows transportation planners to determine which land uses are impacted by accessibility to mass transit modes. Planners can make more informed decisions about how to increase accessibility and address underserved areas. Bicycles are important in Tucson, but only in the Central Business District and the University of Arizona neighborhoods. Bicycle routes in Tucson were not assessed due to the lack of use and definition in the periphery.

The Ford et al. (2015) model provides a streamlined approach to assessing transportation accessibility in a GIS. The London model uses 2001 UK Census zones while not accounting for individual parcels or land use designations (Ford et al. 2015, 130). This method allows transportation planners a means to generalize about an individual parcel's proximity to a bus stop or train station, which leads to errors in accessibility assessments. LUPTAI makes up for that shortcoming by assessing the individual parcel, thus reducing the chance for an error from a generalization.

Other authors made contributions to transportation accessibility analysis methods in different ways after LUPTAI was created. Kwan and Weber (2008) used a GIS-based algorithm (111) on the Portland Metropolitan Area to determine that space-time accessibility measures are too unpredictable due to changes in daily activities with no effect on geographical contexts. Vandenbulcke, Steenberghen and Thomas (2009) created a mathematical transportation accessibility index in a GIS covering the entire area of Belgium. This study was also different because it also took long distance rail lines into account. Litman (2016) conducted a transportation accessibility analysis in a GIS where land use designations were a factor, but there were other factors present including travel time, transportation diversity, and parking costs. The land use designation measurements were important, but the analytical method was different because private transportation was included in the parking cost analysis.

2.5 Access to Destinations

There are also some studies in the U.S. that take an access to destinations approach without taking LUPTAI into account. A study of the Minneapolis-Saint Paul Metropolitan Area consists of 14 reports within 3 study areas completed between 2004 and 2014 (University of Minnesota 2016). Each study analyzed different aspects of transportation accessibility and two studies examined topics assessed in the Tucson Analysis.

In the first study, Horning, et al. (2008), examined accessibility to non-automobile transportation modes in the Minneapolis-St. Paul region based on parcel and land use data. The authors of this study used parcel point and polygon data from the Minneapolis-Saint Paul GIS server, MetroGIS, where point data matched business data to polygons (Horning 2008, 6). The business data came from Dun & Bradstreet tables and InfoUSA data in Esri's ArcGIS Business Analyst (Horning 2008, 3). The data acquisition process is part of a larger analysis by the University of Minnesota to measure automobile and transportation accessibility throughout the Minneapolis-Saint Paul region. The study of Tucson reported here uses a similar approach, except the business data, is matched to points in Esri ArcGIS Business Analyst. Further matching with parcel boundaries requires a spatial join with a polygon feature class representing parcels.

There are other differences between the LUPTAI and the Minneapolis-St. Paul metro studies. This series of access to destination studies measured automobile accessibility as well as public transportation accessibility. Horning et al. (2008) analyzes land uses through Standard Industrial Classification and North American Industrial Classification (NAICS) methods through the creation of a complex dataset with point and polygon data (3-4). This analysis provides more specific land use definitions beyond the ones specified in LUPTAI. Such land uses include barbershops, movie theaters and grocery stores (Horning 2008, 3). The access to destinations approach serves as an inspiration to accumulate land use data that is more specific than LUPTAI. Although this is time-consuming, the advantage is that it allows planners to identify land use classifications when generalized land uses cannot be identified.

A second relevant report issued as part of the Minneapolis-Saint Paul study provides an alternative land use classification spatial definition. Owen, et al. (2012) created land use data based on U.S. Census Bureau datasets where the authors aggregated the number of corresponding land uses within census blocks and used those sums to create corresponding centroids for the census block (15). Census block scale definitions open the authors up to scrutiny where specific locations cannot be examined. The scrutiny derives from classifying the number of jobs within an arbitrary polygon, such as the centroid of the census block, as opposed to points for each job location. However, the centroid creation process also saves data space and computational effort when completing the analysis.

Major metropolitan areas, such as Minneapolis-St.Paul and Tucson have thousands of land uses across thousands of parcels. A polygon vector dataset with thousands of attributes will be slow to process and could jeopardize an analysis if it causes system crashes and interminable processing times. Thus, the centroid creation approach may be required if no other data sources exist and if data space is limited.

LUPTAI was created and published during the early phases of the access to destinations study in Minneapolis-Saint Paul. The LUPTAI analysis was completed in 2005 and the paper with the first publication released in 2006 (Pitot 2006, 1). The University of Minnesota only published one study by 2006 (University of Minnesota 2016) while LUPTAI has already established itself in Queensland, Australia.

The large metropolitan area in Minneapolis and Saint Paul may be inappropriate to introduce LUPTAI in case the large amount of data becomes a burden on the analysis. The work in Minneapolis-Saint Paul also provides very detailed land use designations through two to six digit NAICS codes with both broad and specific definitions (Horning 2008, 8). The Tucson analysis is based on the LUPTAI approach instead because the index offers a chance to summarize land use diversity. LUPTAI minimizes the data capacity issue through broad land use designation definitions.

2.6 Tucson and Transportation Accessibility

Tucson may not have been the primary study area of a past transportation accessibility analyses, but it has been used as a study area in at least one transportation analysis. Tucson was one of seven metropolitan areas studied in a Federal Transit Administration transportation equity analysis with the purpose of comparing it to the six larger metropolitan areas (Grengs 2013, 26-27). The authors of this study addressed accessibility, placing emphasis on people and their relationships to places (Grengs 2013, 4). While Tucson and accessibility to land uses were not the primary focus of the study, Grengs et al. (2013) found that Tucson had the most equitable distribution of accessibility between non-work land uses and transportation of any of the seven cities studied (28). Tucson was also included in a different study of accessibility requirements. However, Tucson was one of 37 metropolitan areas studied and was not a primary focus of this study (Levine 2012, 160).

Lack of emphasis on Tucson as a study area creates an unknown and uncertain initial assessment of accessibility for this metropolitan area in Southern Arizona. This thesis pursues an opportunity to provide the initial accessibility assessment for Tucson. Efforts to contact professors with the University of Arizona School of Geography & Regional Development regarding this topic were not successful. Association of Governments, the City of Tucson and Pima County could not identify such analyses for Tucson either. Furthermore, no such accessibility analysis is present in published literature regarding this topic. The lack of initial transportation accessibility outcomes for Tucson added to the challenge of creating this thesis. There are no published transportation accessibility analyses that focus on the TMSA.

2.7 Effect of LUPTAI on Assessment

The TMSA is small enough to be evaluated with a land use-based model, while large enough to be considered a significant metropolitan area. The TMSA is not much larger than Gold Coast, Queensland, Australia (United States Office of Management and Budget 2013; City of Tucson 2015), which constitutes a different but ample study area to introduce LUPTAI to the United States.

An impact and lesson from LUPTAI are the ability to observe transportation disadvantage and determine social exclusion areas (Pitot 2006, 16). Zonal geography is not able to specifically identify these areas. LUPTAI enables the ability to measure distances from parcels to mass transit stops by reviewing each parcel's proximity to a bus stop or train station instead of a defined zone or region. This approach will be vital in defining an explicit accessibility level area while providing an absolute answer in determining a parcel's accessibility.

Cities and large municipalities, such as counties and even states, will reap large benefits from a land use designation-based modeling process. LUPTAI provides proof of this observation where one of its benefits is the ability to test alternative proposals on land use structure and transportation master plans (Pitot 2006, 16). Combining land use designations with cadastral data and enhances this ability by allowing planners and government employees to accurately determine boundaries as well as specific aspects of such proposals.

2.8 Related Work Summary

Transportation sustainability may be a strong aspect of 21st century transportation planning, but it cannot be achieved without addressing accessibility. Many authors have completed accessibility studies by applying aspects of LUPTAI to drive their methodology. Sadly, none of these authors tested LUPTAI in order to determine its strengths and weaknesses. LUPTAI has not been tested or even addressed in formal academic discussions in the United States. The best way to address accessibility is to address it in a GIS to provide context to transportation planners and urban planners. This approach will lead to stronger transportation sustainability.

Each analysis provided strong impacts to transportation accessibility with a weakness. Spatial analysis and GIS are not used to their maximum potential. The authors of these analyses use GIS to complete visual analyses, make observations, and arrive at conclusions. While the authors also implement their mathematical models in a GIS, they do not demonstrate the GIS implementation methods in their articles. Some of these analyses were completed prior to the creation of LUPTAI, but subsequent analyses have continued to emphasize statistical results over spatial observations to arrive at their recommendations and conclusions.

LUPTAI provides a significant means to assess transportation mode accessibility while balancing statistical and spatial results. LUPTAI lays out a robust method to spatially assess transportation accessibility while pinpointing the effects for individual land use designations. The Tucson assessment took this model one step further by incorporating individual parcels into the analysis. LUPTAI provides a strong basis for conducting future transportation accessibility analyses for this reason.

Chapter 3 Research Design and Methods

This chapter describes the research design and methods that took place to complete the analysis of transportation accessibility in Tucson. The chapter begins with a summary of the model structure and scoring. A review of all data from various sources used to carry out the analysis provides context to how the modeling process was implemented. A summary of every variable used in this analysis with the data source noted follows. Software requirements are noted, and the analysis methods are then introduced in order to provide further context into how the accessibility scores were calculated.

The modeling process of transportation accessibility created for this study is loosely based on LUPTAI. There is an equally weighted equation for accessibility of a diverse set of destination types or land uses from each residential location, just as in LUPTAI. However, several of the underlying data layers and calculation of accessibility scores differ from LUPTAI because of the available data and urban environment in Tucson. Also, the analysis process for this study is built based on the parcel as the unit of analysis, rather than on a raster grid constructed from underlying parcel data (Yigitcanlar 2007, 18). The author completed the analysis with the objective to maintain as much consistency with LUPTAI as possible.

3.1 Model Structure

This thesis uses a similar analytical process and model to the one used in LUPTAI. However, the analysis takes a separate path than the LUPTAI model. The analytical process is strictly dependent on vector data and involves no raster data. In LUPTAI, accessibility scores are calculated for 500-meter grid cells (Pitot 2006, 8). The accessibility scores are applicable towards residential parcels where the land use values are only applicable towards the calculation of the final score. This thesis is different because the scores are calculated for parcels instead of grid cells.

The modeling process starts with converting parcel polygon features to centroids, creating buffers from bus and streetcar stops and joining parcel and Business Analyst land use centroids with the buffers. Land use densities within the buffers were calculated along with means and standard deviations, resulting in three types of accessibility scores: land use proximity to transit stop based on LUPTAI buffer, distance from the transit stop to transit stop, and land use density within each LUPTAI buffer.

A master transportation accessibility score (MATAS) for each transit stop was calculated with an equally weighted formula of all scores corresponding to all five land use types (see Figure 10). The MATAS score provided a cumulative assessment of land use accessibility to answer two questions:

- How long does it take to travel between transit stops?
- What is the land use density like around the transit stop?

Residential parcel accessibility to transit stops was measured next assessing the proximity between the closest transit stop to the residential parcel based on the bus and streetcar accessibility distance buffers specified in LUPTAI. This process leads to the final score derived from the sum of the MATAS score and the proximity (walkability) of the residential parcel to a a given transit stop. .

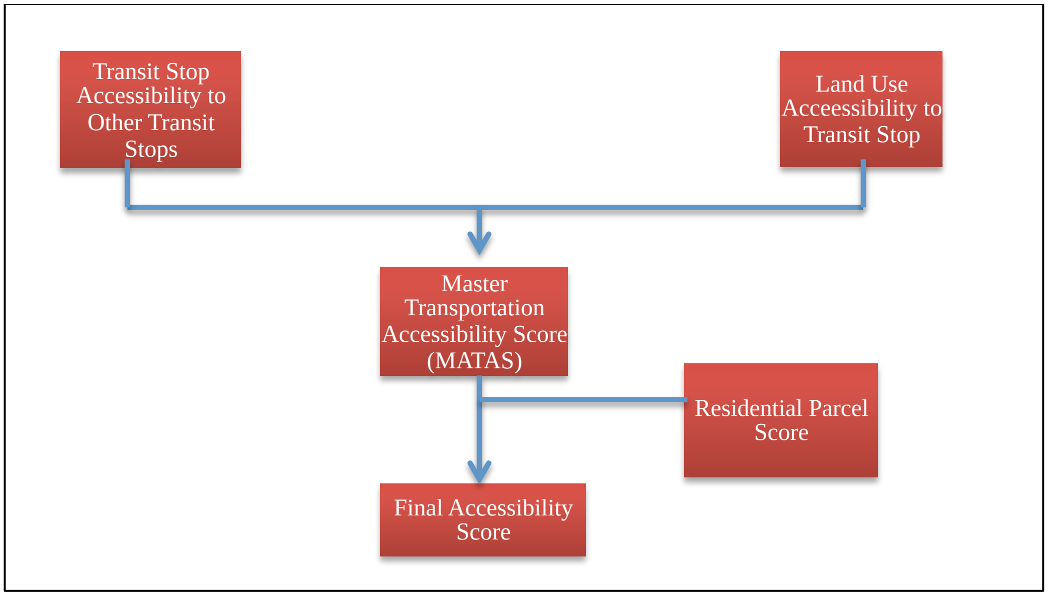


Figure 7 Transportation Score Calculation

3.2 Data Requirements and Variables

The analysis required spatial data both maintained by Pima County and also from other sources. The U.S. Census Bureau, Esri, and independent GIS developers provided additional data sources that were instrumental in completing the analysis. Pima County and its associated suburbs could not provide all the data required to complete the analysis. However, the analysis could not have been completed without data from Pima County, especially cadastral data, which is at the heart of the model.

3.2.1. Pima County Datasets

Three datasets were obtained from the Pima County FTP GIS Server including feature classes representing jurisdictional boundary data, the assessor's parcel data, and the road network. The jurisdictional boundary dataset is a polygon vector dataset that is necessary to define the Pima County boundaries (See Chapter 1). This dataset defined the study area and provided context for analysis in advanced Esri ArcGIS toolsets.

The Pima County Assessor’s Parcel dataset is a vector dataset that is a little more complex than the jurisdictional boundary dataset with a polygon representing every single parcel in Pima County (See Figure 7). Pima County assembled this dataset with information from the Pima County Assessor’s Office. Key attributes include the assessor’s identification number, address, city, and land use code. The assessor’s parcel dataset is one of two important datasets to come from this resource.

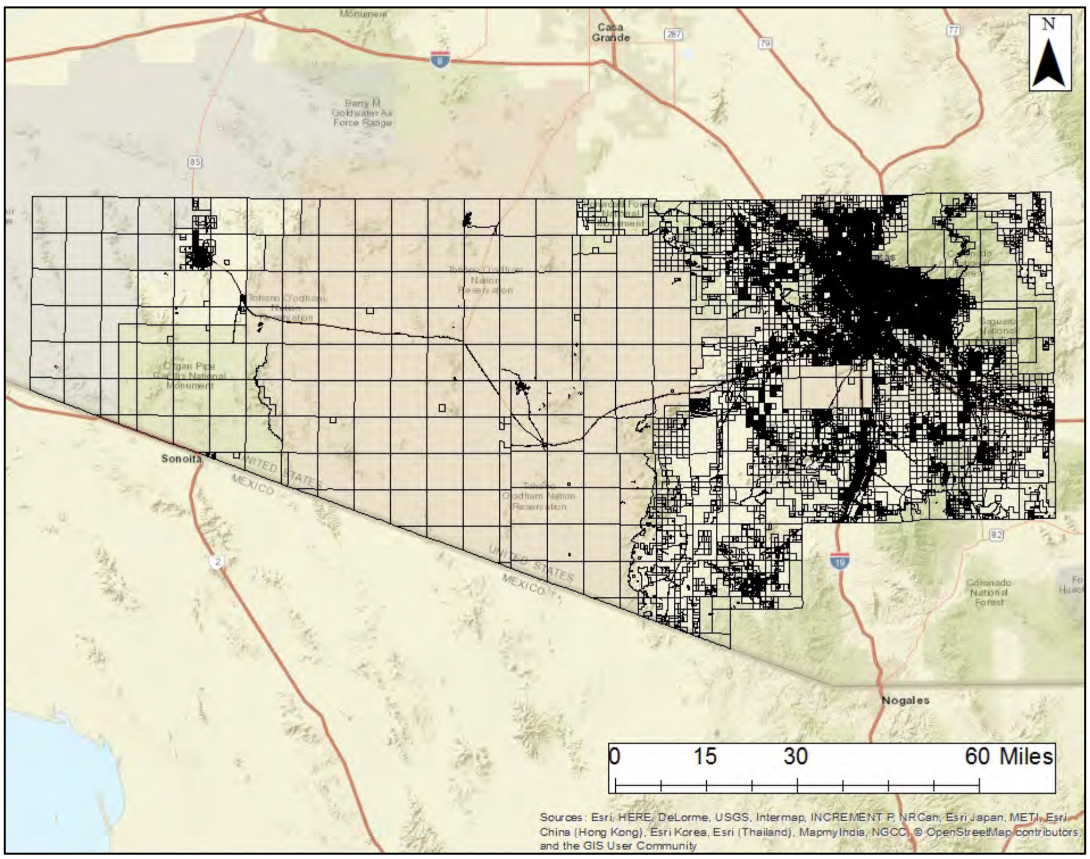


Figure 8 Pima County Assessor's Parcels as Displayed in Esri ArcMap

The feature class depicting all residential properties in Pima County was based on parcel dataset attributes. The author obtained a list of all use codes from the Pima County Assessor’s Office and conducted an attribute join with the parcel data based on the assessor’s land use codes in the parcel dataset. The land use codes matching residential land uses were selected from the parcel dataset, and the author created a new feature class containing all these values.

