MULTIFACETED ANALYSIS OF TRANSIT STATION ACCESSIBILITY CHARACTERISTICS BASED ON FIRST MILE LAST MILE

by

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ABSTRACT

The *First Mile Last Mile* (FMLM) challenge garners significant attention as a means to assess the accessibility of the first leg to public transit and the last leg from transit. As a critical barrier to public transit accessibility, the challenge provides many opportunities to closely analyze conditions from the level of the transit station upwards to the level of the system-wide network. Its usefulness in contributing to the body of knowledge on barriers to transit access provides planners and researchers important information with implications towards increasing ridership, transit efficiency, multimodal travel options, and mobility. Salt Lake City area is experiencing a rapid growth in transit infrastructure. The ambitious program of transit construction spans across light rail, Bus Rapid Transit (BRT), streetcars and commuter rail simultaneously. This transit expansion program, led by Utah Transit Authority (UTA), strives to provide a multimodal system that can meet the daily transportation needs of the residents. FMLM strategy evaluations find strategy appropriateness and relevancy in many different contexts, but may still retain unique challenges imposed by such things as weather conditions, population characteristics, and cultural norms. This study proposes a methodological framework for analyzing the FMLM problems in the State of Utah. It utilizes microscopic and macroscopic data collection and analysis techniques, as well as network modeling, in an effort to quantify and understand the FMLM challenges facing each fixed transit station. The research aims to construct a set of station categories based on access mode

characteristics investigated via discrete choice modeling and accessibility analysis to facilitate planning and to accommodate characteristics of potential and existing riders at rail stations in the UTA network.

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CHAPTER 1

INTRODUCTION

Public transportation constitutes an integral part of many urban landscapes in the United States. The routes and lines that comprise transit networks traverse a myriad of geographies, topographies, and land types. Further deconstructed, these geographies, topographies, and land types also constitute many other layers of diverse transit landscape characteristics, including demography, social conditions, environment, and infrastructure. Consequently, public transportation networks must provide services sensitive to specific contexts through the process of planning and designing routes as well as stations serving as access/egress means to reach destinations via transit systems.

Transit stations are the primary points of access to and egress from public transportation systems. The success of public transit systems relies heavily on users' perceptions of transit station accessibility, among other things. The access mode to transit stations is a critical component when evaluating such functionality; it demands thorough investigation in response to overarching goals of increased transit use [1]–[3]. Analysis of mode choice to access transit stations on the existing network thus presents an important steppingstone towards an improved understanding of relationships between transit users and opportunities to increase public transit accessibility. Mode choice analysis also remains a prerequisite to enhancing current understanding of how to create and encourage multimodal transportation reflective of the myriad of types and levels of access afforded to transit users. Thorough, quantitative analyses of ways to access transit stations have been overlooked, even though access mode constitutes an integral component of trip-making via transit. An opportunity exists to determine how selected factors perform in the context of modeling access options to transit stations. Furthermore, accessibility analysis calls for the investigation of relationships between demand areas and destination points in space. The results of mode choice modeling in this study serve as proxy measures of various demand types in the analysis of accessibility via accessibility measures development as well as spatial distribution of demand.

The effort briefly described is applied to analysis of the State of Utah's rail network operated by the Utah Transit Authority (UTA). The reach of UTA's network provisions is concentrated predominantly in northern Utah, specifically along the Wasatch Front which encompasses the majority of metropolitan areas in Utah. Services provided by UTA traverse six counties. The services provided by UTA include paratransit, ski bus, local bus, bus rapid transit (BRT), FLEX routes, light rail, streetcar, commuter rail and vanpool.

The outcome of this analysis effort informs the development of general station categories. Station categories have found usefulness as a tool to present digestible characteristics of stations to facilitate planning processes. The station categories presented in this thesis intend to elicit discussion about resource prioritization and interrogation of context-sensitive FMLM implementations to meet different demand types served in the UTA network.

This thesis begins with a review of literature, which discusses influences on mode choices as well as analysis methods utilized to suggest the relevance of such influences. A methodology section follows which discusses the data used for analysis and delineates techniques used to model mode choice for accessing transit stations. The final sections of this study provide analysis results, interpretations, and concluding remarks on envisioned next steps as well as implications.

CHAPTER 2

LITERATURE REVIEW

Research in FMLM connectivity has been produced by transit agencies, academia, and various entities with interests in achieving diminished single-occupancy vehicle use [3]. Discussions on FMLM connectivity have focused significantly on changes to built environment characteristics to accommodate and prioritize increased multimodal transportation options to and from transit stations. Though existing research demonstrates commonalities in approaches to evaluating FMLM connectivity, variations in interpreting research components, such as the defined scope of analysis and strategies, lend weight to the context-sensitive nature of defining an appropriate methodology for FMLM analysis. The following section deconstructs elements of FMLM analysis as well as approaches to understanding factors that influence how transit users reach transit stations in an effort to frame a backdrop for the research methodology employed in this study.