The residential designations were the most important factor in this analysis because access to mass transit from residences is how the model defines the final accessibility values. The cadastral dataset identified the proper land uses through an attribute join with the Pima County Assessor's Land Use Code list. Six attributes are present on this list where codes and descriptions define the parcel use code, primary property type and the secondary property (Pima County Assessor's Office 2016). The four-digit parcel use code was the attribute to which the join was focused.

The resulting dataset consists of a synthesis of all single-family and multi-family land uses as well as any additional land use where the primary property type is residential. Mixed uses are included in this dataset, but not as a primary use and only as a secondary designation (See Tables 2 and 3). Primary uses are explicitly specified to have residential land uses present.

Table 2 Pima County Primary Use Descriptions and Codes

USE DESCRIPTION CODE	**USE DESCRIPTION**
A	Agricultural
C	Commercial
I	Industrial
M	Miscellaneous
R	Residential
V	Vacant Land
X	Not Used

Table 3 Pima County Secondary Use Classifications

SECONDARY USE CODE	SECONDARY USE CLASSIFICATION
20	Single-Family Residential
21	Residential Twoplex
22	Residential Tri/Fourplex
23	5-24 Apartment Units
24	25 or more Apartment Units
25	Condo/Townhouse
26	Mixed Use
27	Subdivided Mobile Home Property
28	Unsubdivided Mobile Home Property
29	Mobile Home with Additional Land Use
30	Mobile Home Park
31	Residential Parcel larger than 5 Acres
32	Residential Rental
35	Timeshare
36	Timeshare
39	Other

Some Pima County Datasets could not be used due to limitations in the data. Point of interest data was going to be used in identifying some of the LUPTAI-specified land uses and measuring accessibility to cultural landmarks in Tucson. This dataset was abandoned because not all land uses were identified in the dataset and many cultural landmarks could not be properly classified into one of the LUPTAI-specified land uses. Lack of compatibility with the land uses would divert from the initial LUPTAI calculation. Jurisdictional land use and zoning data from Pima County was also acquired and omitted from the analysis because it was similarly inconsistent and incomplete.

3.2.2. Sun Tran Data

Pima County also acquired updated bus route data from Sun Tran to create a vector polyline dataset representing all bus routes in Tucson. Sun Tran does not maintain any GIS data, but it does provide a key data source for network analyses. Regular Sun Tran routes were delineated in both the 2009 and 2014 datasets while Sun Tran Express rush hour routes were only in the 2014 dataset. Although the Sun Tran Express rush hour services were only included in the 2014 dataset, they likely existed in 2009. Therefore, in some limited cases, the network analysis may demonstrate service improvements in the study interval when they did not take place. Sun Shuttle commuter routes were not included in this analysis because neither Pima County nor Sun Tran had the applicable route data available for either year. Aside from commuter routes, every single bus stop in Pima County is mapped in a vector point dataset by Pima County regardless of express or local status with data provided by Sun Tran, excluding the Sun Shuttle commuter bus stops.

3.2.3. General Transit Feed Specification (GTFS) Tables

General Transit Feed Specification (GTFS) Tables played a vital role in completing the analysis. GTFS tables include geographic coordinates for stops and routes, schedule data associated with every stop, and trip frequency tables. The coordinates provide the basis for completing the network analysis by providing a temporal aspect to the transit data.

One of the roles of the GTFS data is to decipher the time it takes to travel between transit stops of different modes. GTFS datasets have become the most popular transit route datasets to use, and hundreds of programming organizations use GTFS data to create applications (Antrim 2010, 8; Trillium Solutions Inc. 2014, 11). The widespread of GTFS datasets demonstrates that they are a sort of de facto standard in assessing public transportation networks. Sun Tran is solely responsible for the creation and maintenance of the GTFS tables.

It is not easy to build feature classes from GTFS data. Spatial joins help analysts create or analyze transit features, but an independent GIS developer created a solution. Melinda Morang created the “Yay! Transit Toolboxes” to aid in interpreting GTFS Data in a GIS. Morang created multiple toolboxes that included adding GTFS Data to network datasets, generating GTFS shapes, and estimating unknown stop times based on present data (Morang 2013). The “Yay! Transit Toolboxes” provide the best type of data in order to assess travel times based on transit system schedules and stop locations.

The thesis author created a network dataset and associated feature classes with these toolboxes. The resulting feature classes provided more information than the data provided by Pima County. Sun Tran Express and Sun Link stops were included in the resulting dataset (see Figure 8). The 2014 feature classes from the GTFS toolboxes were similar to the 2009 Pima County bus stop and route datasets which provided a basis for completing a strong analysis for 2014.

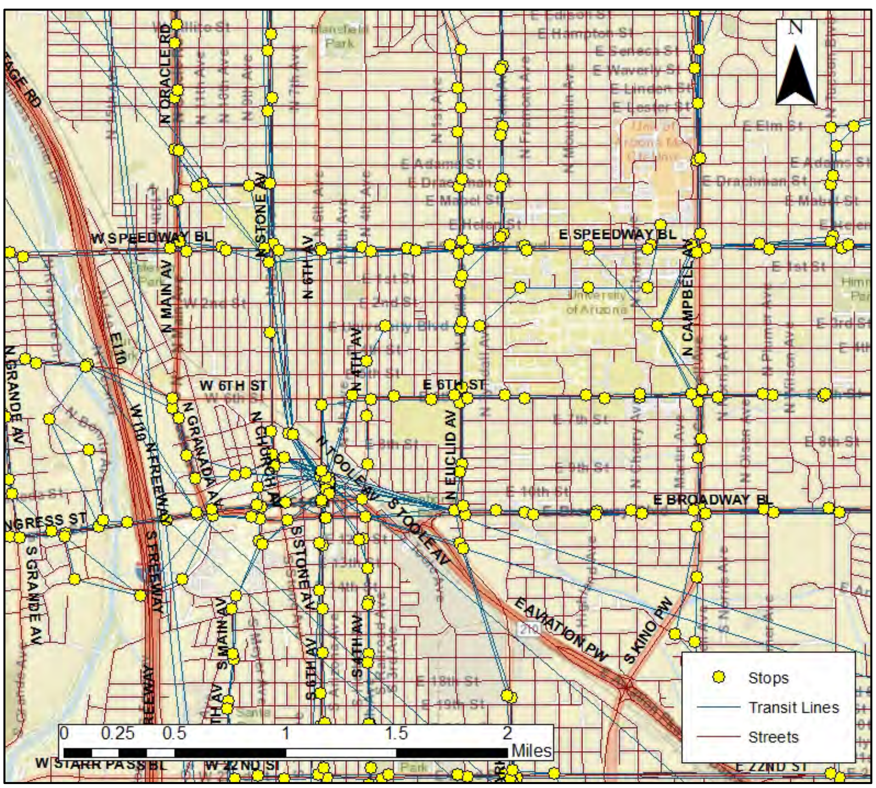


Figure 9 GTFS-based Network Dataset of 2014 Sun Tran Network

Unfortunately, the GTFS data availability presented a significant limitation. Pima County does not maintain GTFS data, and Sun Tran is the only source for the GTFS text tables. Sun Tran did not properly archive their GTFS data and did not have 2009 GTFS data for this reason. Instead, the author created a dataset with 2009 Pima County bus stop and bus route datasets based on the 2014 Sun Tran GTFS data. This approach required estimation and was based on an alternative approach to compensate for this data omission (See Section 3.4.4 and Table 9).

3.2.4. U.S. Census Bureau Data

Even though the unit of analysis for this study is parcel boundaries, the U.S. Census Bureau provided additional data, which guided the analysis. The U.S. Census Bureau provided data to Pima County based on results from the 2000 and 2010 Census. Census data was overlaid at the census tract scale, and values were estimated for each parcel. Employment and job center data is important because it is one of the five land uses examined in this analysis.

Esri ArcGIS Business Analyst (see Section 3.1.5) contains NAICS Codes and business locations, but it does not adequately identify employment centers. The U.S. Census datasets for Pima County provide a solution. The census tract vector polygon feature classes contain a number of demographic attributes, but the most important attributes are the polygon area and the total employment in the census tract. These attributes enabled the author to calculate a job density statistic. No other census data was used to complete this analysis.

3.2.5. Esri ArcGIS Business Analyst Data

Esri ArcGIS Business Analyst played a significant role in completing the analysis. LUPTAI-defined land uses for all index categories except for employment are defined for parcels from datasets accessible with this extension. The author attempted to use public land use and zoning data in this analysis. The jurisdictional land use data was incomplete because Pima County and Tucson had the only land use feature classes available to the public. Feature classes in both the cadastral and zoning data sets did not provide the specific land use classifications needed to translate to the land uses given in LUPTAI.

Zoning datasets were more accurate than cadastral data because each zoning designation corresponded to a particular land use. The Pima County Assessor’s Parcel Feature Class provided every zoning designation regardless of jurisdiction (see Figure 9). However, ground truthing revealed inaccuracies between some zoning designations and actual land uses. The land uses specified in LUPTAI were also not compatible with the zoning data. The large number of jurisdictional zoning designations would also have provided an incomplete basis for the analysis.

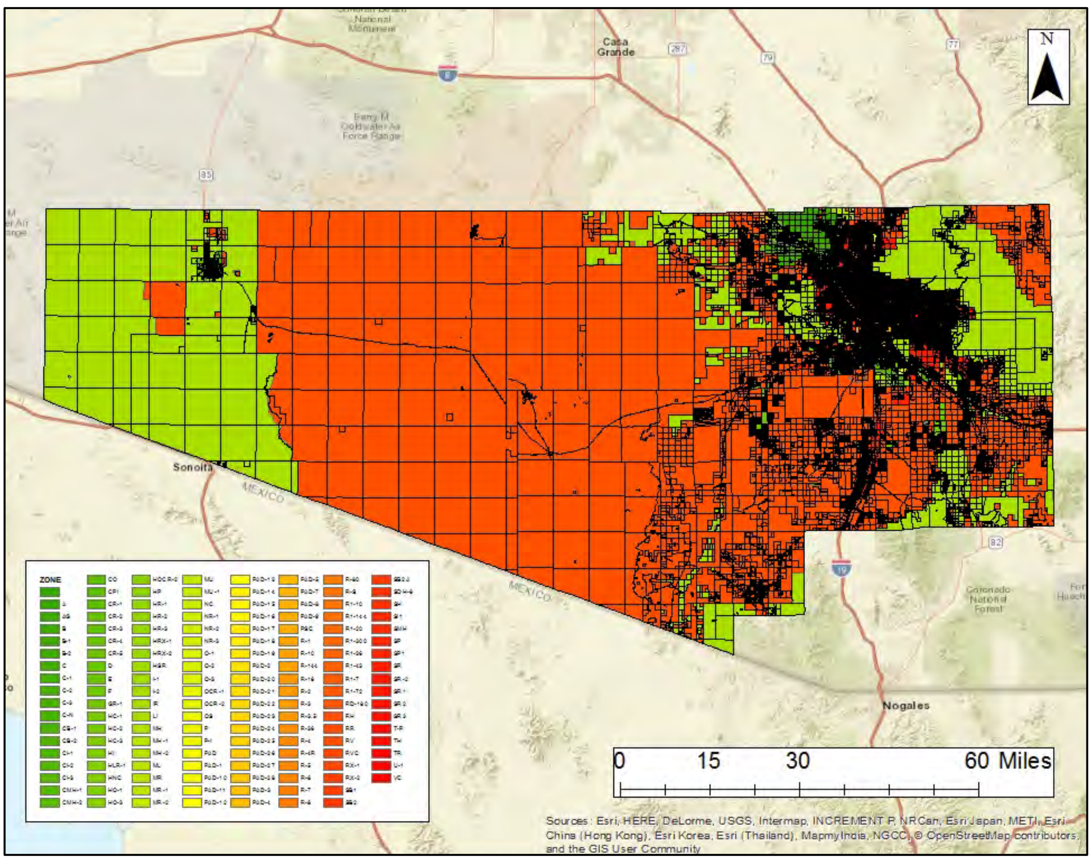


Figure 10 Pima County Zoning Designation Data as Viewed in Esri ArcMap

NAICS Codes from Esri ArcGIS Business Analyst provided the best identification of LUPTAI-specified land uses. Each of the land uses specified in LUPTAI has a unique NAICS designation. A table with all NAICS codes and a list of all businesses in Tucson was required to identify the land uses with specific codes pinpointed to each specific land use in LUPTAI (See Table 4). NAICS Code levels from 2 digits to 6 digits used to identify the land uses include sector, subsector, industry group, NAICS industry and U.S. industry digit identifiers.

Table 4 NAICS Codes for LUPTAI-Specified Land Uses

LUPTAI LAND USE	**NAICS CODE**	**LUPTAI LAND USE CATEGORY**
Primary Schools	611110	Education
Secondary Schools	611110	Education
Tertiary Education	611310	Education
Employment Centers	See Table 6	Employment
Banks	All Sector 52 Designations	Finance
Post Offices	491110	Finance
ATMs	522320	Finance
Dentists	All Industry Group 6212 Designations	Medical
Doctors	621111	Medical
Hospitals	All Subsector 622 Designations	Medical
Pharmacists	All Industry 44611 Designations	Medical
Shopping Centers	All Designations for Sectors 42, 44 and 45	Shopping
Newsstands	451212	Shopping

Multiple spatial joins would have been required to complete the data set for the land uses and would have added extra time to the analysis. The Esri ArcGIS Business Analyst extension provided a way around this tedious process. NAICS Codes can be searched in this application and the author compiled a list of all applicable codes that matched the LUPTAI land uses. The required NAICS codes were then searched in business analyst, and a single feature class was created that corresponded to each land use. The associated data was extracted into point feature classes and merged with the parcel feature class for use in the analysis.

3.3 Variable Summary

The author created multiple attributes and variables for use in the analysis. Attributes and variables already in use by Pima County, Esri, and Sun Tran were also included in the analysis. Table 5 lists all variables and data sources used to complete this analysis:

Table 5 Attribute and Variable Summary

ATTRIBUTE/VARIABLE	DATA SOURCE	PROCESSING
Education Land Uses	Esri ArcGIS Business Analyst	Merger of NAICS point feature classes (see Table 4)
Finance Land Uses	Esri ArcGIS Business Analyst	Merger of NAICS point feature classes (See Table 4)
Medical Land Uses	Esri ArcGIS Business Analyst	Merger of NAICS point feature classes (See Table 4)
Shopping Land Uses	Esri ArcGIS Business Analyst	Merger of NAICS point feature classes (See Table 4)
Employment Land Uses	Pima County 2000 and 2010 Census Tract Employment Polygon Feature Classes	Feature to Point tool calculation and Delete Field tool processing for irrelevant fields
Transportation Accessibility Buffers	Sun Tran GTFS Data and Pima County Bus Stop Point Feature Class	Undissolved Multiple Ring Buffer of 4 measures specified in LUPTAI
Walking Accessibility Buffers	Sun Tran GTFS Data, Pima County Bus Stop Point Feature Class and Pima County Road Network Line Feature Class	Network dataset creation with specified feature classes. Network analysis to calculate times.
Residential Parcels	Pima County Assessor’s Parcel Feature Class and Land Use Table	Spatial Join between table and feature class to isolate residential land uses

3.4 Software Requirements

Esri ArcGIS and Microsoft Office Programs comprise the software required to complete this analysis. Esri ArcMap provided the required program to complete the analysis and visualize the results. Extensions were enabled to complete the analysis, including Business Analyst and Network Analyst. This analysis did not require any further extensions.

Microsoft Excel provided a lifeboat when calculations took too long or took up too many data. The author exported incomplete attribute tables, such as percent change or transportation score tables, from Esri ArcGIS into an Excel spreadsheet to complete the calculation. This solution was employed when the percent change calculations between the 2009 and 2014 analyses proved to be too much for Esri ArcGIS to handle. The export situation also occurred when final score calculations took place.

The spreadsheet with completed calculations was then reduced to provide a manageable number of columns. The column reorganization led to a spatial join with the original feature class resulting in the classification of the features based on the original values. Any situation where an attribute was not properly displayed was remedied with the creation of a new field and calculation of the values of interest based on the non-conforming attribute.

3.5 Accessibility Scoring

The accessibility score equation is the same as the one used in the LUPTAI Model. The equation consists of the equally-weighted product of 0.2 and the respective land use score summed together to arrive at the MATAS score (see Equation 1). The MATAS score applies to all mass transit stops in the Sun Tran network based on the distance between each land use and the transit stop.

$$MATAS = 0.2 * Education + 0.2 * Employment + 0.2 * Finance + 0.2 * Medical + 0.2 * Shopping$$

Equation 1: Master Accessibility Score Equation (Yigitcanlar 2007, 16)

3.5.1. Variable Retrieval and Calculations

Esri ArcGIS Business Analyst was a significant source for the land use data. The author identified each LUPTAI-specified land use category by NAICS code and extracted the resulting data into centroids to the study area. Each land use centroid layer was then merged into the specific category based on its classification with the LUPTAI-specified land use. One specific category used in LUPTAI was excluded during this process. The authors of LUPTAI include ATMs, banks, and post offices in the finance land use (Pitot 2006, 4). ATMs are a part of the financial land use definition, but they can also be found at hundreds of locations in a large heavily populated area.

Pima County is no exception to the ATM saturation because there are a large number of ATMs spread out across the county. The ATM abundance would create an overestimate of accessibility to financial services. The idea of financial service in the LUPTAI model goes beyond just basic deposit and withdrawal sorts of banking activities and includes a range of consumer financial services found at full service at banks and brokerages. Thus, ATMs were excluded from the finance layer.

As shown in Table 2, Esri ArcGIS Business Analyst accounted for four of the five LUPTAI-specified land use types. It might be possible to estimate employment centers from NAICS codes, and in fact, Business Analyst has data on the number of employees at each location. However, this would result in a long, tedious data extraction process and the quality of the data is unknown. U.S. Census Data for Pima County remedies this issue because it allows for a count of the amount of jobs within census tract boundaries.

Pima County provided a polygon feature class by census tract from the U.S. Census Bureau. The author converted this feature class into a point feature class to correspond with the other land use types as centroids. The centroids contained the number of jobs within the census tract, leading to calculations made later in this analysis. In a similar approach, the study of Minneapolis-St. Paul covered in Chapter 2 created centroids based on the number of jobs within each census block (Owen 2012, 15). The centroid creation approach is consistent with the Business Analyst extraction process because the data from Business Analyst is depicted as a point feature class.

Buffers from bus stops and streetcar stations were calculated concurrently with the Business Analyst land use data extraction. The 2014 bus stop and streetcar station data were created with Tucson Sun Tran GTFS data in Melinda Morang's Yay Transit! Toolboxes. The 2009 bus stop data came directly from Pima County because no GTFS data was available from that year. As an estimate of walkability from a given parcel to a bus or streetcar stop, this analysis used the same buffer distances as those used in LUPTAI, as specified in Table 6. The theory is that people are willing to walk somewhat further distances for rail or streetcar transit than for bus transit.

Table 6 LUPTAI and Tucson Accessibility Model Transportation Buffers (Pitot 2006, 6)

ACCESSIBILITY TYPE	BUS BUFFER	BUS BUFFER MILES	STREETCAR/TRAIN BUFFER	STREETCAR/TRAIN BUFFER MILES
High	300 meters	0.19 miles	600 meters	0.37 miles
Medium	400 meters	0.25 miles	800 meters	0.5 miles
Low	800 meters	0.5 miles	1,000 meters	0.62 miles
Poor	1,000 meters	0.62 miles	1,200 meters	0.75 miles
None	> 1,000 meters	> 0.62 miles	> 1,200 meters	>0.75 miles

Calculating the individual buffers with the Esri ArcGIS Buffer tool is a timely process that would take up a large amount of data space and result in a system crash during the calculation. Multiple ring buffers remedied this issue. The author implemented multiple ring buffers without dissolving the resulting buffer. The conjoined buffers allowed a proper connection between each parcel centroid and the closest buffer to the transit stop regardless of whether it was a streetcar or bus stop (See Figure 11). This approach shows the accessibility of Downtown Tucson and the University of Arizona area where no parcel is more than one kilometer from a bus stop.

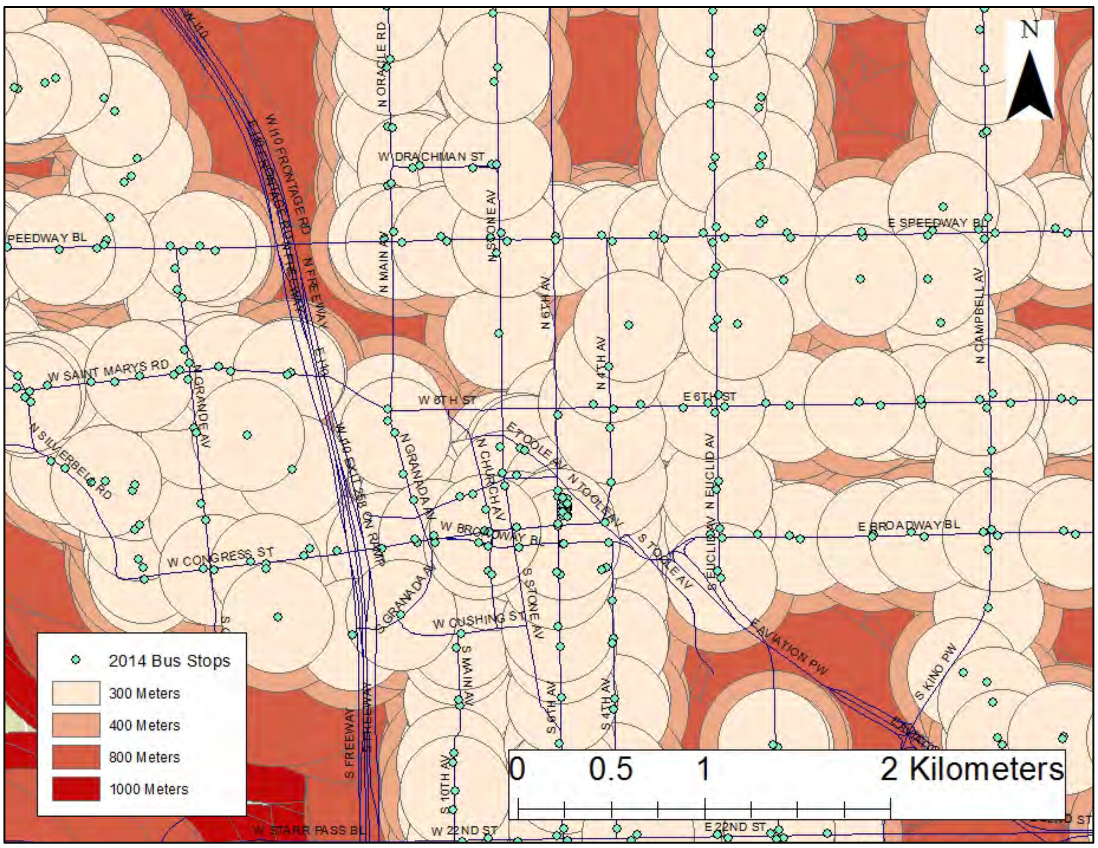


Figure 11 Multiple Ring Buffers with Bus Stops Around Downtown Tucson and the University of Arizona

3.5.2. Land Use Density Calculations and Scoring

Land use densities for all five LUPTAI-specified land use types through two different approaches were calculated for all transit stops once all land use data was extracted, and transit accessibility buffers were calculated. Education, finance, medical, and shopping land use densities were calculated for the number of land use centroids within the specific buffers. Spatial joins with the transit stop multiple ring buffer were required to complete this calculation. The result was a polygon layer with the number of land uses within the specific transit stop buffer. The buffer area was then converted from square feet to square miles. The density was then calculated in the buffer layer as the quotient of the number of land uses and the area in square miles. Figure 12 visualizes this process with an intersection northwest of the University of Arizona.

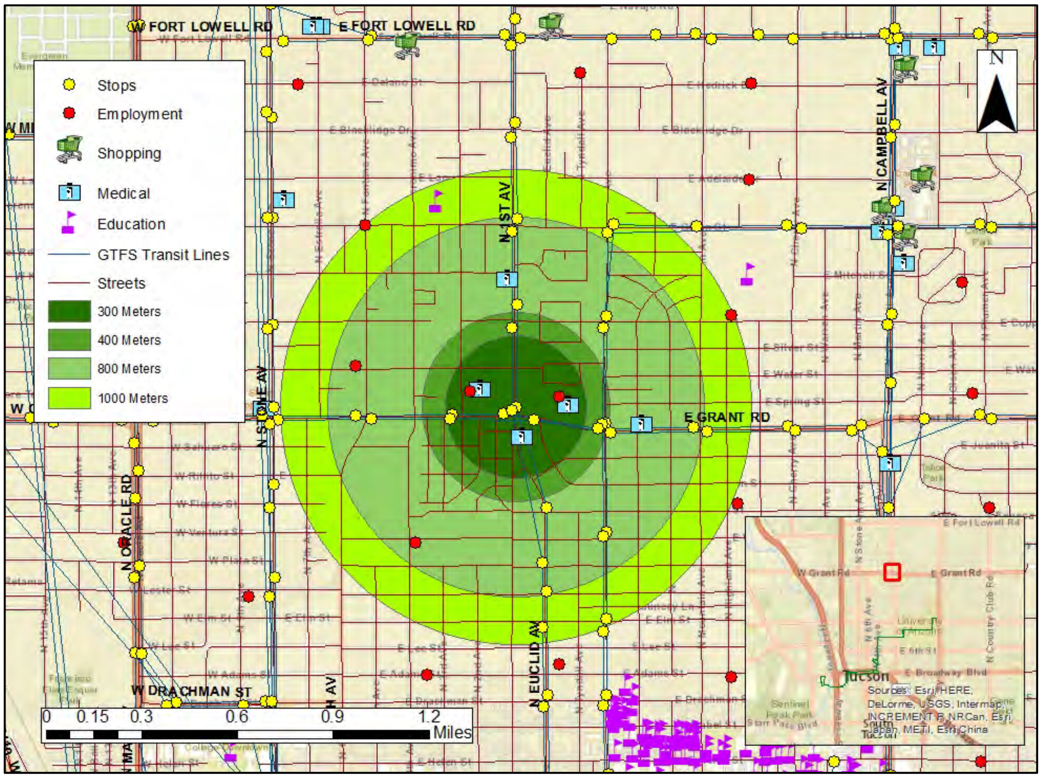


Figure 12 Land Use Diversity and Transit Score Calculation Example: 1^{st} Avenue and Grant Road

A different measure was required for the employment data. Since Esri ArcGIS Business Analyst provided a poor land use definition that would consume time and data, Pima County U.S. Census data was used instead. Data from 2000 and 2010 corresponded closest with the study interval. The same spatial join took place as the one with the four other land use types, and the area was also converted from square feet to square miles. Once these processes took place, the employment density was calculated as the number of jobs within the census tract divided by the area of the closest buffer in square miles.

All land use densities enabled the scoring of the land use type proximity to each transit stop. The author calculated the mean and standard deviation of all land use density types within the transit stop buffer. From there, the author assigned a score based on the mean and standard deviation of the land use density as specified in Table 7 below.

Table 7 Land Use Density Score Calculation Criteria

SCORE	CRITERIA
4	>1 standard deviation above mean to maximum density
3	Mean to 1 standard deviation above mean
2	1 standard deviation below mean to mean
1	>1 standard deviation below mean

Other than with the employment land use, each land use table was then merged and edited, which allowed the scores for each transit stop to be summed for each land use. The merged output resulted in scores between 14 and 26. Score splits by quartile, as specified in Table 8, provided the basis for determining land use density score for each transit stop with the intent to maintain consistency with LUPTAI by providing scores within one of the four LUPTAI accessibility levels:

Table 8 Transit Stop-Land Use Density Score Criteria by Quartile

LAND USE DENSITY SCORE	LAND USE SUM CRITERIA
4	24-26
3	21-23
2	18-20
1	14-17

Employment scores were not included in the classification demonstrated in Table 8 as a result of the data discrepancy. Instead, the score was calculated as a total number of jobs per square mile from U.S. Census data at the census tract level. Direct calculations took place within the census tract centroid data based on the mean and standard deviation of the employment densities in a similar approach demonstrated in Table 8. The closest employment centroid to the transit stop received the score for a given transit stop. If a parcel is located in more than one buffer within the closest distance to a transit stop, the parcel received the score related to the closest transit stop. This approach eliminates duplicate scores and gives a reasonable estimate of accessibility.

3.5.3. Accessibility by Transit Stop

The next step towards completing the analysis was to complete a network analysis in Esri ArcGIS Network Analyst. A GTFS network dataset was created from the Sun Tran GTFS Tables with “Yay! Transit Toolboxes.” The author created an origin-destination cost matrix (O-D matrix) of given transit times from each bus stop and streetcar station to every other station in the Pima County transit network afterward. The times calculated in the O-D matrix were based on the times calculated to travel along the straight paths between stops with midday Monday through Friday travel times around 12 noon.

The O-D matrix was successfully calculated despite some significant issues. The Sun Tran GTFS data was missing some attributes that would enable the routes to snap to the Pima County street network feature classes. Therefore, a crucial step was hand to snap the routes to the street network by hand using the integrate tool and corresponding line edits in ArcGIS (See Figure 11).

Also, there was no Sun Tran GTFS Data from 2009. To compensate for this issue, the author used the Sun Tran schedule from 2014 to estimate travel times. The author estimated missing travel times based on travel times for comparable distances in the 2014 schedule. The lack of information for 2009 did not affect the network analysis because of similarities between the network in both 2009 and 2014.

The network analysis led to the second score, which assessed the time it takes to travel on the transit network from one transit stop to another. A score between 0 and 4 was assigned based on the distance between the subject transit stop and the nearest transit stop (See Table 9). The score factors corresponded to one of the five score types specified in LUPTAI. The time it took to transfer between stops at transit centers or near adjacent stops factored into this score calculation.

Table 9 LUPTAI Accessibility Types for Times Between Transit Stops with Transfer Times

ACCESSIBILITY TYPE (with Score Factor)	**TIME**
High (4)	0-10 minutes
Medium (3)	10-20 minutes
Low (2)	20-40 minutes
Poor (1)	40-60 minutes
None (0)	>60 minutes

3.5.4. Scoring Land Use Diversity Surrounding the Closest Transit Stop

The author took similar measures to calculate the third accessibility score. Similar to the second score calculation method, the author measured travel times between land use centroids and transit stops with the results of the network analysis from the GTFS data. With 2009 GTFS data unavailable, the author once again estimated the travel and transfer time for that year based on the 2014 schedule and GTFS data (see above).

A score factor that corresponded with one of four LUPTAI accessibility types (see Table 9 and Section 3.4.4) was added to the average land use density scores to complete the third land use score calculation. The third land use score assessed the accessibility based on travel times between the land use and the closest transit stop.

There were now three scores that demonstrated land use accessibility based on the land use densities, transit stop accessibility and distances between land uses and the closest transit stop. The resulting scores were then summed together to form a score for each LUPTAI-specified land use. The resulting sums were then plugged into the equally weighted master formula demonstrated in Equation 1. The MATAS score measured the accessibility from all five land uses to all bus and streetcar stops with scores between 0.1 and 4 (see Equation 1 and Table 6).

3.5.5. Residential Parcels and Final Scoring

Pima County residential parcels provide the basis for the final accessibility scores. The majority of parcels in Pima County are residential regardless of whether they are single-family or multi-family residences. Residential parcel abundance is a strong characteristic of a sprawling region, where single-family residences are spread out with miles in between services. In sprawl, the distances between the residential property, jobs, and services give limited accessibility to each land use type even before transit is considered.

The Pima County Assessors Office’s land use codes identify all residential parcels in Pima County. A spatial join between the land use code table and the Pima County Assessor’s Parcel feature class enables the identification of land uses for every parcel. From there, the author conducted an attribute selection for properties identified with the “R” designation and created a feature class containing every residential parcel in Pima County (see Figure 13 and Table 1)

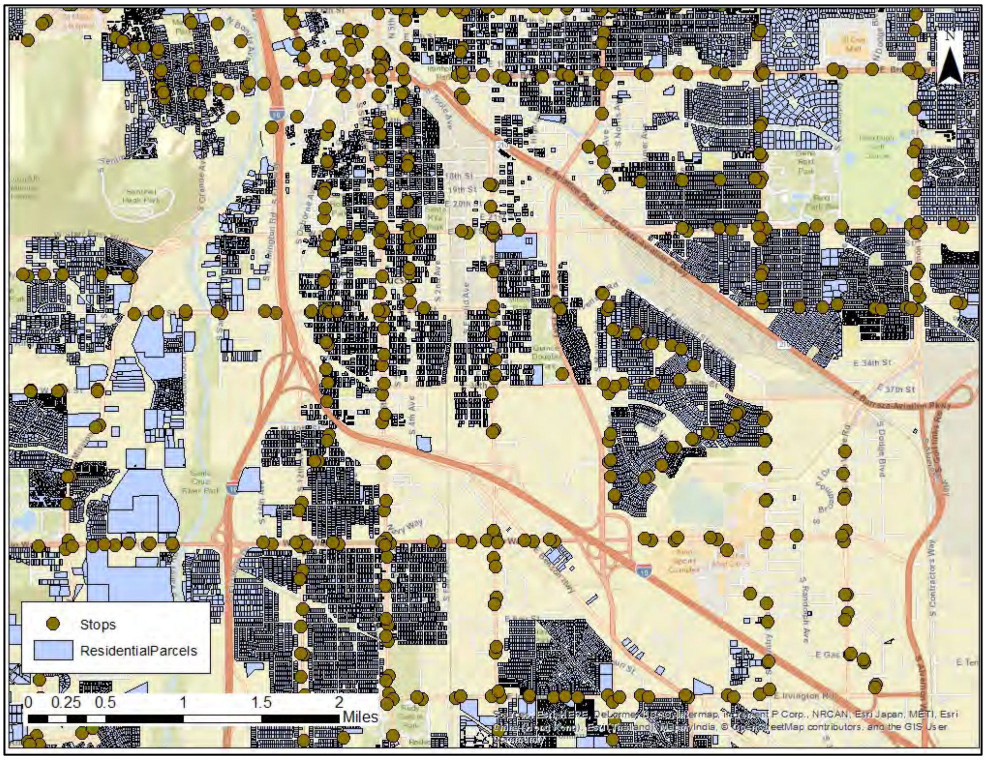


Figure 13 South Tucson Residential Parcels

Once all residential parcels were isolated, the author identified the parcels that were within the mass transit accessibility buffers (See Table 6). All parcels not within any buffer were automatically scored as having zero accessibility. If a parcel was located within two or more buffers, the smallest buffer from the closest transit stop was identified. The first score calculation comprised the sum of the MATAS score for the closest stop, which ranged between 1 and 4, and a different score between 1 and 4 based on the buffer in which the parcel was located (i.e., how close the parcel was to its nearest stop). The two scores were added together, resulting in a score between 2 and 8.

The final score equally weighs the travel distance to the closest transit stop and the accessibility to various land uses through the transit network. The score is then divided by 2, giving a final score for each residential parcel in Tucson between 1 and 4 for all parcels within the transit stop accessibility buffers (see Table 10).

Table 10 LUPTAI Score Criteria

ACCESSIBILITY TYPE	SCORE
High	4
Medium	3
Poor	2
Low	1
None	0

3.5.6. Comparisons between 2009 and 2014

The entire process was repeated for 2009 after completing the 2014 analysis. Some datasets had to be substituted where 2009 data was missing. For example, there is no GTFS data for 2009, so Pima County bus stop data was used instead. Business Analyst datasets from 2009 were also not retrievable, so the 2014 data was used instead. The 2009 data shortcoming brings about a similar solution even though it also creates a major limitation for the analysis (see Chapter 5).

Comparisons between 2009 and 2014 final scores took place after the processes were complete. Such comparisons included changes in residential land uses and changes in scores between 2009 and 2014. The author created percent change maps in order to assess the score changes. The maps derived from the percent change formula where the author subtracted the 2014 score from the 2009 score and divided the difference by the 2009 score. The percent change maps and residential land use change observations determined whether the Sun Link system had any impact on transportation accessibility changes before and after the Sun Link system opened.

Chapter 4 Results

Transportation accessibility for residential parcels in Tucson improved between 2009 to 2014, but there was a decline in the accessibility measures for the transit stops themselves. This discrepancy relates to the addition of bus routes and stops in the periphery and the buildout of housing in these areas. Changes affected specific neighborhoods around Pima County differently. There were improvements in the suburbs and declines in Central Tucson and neighborhoods close to the Central Business District. Ironically, this included small decreases in accessibility scores around the Sun Link Route. In general, exurban neighborhoods saw little or no change to accessibility, while suburban neighborhoods saw increases in accessibility, and central neighborhoods, including those around the Sun Link route, saw mixed results. In both 2009 and 2014, accessibility remained relatively high around Central Tucson and in select suburban neighborhoods, while accessibility was low in the majority of periphery neighborhoods.

Mean transportation accessibility scores for residential parcels increased by more than 50% between 2009 and 2014. Closer proximities between transit stops and residential parcels were the main observable reason for this increase. New development and additions of routes and stops in areas that were already accessible to the Sun Tran network facilitated the closer proximities. However, in general, the accessibility increases were not the result of a greater diversity of land uses in proximity to transit stops.

This chapter begins with an overview of the aggregate scores calculated in this model. Specific regions are examined to provide context to the results. The Sun Link system area is examined next with particular context to Downtown Tucson and the University of Arizona. A comparison of two outlying neighborhoods follows. A region where scores decreased, the Tucson Mall and Rillito Downs area, is observed first followed by a region where scores increased, The East Side of Tucson.

4.1 Aggregate Scores

Between 2009 and 2014, there was a 6.4% increase in the total number of residential parcels in the Tucson metro area from 319,903 to 340,380 parcels. New residences were constructed on the periphery of Pima County and the City of Tucson as well as the suburbs of Marana, Oro Valley, and Sahuarita. The area around the Sun Link route has a number of existing single-family residences and apartment complexes. The only residential buildings that were not considered for this analysis were the University of Arizona residential halls. These buildings were counted as an educational land use pursuant to Pima County Assessor's codes and parcel files.

Land use accessibility not only differed in the study interval, but it also differed between the individual land uses. Accessibility scores ranged from zero to four, where increases in scores indicate increases in accessibility. For many of the land uses, scores varied based on their proximities to bus and streetcar stops, as modeled by their location within the accessibility buffers. Otherwise, scores were consistent between 2009 and 2014 because Business Analyst data was only used from 2014 (See Table 11 and Figures 14 and 15). As indicated in Table 11, the average MATAS score per stop between 2009 and 2014 decreased from 1.98 to 1.73.

Table 11 Mean Land Use Accessibility Scores for Tucson Transit Stops

LAND USE	2009 MEAN SCORE	2014 MEAN SCORE
Education	1.73	1.53
Employment	2.56	2.26
Finance	1.66	1.66
Medical	1.9	1.88
Shopping	1.33	1.32
AVERAGE	1.98	1.73

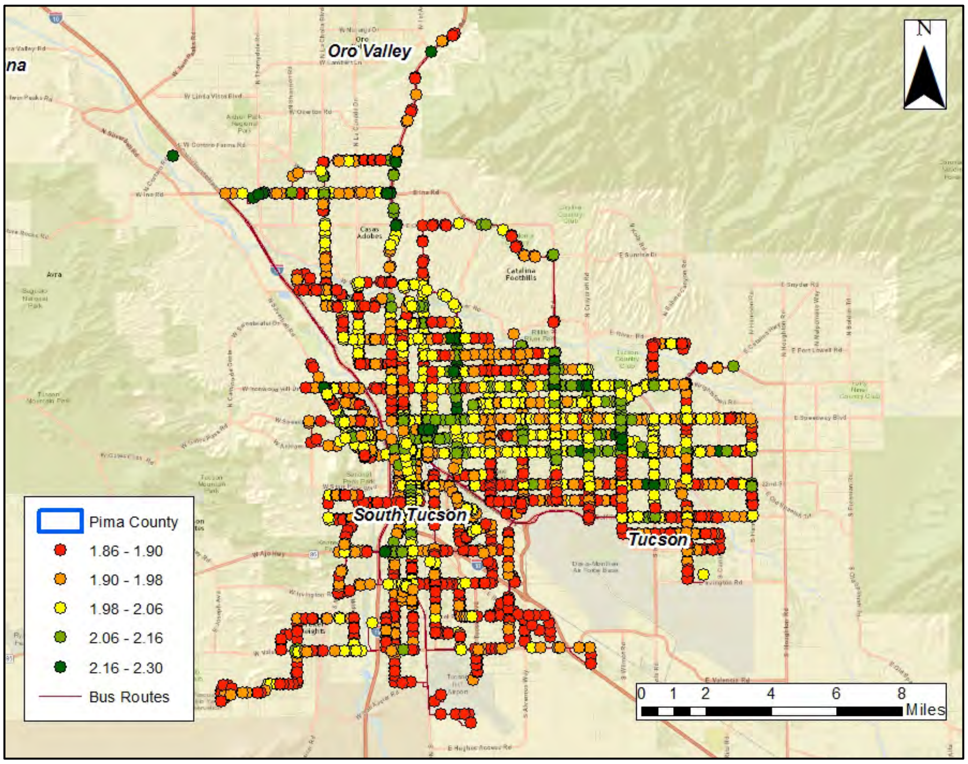


Figure 14 MATAS Scores by Transit Stop, 2009

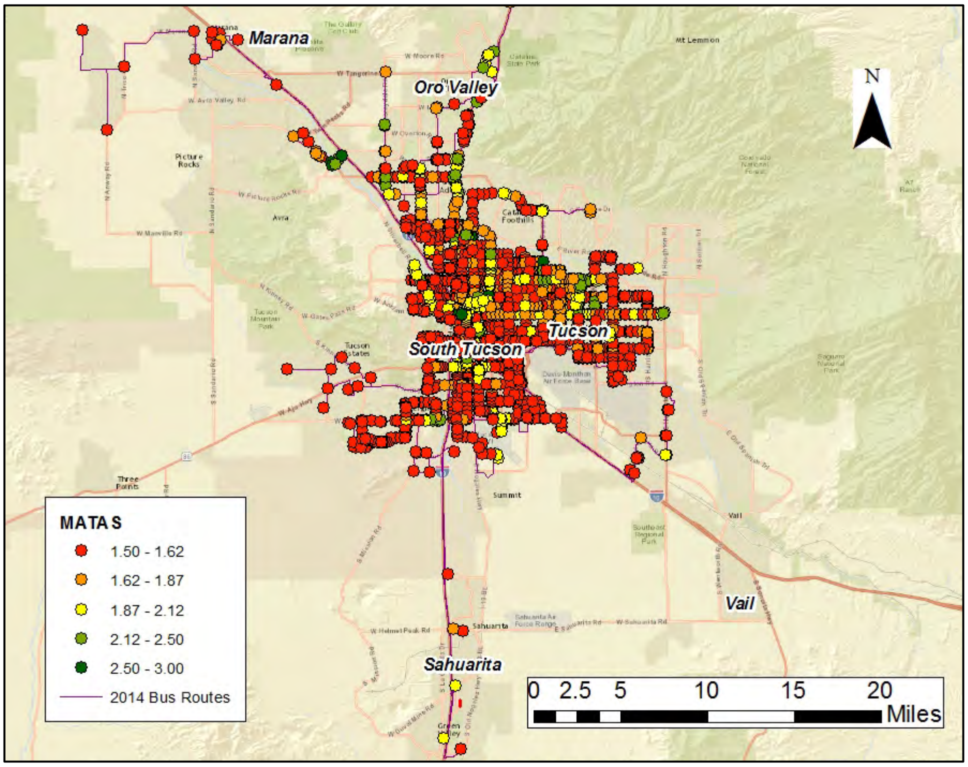


Figure 15 MATAS Scores by Transit Stop, 2014

The lower accessibility means for transit stops for given land use categories are due to changes in the Sun Tran network within the study interval such as bus route extensions or reductions and bus stop openings or closures. Specific land use locations within the accessibility buffers factor into the lower accessibility. Finance, medical, and shopping land uses are not located close to the Sun Link system area (See Figure 16), while educational and employment land uses generally are not located close to Sun Tran stops with the University of Arizona area serving as a significant exception (See Figure 17). With different buffers implemented for the bus and streetcar, the large number of land uses outside the maximum streetcar buffer decreased the accessibility for these land uses.

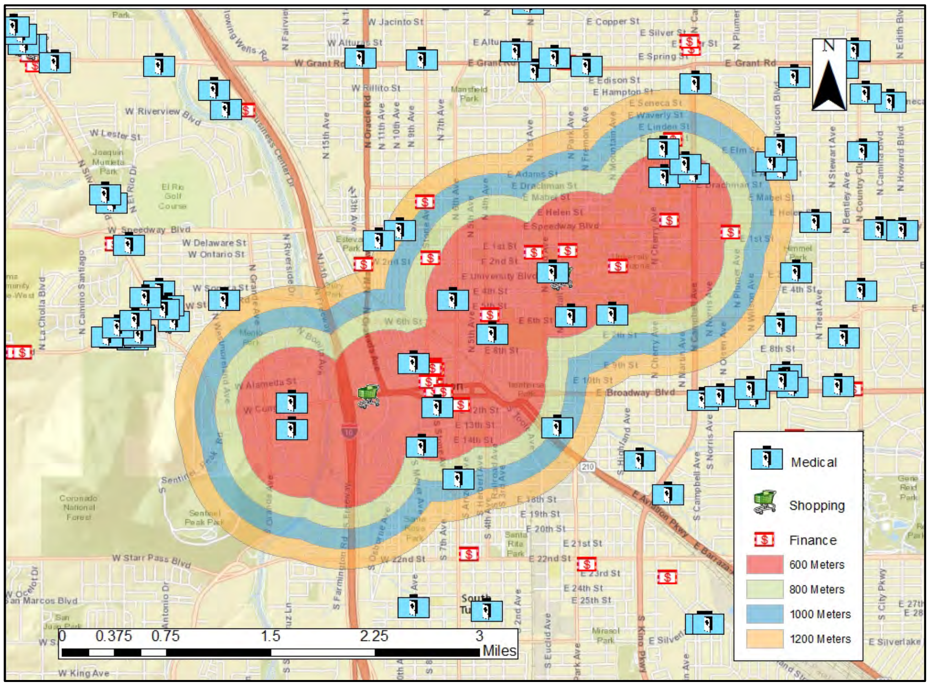


Figure 16 Finance, Medical and Shopping Land Uses within streetcar accessibility buffers

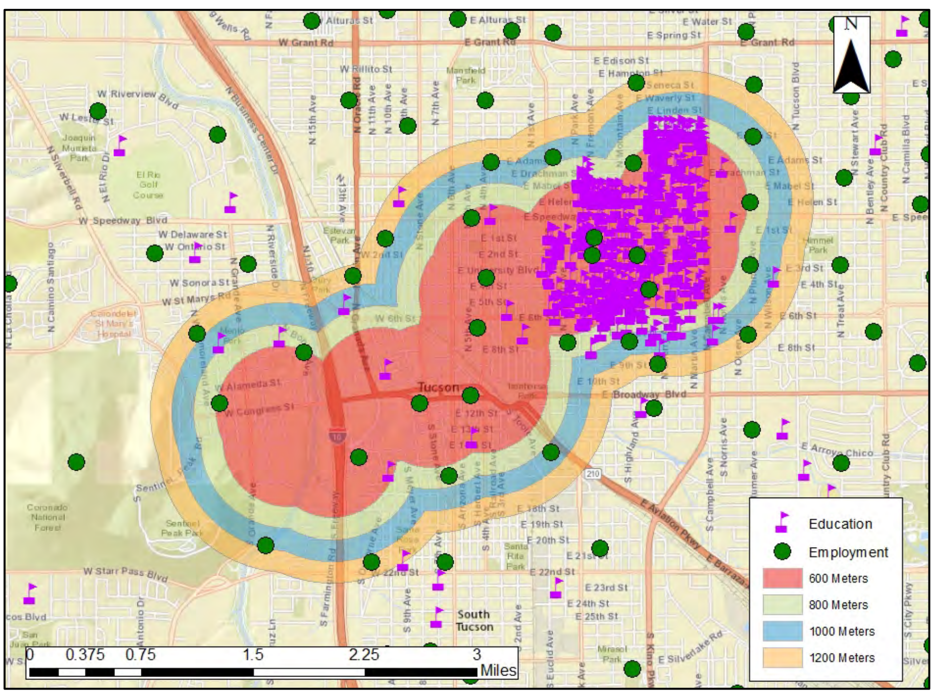


Figure 17 Education and Employment Land Uses within streetcar accessibility buffers

There were higher residential accessibility scores for parcels close to the Central Business District and lower scores around the periphery in both years (See Figures 18 and 19 and

Appendices A & B). A significant factor in calculating the scores was the proximity between the residential parcel and the closest bus or streetcar stop. Residential parcels with no score were either far from the largest accessibility buffer or within buffers where few contrasting land uses were present. Bus route expansions took place on the far East Side of Tucson, south of Davis-Monthan Air Force Base and in suburban communities, such as Marana and Oro Valley to the north leading to the accessibility score increases.

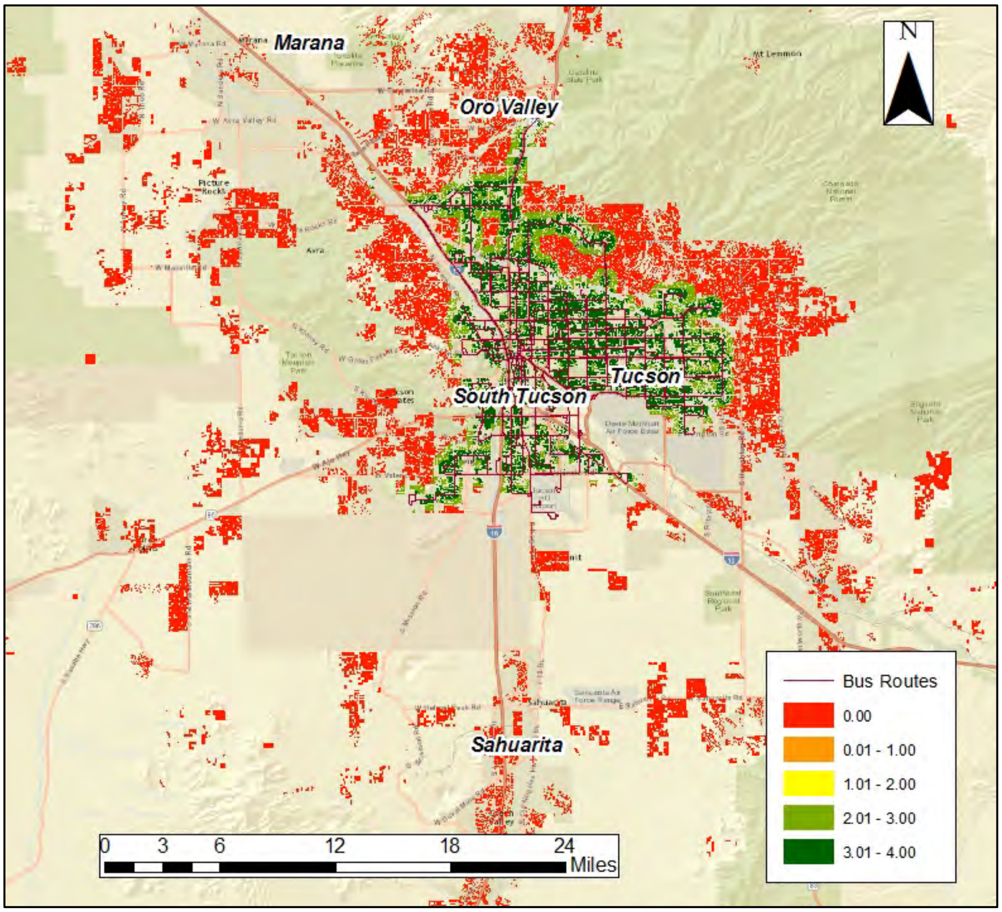


Figure 18 Tucson Residential Parcels Visualized by Final Accessibility Score, 2009

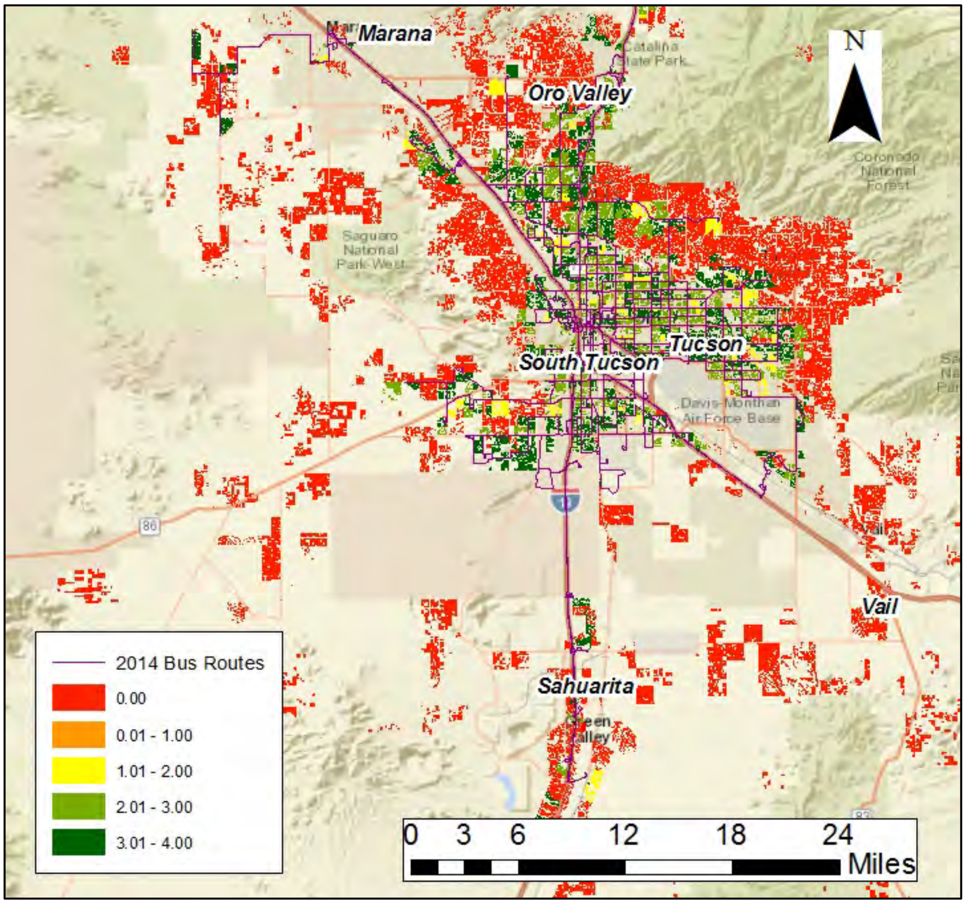


Figure 19 Tucson Residential Parcels Visualized by Final Accessibility Score, 2014

Transit stop accessibility scores factored differently. The MATAS score provided the accessibility from each land use to the transit stop. Mean MATAS scores for individual stops decreased and residential parcel scores increased from 2009 to 2014. Many land uses specified in LUPTAI and used for the Tucson analysis do not have access to stops throughout the Tucson Metropolitan Area. Such neighborhoods are located in the periphery or directly west of Downtown Tucson.

Residential accessibility to transportation collectively increased between 2009 and 2014. However, the majority of parcels either had high accessibility or no accessibility in both years. Table 11 reports the changes in accessibility levels between 2009 and 2014. The biggest changes occurred with the medium and low accessibility levels. None of the residential parcels in Pima County received a poor accessibility score. Most changes occurred at the medium accessibility levels and low accessibility levels. In 2009, no parcels received a low accessibility score. This trend changed where 21,119 parcels with no accessibility in 2009 achieved low accessibility in 2014, and 10,099 parcels with newly designated residential parcels by 2014 achieved a low accessibility score.

Medium accessibility scored parcels also increased during the study interval (See Table 12). New residential parcels contributed to the increase, where 11,208 parcels that had no accessibility and 3,387 new residential parcels achieved medium accessibility. At the same time, 45,371 parcels that scored high in 2009 decreased to a medium accessibility score in 2014. While many parcels saw score changes, 158,721 parcels did not change during the study interval.

Table 12 Residential Parcels by Accessibility Score Level

CATEGORY	**2009 COUNT**	**2009 PERCENT**	**2014 COUNT**	**2014 PERCENT**	**PERCENT CHANGE**
None	154,901	48.42%	146,506	43.11%	-5.42%
Low	0	0%	21,249	6.25%	-
Medium	38,494	12.03%	70,717	20.81%	83.71%
High	126,508	39.55%	101,332	29.82%	-19.9%
TOTAL	319,903	100%	339,804	100%	6.22%

The average transportation accessibility score for residential parcels across the entire region increased by from 1.84 to 2.75 (about 62%) between 2009 and 2014, while the average score for parcels in the Sun Link street car system area decreased from 3.89 to 2.77 (see Table 13). Such score category changes included score increases resulting from non-residential properties becoming residential between 2009 and 2014. The properties around the Sun Link system demonstrate a lower average score than the entire region even though the properties are located along or close to the route (see Section 4.2 and Figures 20 and 21).

Table 13 Average Residential Accessibility Scores in Study Interval

YEAR	AVERAGE ACCESSIBILITY SCORE	STANDARD DEVIATION
2009	1.84	1.81
2014	2.75	0.83
2009 Streetcar Area	3.89	0.33
2014 Streetcar Area	2.77	0.66

Different neighborhoods saw increases and decreases throughout the TMSA. Small decreases in accessibility took place in neighborhoods closer to Downtown Tucson as well as in neighborhoods within the City of Tucson. More accessibility increases took place in the periphery, and more decreases or non-changes in accessibility took place in Central Tucson neighborhoods (See Figures 16 and 17). The average residential parcel in the TMSA witnessed a 13% increase in accessibility between 2009 and 2014. Residential parcel score decreases within Tucson city boundaries contributed to the low average accessibility change.

Decreases as low as 1% took place throughout Central Tucson neighborhoods. Even though the average residential property saw a 13% increase in accessibility, the decreases were less prolific than the increases throughout the TMSA. The decreases in residential accessibility in Central Tucson could be the result of low scores for the five land uses located far distances from the maximum streetcar buffer and bus route eliminations. In order to make that conclusion, specific neighborhoods and the area around the Sun Link System need to be explored.

4.2 Sun Link Route

The Sun Link route area presents an unexpected result. Transportation accessibility scores decreased between 2009 and 2014 along the Modern Streetcar route through Downtown Tucson and the University of Arizona (See Figures 20 and 21).

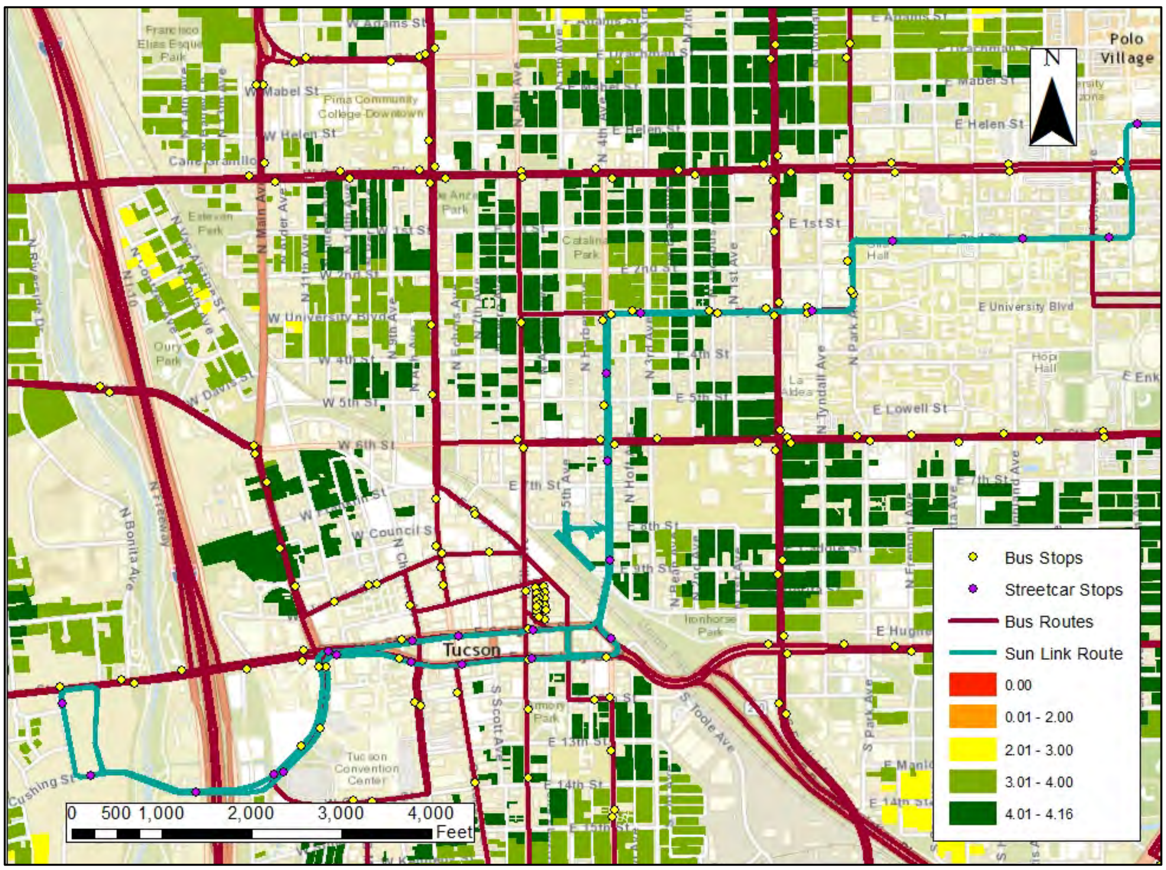


Figure 20 Sun Link Route Area Accessibility Scores, 2009

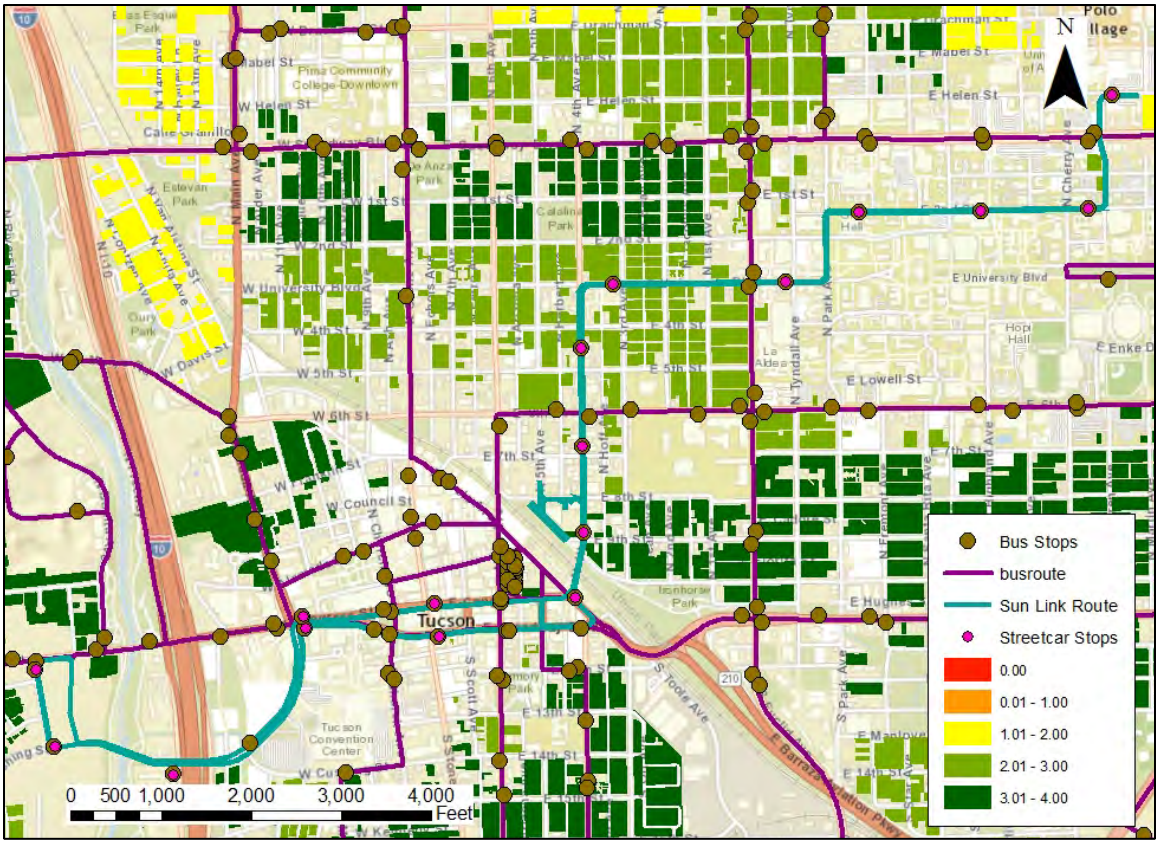


Figure 21 Sun Link Route Area Accessibility Scores, 2014

On average, even in 2014, the Sun Link system area still had parcels with higher accessibility scores than properties in the periphery even though the average accessibility score along the Sun Link system decreased. Between 2009 and 2014, average parcel accessibility scores decreased by about 0.29% (see Table 13 and Figures 20 and 21). Sun Tran eliminated some bus routes in order to ensure smooth Sun Link system operations. The bus stops provided better access from older single-family residences along the route along 4th Avenue and University Boulevard to different land uses in spite of the larger streetcar buffers.

Larger buffers from the streetcar stops, based on the idea that people would be willing to walk further to a streetcar than a bus, helped a few parcels increase scores. However, the elimination of bus routes and stops also decreased the score for some other parcels. In addition, there are few LUPTAI-specified land uses near the intersection of 4th Avenue and University Boulevard where a number of single-family residences are located (See Section 4.1 and Figure 13). Each Tucson neighborhood saw some accessibility change as a result of service changes between 2009 and 2014. Two areas that witnessed significant changes were the Tucson Mall/Rillito Downs area and the Tucson East Side.

4.3 Score Decrease Area: Tucson Mall/Rillito Downs

Tucson Mall and Rillito Downs (or Rillito Park) are located north of Downtown Tucson along the Rillito River. The Rillito River also serves as an informal boundary between central Tucson and the Catalina Foothills. This commercial and attraction corridor consists of single and multi-family residences, as well as significant shopping and finance landmarks within the area. These landmarks are consistent with the LUPTAI land uses. The Sun Link system is more than 1,200 meters away from this area and accessibility to the Sun Link route is poor. Accessibility to bus stops is strong, especially with a transit center on Stone Avenue adjacent to Tucson Mall. The transit center is depicted with many closely aligned bus stops east of Tucson Mall in Figure 22 and 23.

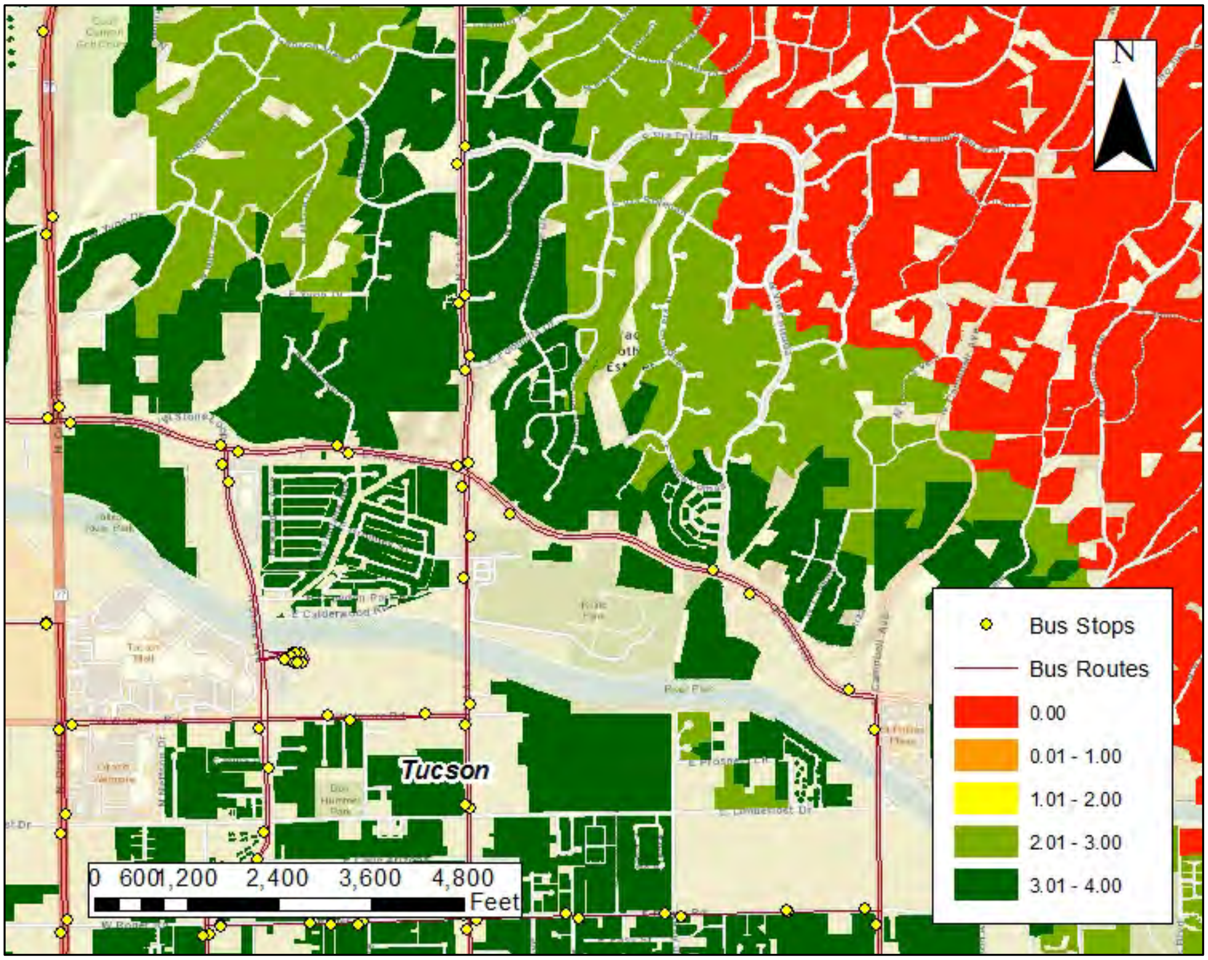


Figure 22 2009 Residential Accessibility Scores and Bus Stops, Tucson Mall/Rillito Downs Area

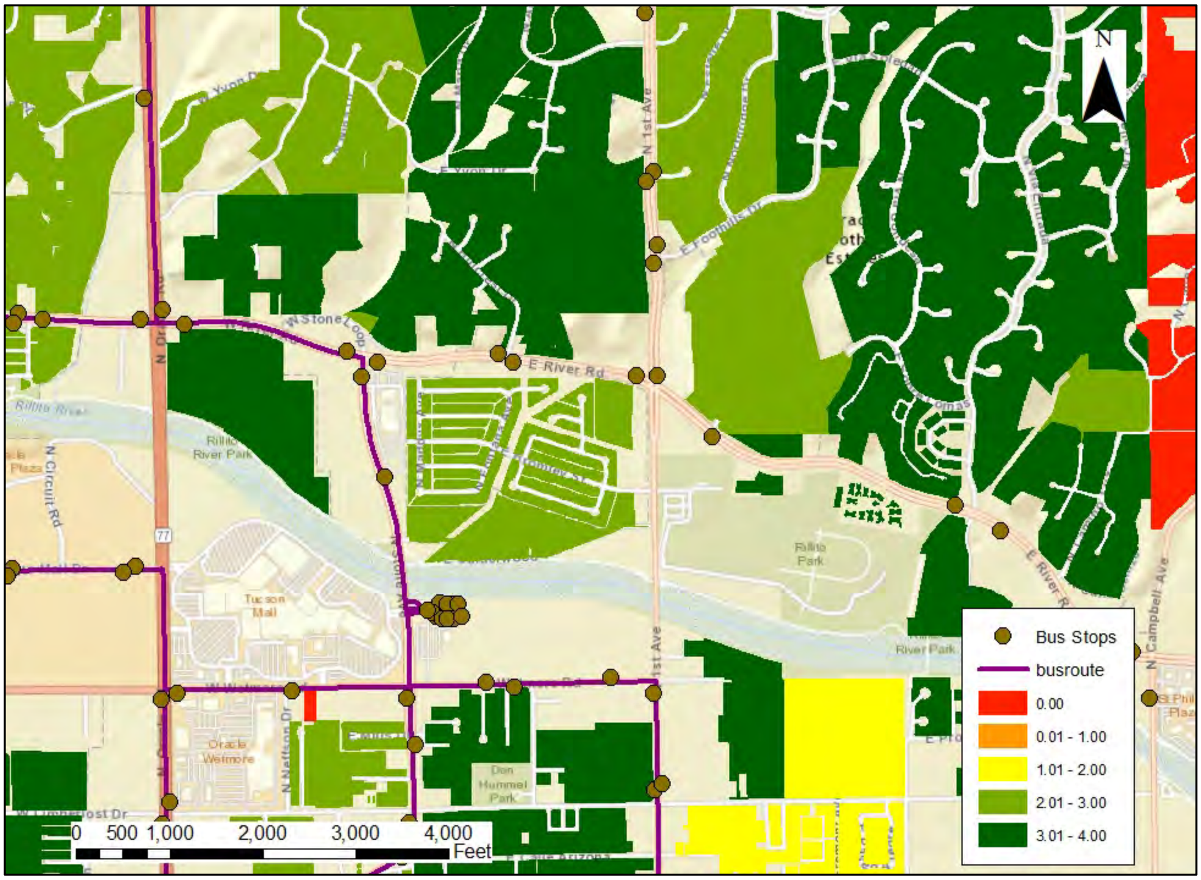


Figure 23 2014 Residential Accessibility Scores and Bus Stops, Tucson Mall/Rillito Downs Area

The changes in this area were mixed. Some parcels south of the Rillito River have decreased in accessibility present where score levels were maintained, even though some parcels to the north and closer to Rillito Downs saw accessibility increases into high or medium accessibility levels. While some new residential parcels were added between 2009 and 2014, new routes north of the Rillito River and stops south of the Rillito River were added to the area in that same timeframe contributing more to the accessibility increases than the new residences (See Figures 24 and 25 and Section 4.4).

The distance between streetcar stops and this area as well as the distances between land uses and bus stops play a role in the decreases south of the Rillito River. Tucson Mall is a major attraction and lifestyle destination, and there are many bus stops around the mall and its surrounding plazas. The residential parcels near Tucson Mall benefit from the proximity to this activity corridor and bus stop cluster.

4.4 Score Increase Area: Tucson East Side

The East Side of Tucson is a neighborhood that saw score increases within the study interval. The East Side of Tucson is a far outlying area broadly defined as anywhere east of Wilmot Road bounded by Davis-Monthan Air Force Base and the Catalina Foothills (Tucson Association of Realtors 2012). The East Side exemplifies urban sprawl through car dependency and single-family residential parcel neighborhoods, while essential services are not within suitable walking distances. There is little Sun Tran service to this neighborhood. Significant residential accessibility score increases occurred in clusters between 2009 and 2014 for multiple reasons even though many parcels achieved no accessibility in 2014 (See Figures 22 & 23).

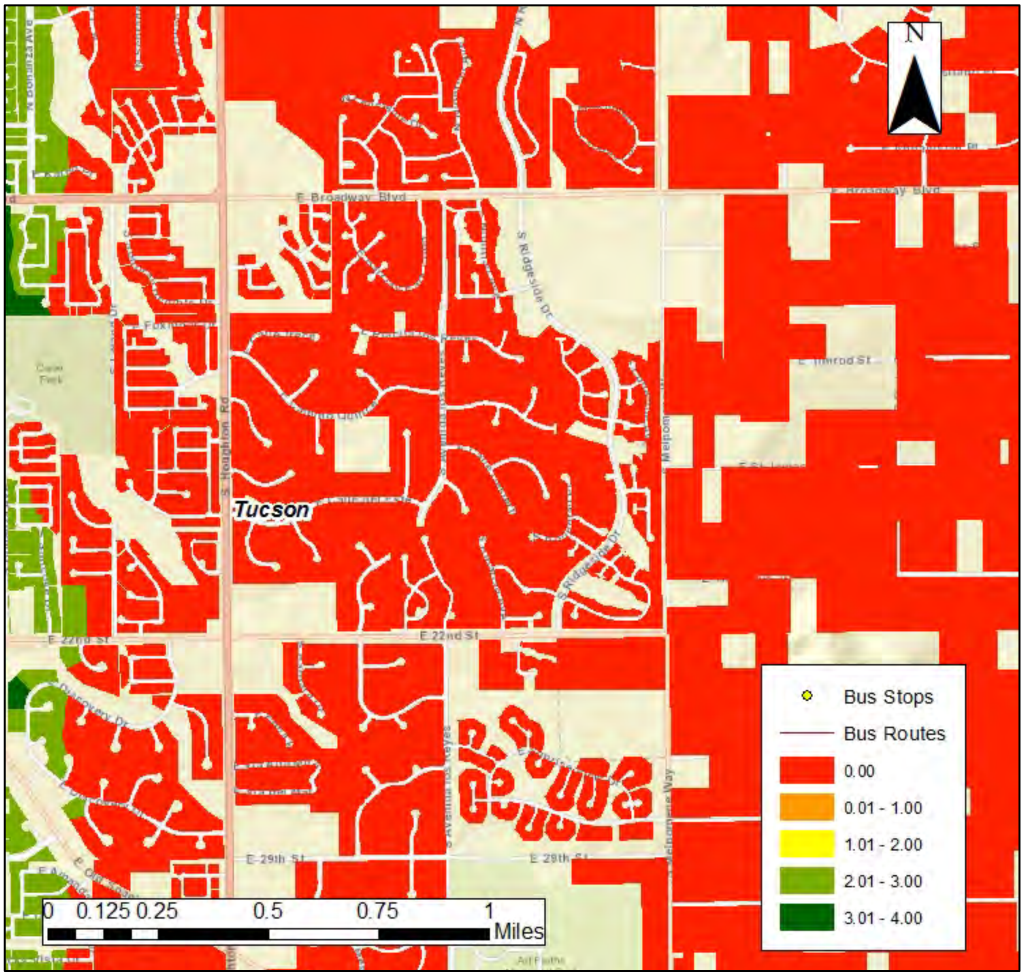


Figure 24 2009 Accessibility Scores, Tucson East Side

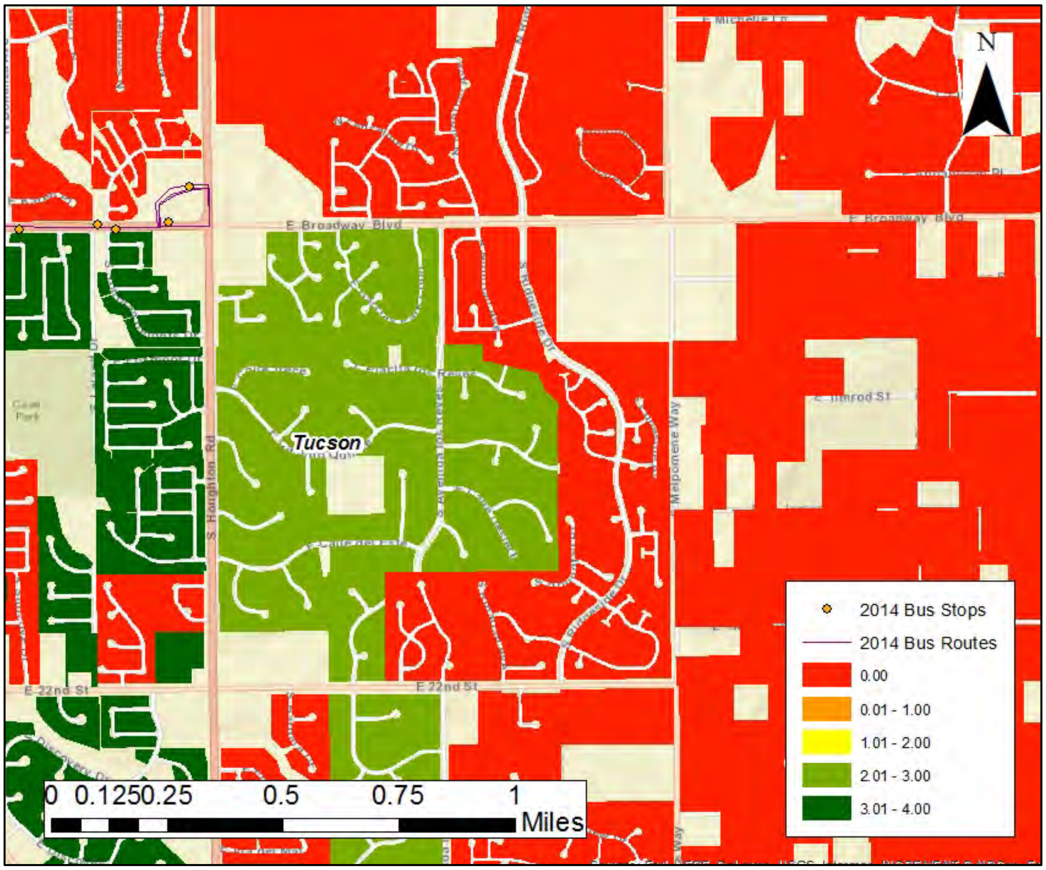


Figure 25 2014 Accessibility Scores, Tucson East Side

A big factor in the change is the construction of new single-family residences. These same parcels may have had low or zero accessibility scores in 2009, but there were either new stops added or new residences constructed between 2009 and 2014 near existing stops (See Figures 26 and 27). Service expansions to the East Side were a strong factor in these score increases where new stops and new routes influenced accessibility scores. New stops and routes opened in Southeast Tucson, Southwest Tucson, and Marana between 2009 and 2014 (See Figure 26).

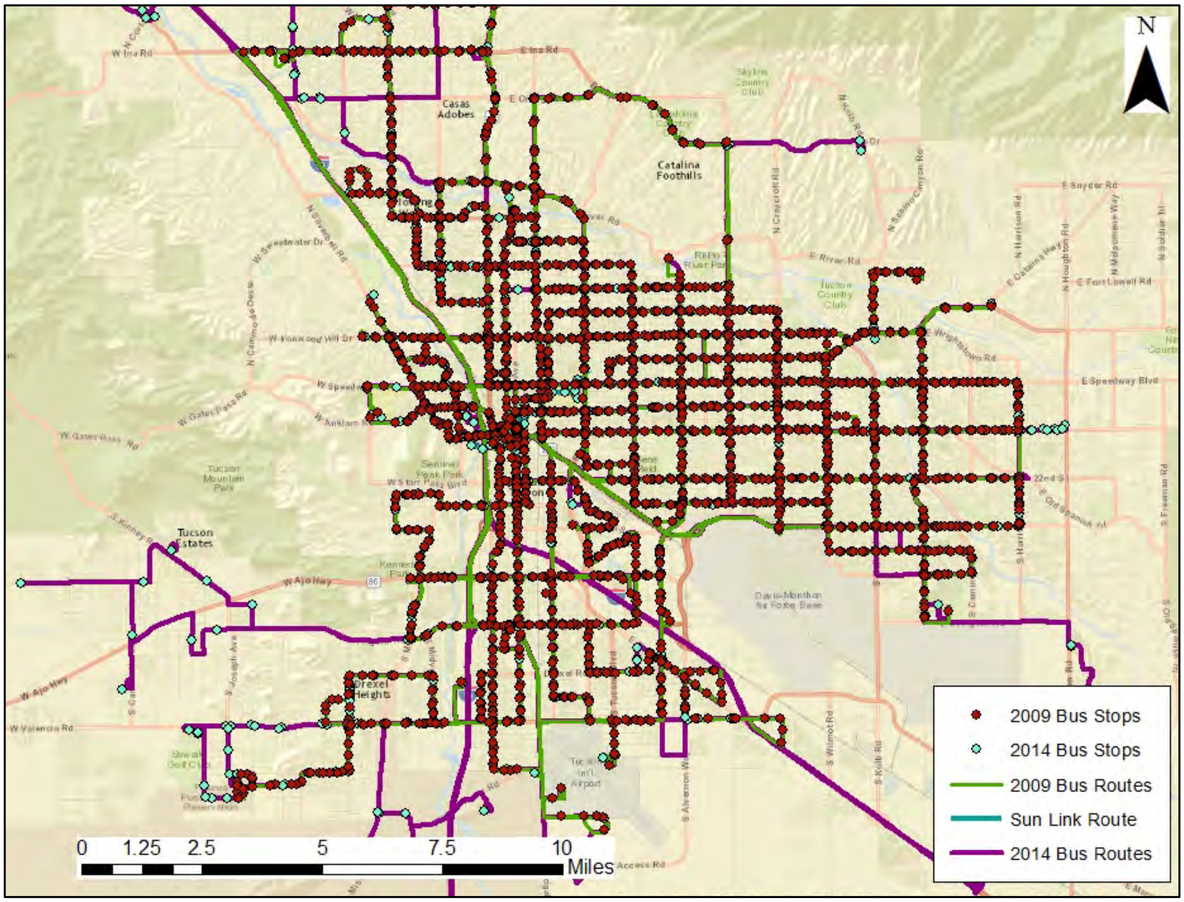


Figure 26 Sun Tran Stops, 2009 and 2014

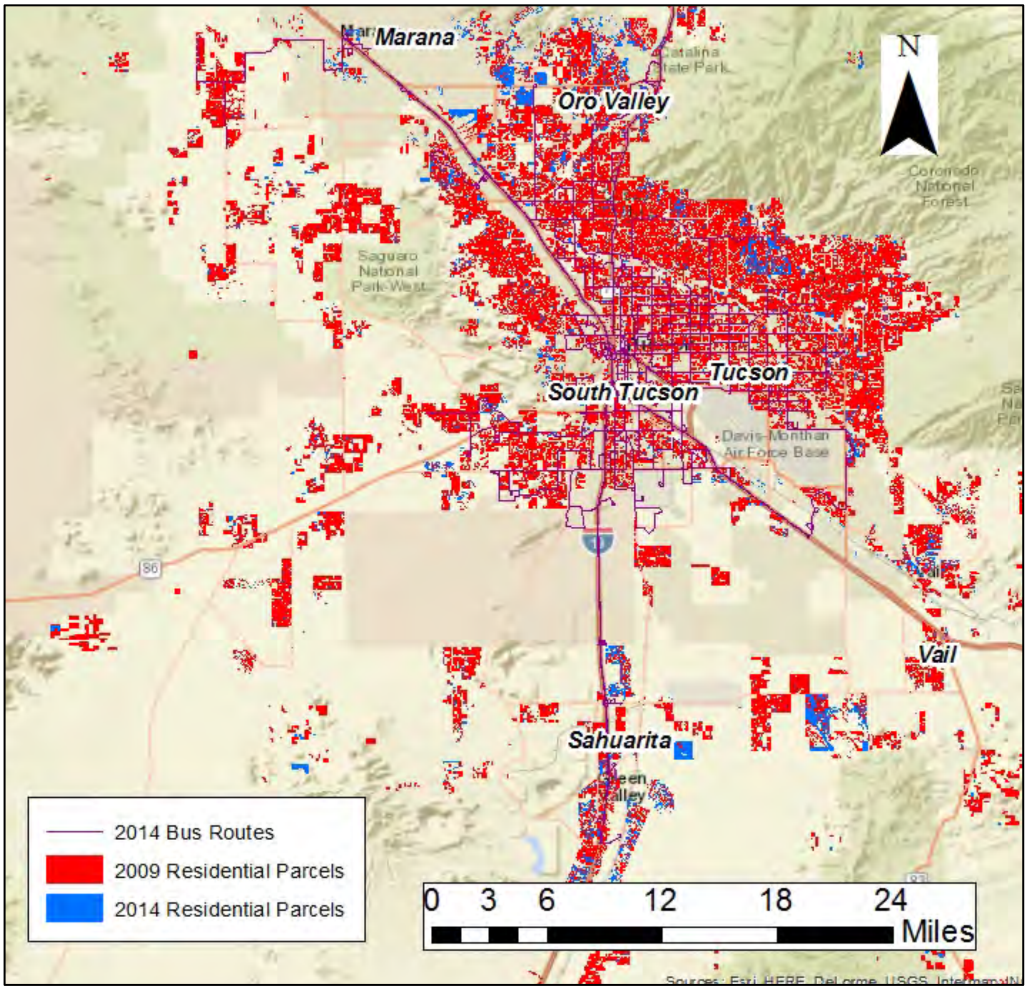


Figure 27 Tucson Residences, 2009 and 2014

Unfortunately, there is not a diverse set of land uses near the new single-family residences. The sorts of services summarized in the LUPTAI index in these areas are spread out and are not located close to public transportation. Thus, master transit stop scores are low in this region. This gives low scores for many of these new parcels, which are an improvement on the zero scores for residences that existed in 2009, but there is little question this is still a type of urban sprawl development pattern. As can be seen in Figure 27, most new residential development during the study interval took place on the periphery of Tucson. Few new residential parcels were recorded in the center of the Tucson metro area from either outright land use conversions or new mixed-used developments.

Another area that has increases in accessibility is Sahuarita. The Rancho Sahuarita neighborhood is a catalyst of new growth in the young city since 2009. A surge in new building permits where the City of Sahuarita, located south of Tucson in Figure 25, granted more than 38,000 building permits from 2010 to 2014 (Flora 2014). This results in accessibility score increases for permits where construction was fulfilled even if the accessibility score was low.

4.5 Results Summary

Each Pima County neighborhood within 50 miles of the Sun Tran network saw different impact change types between 2009 and 2014. Transportation accessibility in the Tucson Metropolitan Area decreased from 2009 to 2014 in neighborhoods closer to Downtown Tucson, yet increased within that same period in the periphery of the metropolitan area. Therefore, the Sun Link system did not remedy poor transportation accessibility trends around the Tucson Metropolitan Area. Unfortunately, the analysis did not include Business Analyst derived land use data from 2009. Also, 2009 GTFS data from would have helped to fortify the analysis results. These are among the many topics that could fortify the analysis if repeated in the future. Regardless of what needs to be addressed, Pima County, the City of Tucson, respective suburbs and stakeholders need to act in order to resolve these accessibility issues.

Chapter 5 Discussion & Conclusion

The concluding chapter starts with a summary of the results presented in the previous chapter with the implications for Tucson. The limitations to the analysis are fully discussed afterward. The future work discussion provides new recommendations rooted in the lessons learned in the 2016 analysis. All discussion points lead to the final conclusion with a summary of recommendations for Pima County, the City of Tucson, and its surrounding suburbs.

5.1 Findings Summary

In Tucson between 2009 and 2014, transportation accessibility increased on average for residential parcels but decreased on average if measured for the transit stations themselves. Generally, accessibility increased on residential parcels either due to new residential construction within the buffer of existing transit stops, bus stop additions, or bus route expansions. This is seen in the large number of parcels that shifted from zero to low accessibility scores.

The analysis results provide implications for the TMSA from multiple perspectives. Sun Tran will need to address areas not properly served in their network. Principals whose organizations fall under one of the analyzed land uses need to address planning strategies to make residences more accessible to the Sun Tran network. Jurisdictions need to use the results to guide policies to close omissions in accessibility. However, limitations to the analysis need to be understood and addressed before the stakeholders start to act.

Regardless of results and limitations, the analysis not only takes LUPTAI one step further but also spatial accessibility analyses one step further with the parcel scale analysis. Still, vector implementation of the LUPTAI model in the United States presents further limitations for computation that will need to be addressed if parcel scale work is done in larger metropolitan areas. Furthermore, the analysis lets policymakers improve transportation sustainability by addressing accessibility pitfalls and creating opportunities to resolve the pitfalls.

5.2 Analysis Limitations

Multiple limitations affect the analysis. Data limitations from different organizations caused analysis issues that could have presented different results. Some proposed datasets either did not exist for one year or both 2009 and 2014. The data omissions left the author no choice but to create new datasets, take alternative measures, or use a dataset that did not correspond perfectly with the year of interest to estimate conditions in the study year.

Land use data presents the most significant limitation. One such example is the Esri ArcGIS Business Analyst Data. Esri did not have information available for the land uses in 2009. Therefore, the analysis only featured 2014 land use data for all land uses except the employment land use, which came from the U.S. Census Bureau, and the residential land uses, which came from and Pima County. The business analyst limitation is significant because it affects the changes in accessibility scores. While the locations of specific non-residential land uses do not typically change extensively in a 5-year period, there would have been somewhat different results with precise data for both years.

Employment land use definitions also presented limitations. Employment clusters are hard to define without a specific land use. There are no land uses or even NAICS codes that explicitly define an employment cluster. The author used a similar approach to the Owen et al. (2012) paper by defining the land use by the number of jobs within a census tract. However, the use of census tracts to aggregate employment data introduced a Modifiable Areal Unit Problem (MAUP) into the analysis. If reliable data could be found to pinpoint jobs to a parcels without having to use larger areal units, such as census tracts, to provide job densities, the MAUP could be avoided.

Sun Tran GTFS data also had limitations. There were no common attributes with the street data to accurately calculate the time it takes to travel between transit stops in cases of missing data. This limitation impeded the proper calculation of travel times along streets, forcing the author to take alternative methods as specified in Chapter 3. Furthermore, Sun Tran did not have any 2009 GTFS data. The author could only use the 2014 data available from Pima County. The GTFS data was useful in creating all transit stop points, and calculating travel times along route polylines.

If LUPTAI had a shortcoming, it was the omission of cultural landmarks and points of interest from their analysis. If a cultural landmark or point of interest did not fall into one of the five land uses, it was excluded from the analysis. This study originally intended to include points of interest in the analysis, but to maintain consistency with the original LUPTAI model, points of interest datasets were excluded from the analysis.

Mixed land use identification was also a limitation in this analysis. The Pima County Assessor's land use code table did not identify an explicit primary designation for mixed uses. There were only secondary designations of either "Residential – Mixed" or "Commercial – Mixed" (Pima County Assessor's Office 2016). This made it difficult (but not impossible) to map mixed land uses. For this reason, the author proposes that the Pima County Assessor's Office create a new primary mixed-use designation in future expanded assessments.

The biggest limitation is in the use of the ArcGIS tool Model Builder to complete the analysis, which was also not specified in the LUPTAI publications. If LUPTAI was implemented in different cities, different feature class definitions would provide for changes in the tools used in Model Builder. The tool changes would create inconsistencies in the model resulting in multiple generations of the original LUPTAI model. While this would be good for the academic community to study ways to improve transportation accessibility measurements, each region would have a different model to measure transportation accessibility with different methods. Comparative analyses between cities cannot take place with inconsistent models and feature classes with inconsistent attributes.

Corrections to the analysis limitations would likely have caused a different result and therefore, provide different recommendations for planners and policymakers in Pima County. These same corrections would have also ensured a smoother implementation of the modified LUPTAI model in Tucson and Pima County. The author managed to address these limitations in order to complete the analysis. However, future work will allow for those exploring the transportation accessibility topic to find different solutions to these limitations.

5.3 Future Work

The 2014 analysis will need to be repeated to test and compare results. New scores need to be calculated at most every five years in order to assess accessibility changes throughout the region. There may be data improvements that may remove some of the limitations in this analysis, such as increased GTFS attributes or improved employment land use definitions. Also, the Sun Link system will have been around for enough time to allow for land use changes to occur. The study interval did not allow for significant land use changes to occur along the Sun Link system. While it is nice to address the future of regional transportation accessibility, additional steps need to be taken to improve the scope of the thesis analysis.

The 2009 land use data needs to be obtained to present a more accurate analysis. Esri does not keep older business analyst datasets. To get around the omission of older datasets, the author proposes retrieving the 2009 data directly from Dun and Bradstreet. The proposed remedy is similar to the land use data retrieval process used in the Minneapolis-St. Paul access to destinations study (Owen 2012, 16). The retrieved data will need to be geocoded prior to use in an analysis. The geocoded results will be converted to point feature classes just like the 2014 Business Analyst dataset.

The analysis would be further improved with additional GTFS attributes. If Sun Tran can work with Pima County to add coordinates to snap with the road network, an improved feature class can be created to allow planners and analysts to assess the Sun Tran network. The network analysis will then run smoother and geodetic buffers would not be required to estimate the time between stops in the 2009 network.

Employment data will need a better definition for future analyses. The LUPTAI authors define the employment land use as employment clusters (Pitot 2006, 4). Employment clusters can be defined as office parks, but the employment cluster definition is poor for a metropolitan area in the United States. Many employment destinations are spread out through a given metropolitan area. Some employers own their very own building and do not provide space for additional tenants. The employment land use needs to be better defined for this reason.

The author proposes to re-define the employment land use to enable dual land use or mixed use scoring. Service and employment land uses will receive two scores based on their applicable land use, which will result in a new formula to reduce bias in the dual scores. The new formula will enable mixed-uses to be scored in future analyses. Mixed uses will receive a residential score and a land use score as an employment land use in a similar method.

Additional aspects will be addressed to the modeling process and resulting analysis. Ridership for each stop and station will guide planners and stakeholders in addressing either shortcomings in ridership figures or locating optimal locations for the five LUPTAI-specified land uses. Walking analyses will be fortified through future network analyses and bicycle networks will be examined in the analysis. Bicycles are allowed on Sun Tran busses and the Sun Link System. In Tucson, results from the annual University of Arizona Parking & Transportation Survey will aid in addressing potential shortcomings in ridership or transport on the University of Arizona campus (Davila 2016).

With further applications of the analytical methods, the public will also be able to participate in land use and transportation planning through strong interactive means. Online interfaces would allow members of the public to suggest changes to a plan without traveling to a public meeting. If a member of the public wants to suggest a change to a proposed plan, planners will have a stronger means to visualize the model data and effectively communicate not only the trends from the model but also the reasons they drafted the proposed plan in a specific manner. Many countries, let alone individual jurisdictions have not yet realized the strength of a land use designation-based GIS transportation accessibility model for involving the public in the planning process.

The future work will lead to a strong legacy for the urban planning community and increased understanding of the LUPTAI method. More informed decisions by public urban planners and more persuasive improvement suggestions from citizens will lead to more effective decisions for communities. It is crucial to be able to measure and visualize the impact of changes in transit infrastructure and land uses (Pitot 2006, 16). Planners have a strong means for envisioning new strategies with land use designations and individual parcels serving as the thematic scale for the model. If an idea proves not to be strong enough, planners can use the resulting model to make corrections where necessary. Ongoing work should persuade urban planners to use the model to make improved proposals, solicit public input, and make more informed decisions rooted in spatial analysis.

5.4 Conclusion

The Sun Link system is a vast improvement on the Old Pueblo Trolley because it extended the trolley line 1.9 miles to the west and 0.9 miles to the east and it improved rolling stock and infrastructure. Trolleys differ from Modern Streetcars due to modern technology used to operate all infrastructure, streamlined rolling stock, and higher operating capacities (Smartlak 2012b). Furthermore, the Sun Link system provided Pima County the initial building block to implement a rail network for the TMSA.

A comparison of changes between 2009 and 2014 intended to help determine whether the Sun Link system introduction had a major impact on the accessibility to mass transit in the TMSA immediately after construction was completed and all route conversions took place in the overall transit system. However, it is too soon to tell what impact the Sun Link system had on Tucson transportation accessibility. For now, the Sun Link system did not improve transportation accessibility in Pima County and the TMSA in spite of residential accessibility increases in the periphery.

Developers, the City of Tucson, surrounding incorporated suburbs, and Pima County need to implement transit-oriented development projects to bring residential and mixed-used residential development around the street car line in order to better improve accessibility results from the initial analysis. Once the transit-oriented development projects are implemented, accessibility scores will improve. Policymakers also need to provide incentives to current and prospective business owners to locate in mixed-use projects near public transportation stops throughout the region. The incentives and resulting relocations will also improve accessibility to mass transit.

An improved analysis will provide a better insight on the Sun Link system accessibility impacts. Better definitions for the employment land use will provide a stronger insight into the analysis. The 2009 Business Analyst data (and older datasets), the improved employment land use definitions, and stronger GTFS definitions will provide policymakers and planners a better transportation accessibility comparison. The overall Tucson analysis will be much stronger once all weaknesses are addressed.

The Tucson analysis provides an initial look at the state of transportation accessibility in Tucson. The results provide an initial benchmark for future analyses to improve on. Transit stop accessibility decreased from 2009 to 2014, while residential parcel accessibility increased in the same study interval. Different LUPTAI-defined land uses were located in the furthest accessibility buffers, resulting in the decreased scores. Weaknesses in the model need to be addressed while policymakers need to provide incentives to improve accessibility. Only time will tell how the Sun Link system impacted transportation accessibility. For now, this analysis and thesis provide an initial look the evolving state of transportation accessibility in Tucson.

REFERENCES

Allen, W. Bruce, Dong Liu and Scott Singer. 1993. “Accessibility Measures of U.S. Metropolitan Areas.” Transportation Research Part B: Methodological. 27B no. 6: 439-449.

Alshammari, Talal O. 2011. "Urban Sprawl of Cities in the Desert a Comparison of Tucson, Arizona and Riyadh, Saudi Arabia." PhD diss.

Antrim, Aaron and Sean J. Barbeau. 2010. “The Many Uses of GTFS Data: Opening the Door to Transit and Multimodal Applications.” Accessed November 30, 2016. https://www.locationaware.usf.edu/wp-content/uploads/2010/02/The-Many-Uses-of-GTFS-Data-–-ITS-America-submission-abbreviated.pdf

Bhat, Chandra, Stacey Bricka, Jeffrey La Mondia, Aarti Kapur, Jessica Guo, and Sudeshna Sen. 2006. *TxDOT Project 0-5178: Metropolitan Area Transportation Accessibility Analysis Tool.* Last Accessed: February 12, 2016: http://smartgrowth.umd.edu/assets/documents/research/acsp_tingma_20141029.pdf

Cervero, Robert. 2005. “Accessible Cities and Regions: A Framework for Sustainable Transport and Urbanism in the 21st Century.” *University of California Transportation Research Center Faculty Research.* Accessed March 16, 2016: http://www.its.berkeley.edu/sites/default/files/publications/UCB/2005/VWP/UCB-ITS-VWP-2005-3.pdf

City of Gold Coast. 2016. *About the Profile Areas: Gold Coast City.* Accessed March 31, 2016: http://profile.id.com.au/gold-coast/about

City of Tucson. 2013. *Ajo/Tucson SW Arizona Map*. Accessed April 2, 2016: http://www.suntran.com/PDF/sun%20shuttle/Area%20Maps/Rt%20486%20Ajo-Tucson%20Map.pdf

City of Tucson. 2014. “Development - Sun Link.” Accessed September 24, 2016: http://www.sunlinkstreetcar.com/benefits/development.

City of Tucson. 2015. Sun Link – the Tucson Modern Streectar: Construction. Accessed February 11, 2016: http://www.sunlinkstreetcar.com/index.php?pg=17

City of Tucson. 2015. "Tucson Update - Population." Accessed May 30, 2016. https://www.tucsonaz.gov/hcd/tucson-update-population.

Davila, Claudia. 2016. Personal Communication, November 30, 2016.

Federal Highway Administration. 2010. *The Travel Model Improvement Program.* Accessed March 22, 2016: https://www.fhwa.dot.gov/planning/tmip/publications/other_reports/technical_synthesis_report/technicalsynthesisreport.pdf

Flora, Chris. "Sahuarita Creates Plan to Accommodate Major Growth." Inside Tucson Business, October 3, 2014. Accessed September 18, 2016. http://www.insidetucsonbusiness.com/news/sahuarita-creates-plan-to-accommodate-major-growth/article_81a0ed6a-4a87-11e4-98eb-1f47dee79813.html.

Ford, Alistair J. , Stuart L. Barr, Richard J. Dawson, and Phillip James. 2015. “Transport Accessibility Analysis Using GIS: Assessing Sustainable Transport in London.” *ISPRS International Journal of Geo-Information* 4: 124-149.

Foth, Nicole, Kevin Manaugh, and Ahmed M. El-Geneidy. 2013. "Towards Equitable Transit: Examining Transit Accessibility and Social Need in Toronto, Canada, 1996–2006." *Journal of Transport Geography* 29: 1-10.

Frumkin, Howard. 2002. "Urban sprawl and public health." *Public health reports* 117, no. 3: 201

Furmaniak, Thomas B., and John W. Schumann. 2014. “Light Rail and Streetcar Systems: How They Differ; How They Overlap.” *American Public Transportation Association.* Last Accessed April 22, 2016: https://www.apta.com/resources/reportsandpublications/Documents/APTA%20Light%20Rail-Streetcars-How%20They%20Differ-How%20They%20Overlap%20Oct%2014.pdf

Geurs, Karst T., and Bert Van Wee. 2004. "Accessibility Evaluation of Land-use and Transport Strategies: Review and Research Directions." Journal of Transport Geography 12, no. 2: 127-40.

Glaeser, Edward, and Matthew Kahn. 2003. "Sprawl and Urban Growth." *Handbook of Regional and Urban Economics*. 4: 2481-2527.

Google Maps. 2016. *Pima County, Arizona Map.* Accessed March 28, 2016: https://www.google.com/maps/place/Pima+County,+AZ/@31.9830177,-112.8325326,8z/data=!4m2!3m1!1s0x86d5e18f3072c27b:0x97100bf0c82023d8

Grengs, Joe, Jonathan Levine, and Qingyun Shen. 2013. *Evaluating Transportation Equity: An Intermetropolitan Comparison of Regional Accessibility and Urban Form*. No. FTA Report No. 0066.

Gulhan, Gorkem, Huseyin Ceylan, Mustafa Özuysal and Halim Ceylan. 2013. “Impact of utility-based accessibility measures on urban public transportation planning: A case study of Denizli, Turkey.” *Cities: The International Journal of Urban Policy and Planning.* 32: 102-112.

Hamilton, W.F. and D.K. Nance. 1969. “Systems Analysis of Urban Transportation.” *Scientific American.* 221: 19-27.

Hansen, Walter G. 1959. *Accessibility and Residential Growth*. Thesis. Massachusetts Institute of Technology. N.p.: n.p., n.d. Web. 25 Sept. 2016. <https://dspace.mit.edu/bitstream/handle/1721.1/74869/32597665-MIT.pdf?sequence=2>.

Herr-Caudillo, Joy. "How Tucson Finally Got Our Streetcar." Southern Arizona Transit Advocates. Accessed November 14, 2014. http://www.transitadvocates.com/how-did-we-get-here/how-tucson-finally-got-our-streetcar-2000-2014/.

Higgins, Christopher D., Mark R. Ferguson, and Pavlos S. Kanaroglou. 2014. "Journal of Public Transportation." Light Rail and Land Use Change: Rail Transit's Role in Reshaping and Revitalizing Cities 17.2: 93-112. Web. 25 Sept. 2016. <http://scholarcommons.usf.edu/cgi/viewcontent.cgi?article=1040&context=jpt>.

Horning, Jessica, Ahmed El-Geneidy and Kevin J. Krizek. 2008. “Access to Destinations: Parcel Level Land Use Data Acquisition and Analysis for Measuring Non-Auto Accessibility.” Minnesota Department of Transportation, Research Services. University of Minnesota Digital Conservancy: http://www.lrrb.org/PDF/200819.pdf

Kain, John F., and Zvi Liu. 1999. "Secrets of Success: Assessing the Large Increases in Transit Ridership Achieved by Houston and San Diego Transit Providers." Transportation Research Part A: Policy and Practice 33, no. 7-8: 601-24.

Kelly, Jane-Frances and Peter Breadon. 2012. “Tomorrow’s Neighborhoods: Building Flexible Neighborhoods.” *Grattan Institute.* Accessed March 23, 2016: http://www.bleuscape.com.au/blog/wp-content/uploads/2012/09/Full-Report-Tomorrows-Suburbs.pdf

Kitamura, Ryuichi, Patricia L. Mokhtarian, and Laura Laidet. 1997. "A micro-analysis of land use and travel in five neighborhoods in the San Francisco Bay Area." *Transportation* 24, no. 2: 125-158.

Kohn, Harold. 1999. “Factors Affecting Urban Transit Ridership.” *Statistics Canada.* Accessed October 31, 2014: http://www.publications.gc.ca/Collection/Statcan/53F0003X/53F0003XIE.pdf

Kwan, Mei-Po, Donald G. Janelle, and Michael F. Goodchild. 2003. "Accessibility in Space and Time: A Theme in Spatially Integrated Social Science." *Journal of Geographical Systems* 5, no. 1: 1-3

Kwan, Mei-Po, and Joe Weber. 2008. "Scale and Accessibility: Implications for the Analysis of Land Use–travel Interaction." Applied Geography 28: 110-23.

Kyte, Michael, James Stoner, and Jonathan Cryer. 1988. "A Time-series Analysis of Public Transit Ridership in Portland, Oregon, 1971–1982." *Transportation Research Part A: General* 22, no. 5: 345-59.

Lafleur, Michael. 2002. "One in a Series Previewing May 21 Election." - Tucson Citizen Morgue, Part 2 (1993-2009). Last accessed November 14, 2014: http://tucsoncitizen.com/morgue2/2002/05/14/227361-one-in-a-series-previewing-may-21-election/

Levine, Jonathan, Joe Grengs, Qingyun Shen, and Qing Shen. 2012. "Does Accessibility Require Density or Speed?" *Journal of the American Planning Association* 78, no. 2: 157-72

Levinson, David M. 1998. "Accessibility and the Journey to Work." Journal of Transport Geography 6, no. 1: 11-21

Litman, Todd. 2011. "Evaluating accessibility for transportation planning." *Victoria, BC: Victoria Transport Policy Institute*. Last accessed April 22, 2016: http://www.vtpi.org/access.pdf

Liu, Suxia, and Xuan Zhu. 2004. "Accessibility Analyst: An Integrated GIS Tool for Accessibility Analysis in Urban Transportation Planning." *Environment and Planning B: Planning and Design* 31, no. 1: 105-24.

Logan, Michael F. *Fighting Sprawl and City Hall: Resistance to Urban Growth in the Southwest*. Tucson: University of Arizona Press, 1995.

Lopez, R., and H. P. Hynes. 2003. "Sprawl In The 1990s: Measurement, Distribution, and Trends." Urban Affairs Review 38, no. 3: 325-55.

Luckingham, Bradford. *Phoenix: The History of a Southwestern Metropolis*. Tucson: University of Arizona Press, 1989.

Mavoa, Suzanne, Karen Witten, Tim Mccreanor, and David O'Sullivan. 2012. "GIS Based Destination Accessibility via Public Transit and Walking in Auckland, New Zealand." *Journal of Transport Geography* 20, no. 1: 15-22.

Miller, Harvey J. and Yi-Hwa Wu. 2000. "GIS Software for Measuring Space-Time Accessibility in Transportation Planning and Analysis." Accessed October 31, 2014: http://www.researchgate.net/publication/2410025_Gis_Software_For_Measuring_Space-Time_Accessibility_In_Transportation_Planning_And_Analysis/file/e0b495284d12cd25de.pdf

Morang, Melinda. 2013. *Yay Transit! - Using GTFS Datasets in ArcGIS Network Analyst*. Accessed May 18, 2016: http://transit.melindamorang.com/.

Morris, Jennifer M., P.L. Dumble and M. Ramsey Wigan. 1978. "Accessibility Indicators for Transportation Planning." *Transportation Research Part A: Policy and Practice.* Vol. 13 no. 2: 91-109.

Owen, Andrew, and Levinson, David. 2012. “Access to Destinations: Annual Accessibility Measure for the Twin Cities Metropolitan Region.” Minnesota Department of Transportation, Research Services. University of Minnesota Digital Conservancy: http://hdl.handle.net/11299/181425.

Pantell, Susan. "Tucson's Light Rail Streetcar Project Making Progress." Tucson's Light Rail Streetcar Project Making Progress - Light Rail Now. *Light Rail Now*, 15 Dec. 2009. Web. 24 Sept. 2016. <http://www.lightrailnow.org/news/n_tuc_2009-12a.htm>.

Pima Association of Governments. 2010. *Pima County Existing Land Use Map - 2009.* Accessed April 1, 2016: http://www.pagnet.org/documents/rdc/gis/mapexistlanduse2009.pdf

Pima County. 2016. *About Pima County.* Accessed March 31, 2016: http://webcms.pima.gov/government/about_pima_county/

Pima County Assessor’s Office. 2016. 4-Digit Use Code Table. Accessed August 6, 2016: http://www.asr.pima.gov/unyear_ftp/UCODES.ZIP.

Pima County Regional Transportation Authority Board of Directors. 2006. “Resolution no. 2006-04: A Resolution of the Regional Transportation Authority Board of Directors Adopting the RTA Implementation Plan for the May 16, 2006, Special Election.” *Tucson, Arizona: Pima County Regional Transportation Authority*. Accessed March 12, 2016: http://www.rtamobility.com/images/stories/pdfs/RTAAdmin/RTAAdminCode.pdf

Pitot, Matthew, Tan Yigitcantler, Neil Sipe and Rick Evans. 2006. “Land Use & Public Transport Accessibility Index (LUPTAI) Tool - The development and pilot application of LUPTAI for the Gold Coast.” *Social Research in Transport (SORT) Clearinghouse* 123: 1-18

Polzin, Steven. 1999. “Transportation/Land-Use Relationship: Public Transit's Impact on Land Use.” *Journal of Urban Planning and Development* 125, no. 4: 135-151.

Reisi, Marzieh, Lu Aye, Abbas Rajabifard, and Tuan Ngo. 2014. “Transport Sustainability Index: Melbourne Case Study.” *Ecological Indicators* 43: 288-296.

Reisi, Marzieh, Lu Aye, Abbas Rajabifard, and Tuan Ngo. 2016. “Land-use planning: Implications for transport sustainability.” *Land Use Policy* 50: 252-261.

Silva, Cecilia. “Comparative Accessibility for Mobility Management: The Structural Accessibility Layer.” (PhD Diss., University of Oporto, 2008).

Smartlak, John. 2012a. Arizona Streetcar Systems: Tucson – Old Pueblo Trolley. Accessed: February 16, 2016: http://www.railwaypreservation.com/vintagetrolley/tucson.htm

Smartlak, John. 2012b. U.S. Streetcar Systems. Last Accessed: April 6, 2016: http://www.railwaypreservation.com/vintagetrolley/vintagetrolley.htm

Southern Arizona Attractions Alliance. 2013. Explore Southern Arizona: Map and List of Attractions. Accessed: February 19, 2016: http://www.tucsonattractions.com/wp-content/themes/mytheme/pdf/South_Arizona_map.pdf

Sun Tran System-Wide Transit Map. 2016. Accessed March 3, 2016: http://www.suntran.com/PDF/Maps/Current System Map Feb 16.pdf

Taylor, Brian D., Douglas Miller, Hiroyuki Iseki, and Camille Fink. 2009. "Nature And/or Nurture? Analyzing the Determinants of Transit Ridership across US Urbanized Areas." *Transportation Research Part A: Policy and Practice* 43, no. 1: 60-77.

Thompson, Elizabeth, Abdulnasar Arafat, William O'Dell, Ruth Steiner, and Paul Zwick. 2012. "*Helping Put Theory into Practice for Planning Sustainable Communities: A GIS Tool for Measuring Transit Accessibility*." Gainesville, FL: University of Florida-Shimberg Center for Housing Studies. Last Accessed November 14, 2014: http://www.shimberg.ufl.edu/publications/7c4_E_Thompson_UFL_Transit_Access_UAA_conf_paper_9APRIL2012.docx

Trillium Solutions, Inc. 2014. "Opportunities to Leverage GTFS Data." Accessed November 30, 2016. https://docs.google.com/document/d/17CoxTgGQPoUenz1HCW3kdCnX0sciPLvTa_wGRPZcqPc/edit#

Tucson (Ariz.). Land Use Code of the City of Tucson: Conversion of Zones. Tucson, AZ: City of Tucson, 2000

Tucson Association of Realtors. 2012. "Tucson Area Map." Accessed September 10, 2016: http://www.tarmls.com/docs/areaboundaries.pdf.

U.S. Census Bureau. 2015. "Annual Estimates of the Resident Population: April 1, 2010 to July 1, 2015 - United States -- Metropolitan and Micropolitan Statistical Area; and for Puerto Rico." Population Division Table 1: http://factfinder2.census.gov/bkmk/table/1.0/en/PEP/2014/GCTPEPANNR.US23PR

United States Office of Management and Budget. 2013. "OMB Bulletin No. 13-01: Revised Delineations of Metropolitan Statistical Areas, Micropolitan Statistical Areas, and Combined Statistical Areas, and Guidance on Uses of the Delineations of These Areas." *Executive Office of the President of the United States.* Accessed March 20, 2016: https://www.whitehouse.gov/sites/default/files/omb/bulletins/2013/b13-01.pdf

University of Minnesota. 2016. "Access to Destinations Study Publications." Accessed September 25, 2016. http://access.umn.edu/publications/related/destinations/

Vandenbulcke, Grégory, Thérèse Steenberghen, and Isabelle Thomas. 2009. "Mapping Accessibility in Belgium: A Tool for Land-use and Transport Planning?" *Journal of Transport Geography* 17, no. 1: 39-53

Waddell, Paul. 2002. "UrbanSim: Modeling Urban Development for Land Use, Transportation, and Environmental Planning." *Journal of the American Planning Association* 68, no. 3: 297-314

Waddell, Paul, Gudmundur F. Ulfarsson, Joel P. Franklin, and John Lobb. 2007. "Incorporating land use in metropolitan transportation planning." *Transportation Research Part A: Policy and Practice* 41, no. 5: 382-410

Walk Score. 2016. “Walk Score Methodology.” Accessed November 30, 2016. https://www.walkscore.com/methodology

Wang, Dong, Iderlina Mateo-Babliano, and Gregory Brown. 2013. “Rethinking Accessibility in Planning of Urban Open Space Using an Integrative Theoretical Framework.” *State of Australian Cities Conference 2013.* Accessed March 22, 2016: http://www.soacconference.com.au/2013-conference/wp-content/uploads/2013/12/Wang-Social.pdf

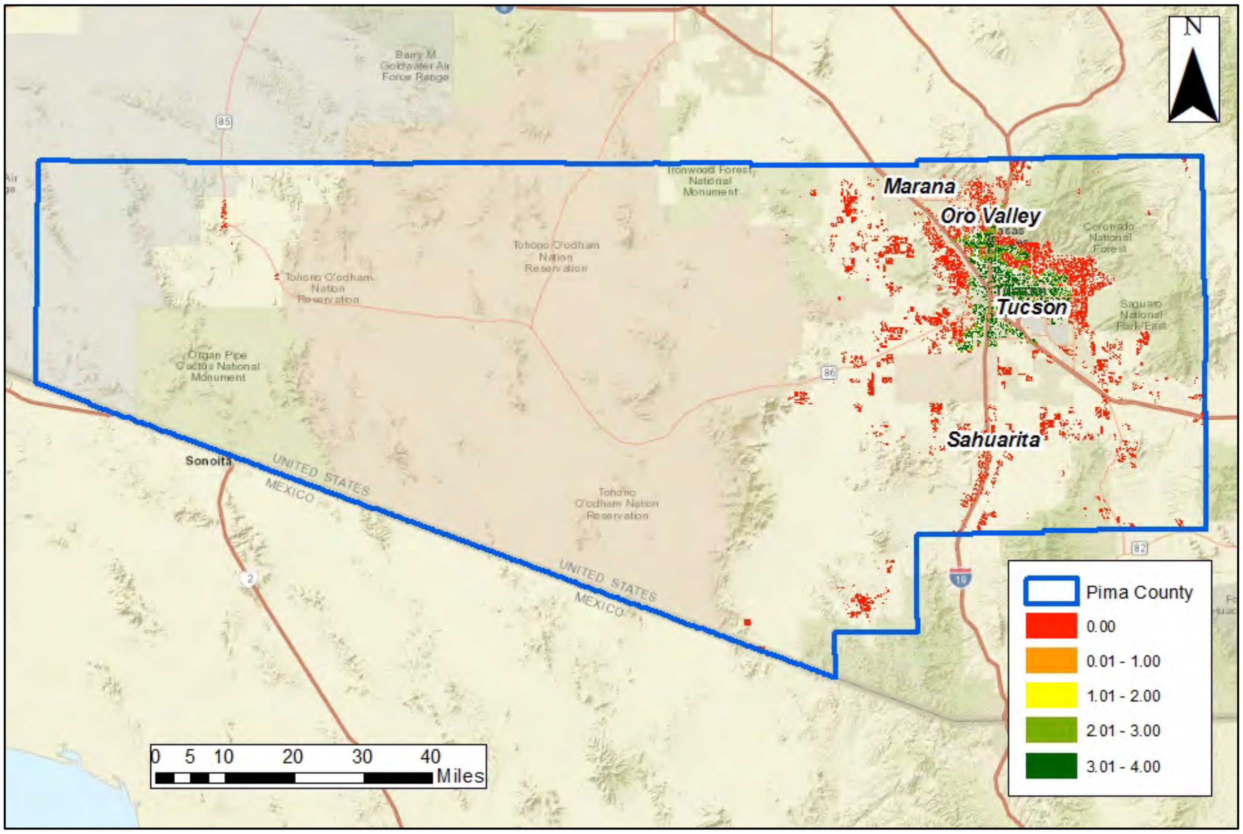
Witten, Karen, Jamie Pearce, and Peter Day. 2011. "Neighbourhood Destination Accessibility Index: A GIS Tool for Measuring Infrastructure Support for Neighbourhood Physical Activity." Environment and Planning A 43, no. 1: 205-23.

Yan-Yan, Chen, Wei Pan-Yi, Lai Jian-Hui, Feng Guo-Chen, Li Xin, and Gong Yi. 2016. "An Evaluating Method of Public Transit Accessibility for Urban Areas Based on GIS." *Procedia Engineering* 137 (2016): 132-40.

Yigitcantler, Tan, Neil Sipe, Rick Evans and Matthew Pitot. 2007. A GIS-based Land Use and Public Transport Accessibility Indexing Model. *QUT Digital Repository*. Last accessed November 13, 2014: http://eprints.qut.edu.au/17552/1/17552.pdf

Zhang, Tingwei. 2001. "Community Features and Urban Sprawl: The Case of the Chicago Metropolitan Region." Land Use Policy 18, no. 3: 221-32

Appendix A: Map of Final Accessibility Scores for Pima County in 2009



Appendix B: Map of Final Accessibility Scores for Pima County in 2014