2.1 Catchment Area

The catchment area presents a popular definition for evaluating FMLM connectivity. The transit catchment area typically describes the distance people are willing to walk to access a transit station [4], [5]. Federal law assumes that transit users are willing to walk up to a half-mile to access a transit stop [6]. In the Transit Capacity and Quality of

Service Manual, catchment areas for individuals driving to a park-n-ride lot range from 2 to 3 miles [7]. Suggested catchment areas commonly take on the form of a perfect circle with a radius of a half-mile or less centered on the transit stop of interest. Some studies define the catchment area based on roadway network distances considering the fact that the actual grid does not emanate radially from the station [8],[9]. Transit planners use catchment areas to analyze land use and socioeconomic impacts of transit as well as to predict transit ridership. The catchment area technique tends to lack a nuanced perspective of challenges influenced by variable weather conditions, type of modal travel used, and various forms of travel impedance for various users. It also heavily assumes that travel distances to and from stations constitute the primary influence on users' decision to use or not to use transit. Yet, the catchment area provides a robust starting point for visualizing accessibility to guide transit-oriented development (TOD).

2.2 Station Categorization

Studies acknowledge that certain transit stations pose FMLM challenges that stem from specific attributes of station typology. As a result, several studies attempt to categorize chosen stations for analysis according to station typologies. Prevalent station typology characteristics include existing and future land use densities, transportation network characteristics, station site, mode split, mobility, building heights, and street and block patterns [10], [11]. Several studies pursue the station characterization using population and employment projections, and U.S. Census data [10]. The subsequent categorization of stations, following observations of station typologies, informs understanding of accessibility conditions within catchment areas and also facilitates transferability of FMLM recommendations among stations with similar typologies.

2.3 FMLM Strategies Commonly Implemented

Common strategies to address FMLM connectivity in studies center on "active transportation" improvements. Active transportation refers to modes of transportation that rely on user energy and power [12]. As pedestrian and bicycle transportation constitute the most common active transportation means, the enhancement of FMLM connectivity oftentimes requires deliberate consideration of facilities for pedestrians and cyclists that increase their safety, security (sometimes captured in a measure of overall quality of service), and efficiency. Typical recommendations for pedestrian facilities include continuous pedestrian sidewalks, direct pedestrian paths to transit stations, and pedestrian amenities at transit stations [13], [14]. Bicycle facility improvements commonly suggested include extensive bike lane networks, secure bike storage areas at transit stations, and space for bikes on transit vehicles. Pedestrian and bicycle facility improvements also strive to reduce pedestrian and bicycle interaction with vehicles to improve the safety of active transportation users via features such as traffic calming and active transportation priority at signalized intersections [10], [13], [15].

2.4 Mode Choice Modeling

An exhaustive body of research exists on the topic of modeling mode choice decisions involved in trip-making. Typically, such research employs discrete modeling methods such as multinomial logit or nested logit models [16] in order to characterize the influence of trip, individual, and built environment attributes on mode choice. Additionally, mode choice models by convention are based on disaggregated data such as travel surveys or diaries [16]. In several cases, ArcGIS functions have been utilized in merging more aggregated, environmental data to more disaggregated data on individual characteristics to explore the influences of "local" or surrounding environment characteristics on mode choice decisions [17], [18].

Some studies consider socioeconomic variables as direct or indirect factors of influence on mode choice. Directly, these characteristics have explicit consequences on the limitations or opportunities in an individual's mode choice set. To illustrate, an individual who does not own a private automobile may have higher propensity to rely on transit in comparison with an individual who does own a car. Indirect characteristics include those which might influence mode choice by modifying sensitivity to other characteristics. One example describes varying degrees of sensitivity to built environment characteristics influencing mode choice for high-income individuals with automobile access in comparison with low-income individuals with automobile access [19]. Such assessments highlight possible interaction effects between trip, individual, and built environments on mode choice.

Incorporating built environment characteristics into mode choice models has become more commonplace in mode choice literature. Research asserts that the built environment influences transportation characteristics such as travel times and mode-specific travel costs, which are critical to mode choice [20], [21]. This same research, therefore, also contends that exclusion of built environment characteristics might lead to biased estimates of parameters in mode choice models, leading to over- or under-estimates of variable elasticity. Attempts have also been made to incorporate these variables as proxy measures for mode-specific comfort, but have fallen under critique where their integration was supported only by weak statistical evidence [18]. Moreover, the inclusion of socioeconomic characteristics used as proxy measures for built environment demands attention to the geographic unit of analysis due to assumptions about the geographical extent of their influence [18], [22].

2.5 Transit Access Mode Analysis

Few studies exist that have sought to analyze mode choice to and from transit stations. Conventional factors related to mode choice have more often been considered in planning and design of access and egress to and from stations, but the quantitative significance of these relationships has not been extensively tested beyond airport access, railway access, or intercity travel.

Several studies modeling mode choice to and from transit stations have been applied in contexts outside of the United States. One Beijing study conducted on railway users' access mode applied a multinomial logit model to determine station access behavior [23]. The study found that income and vehicle ownership significantly influenced types of access and egress modes to and from stations. A Netherlands study employed a nested logit model to simultaneously analyze egress station choice and access mode choice in order to develop a railway accessibility index [24]. Studies on access mode choice in the United States have focused on airports and intercity railways. A mode choice study on the Westside Express in Portland, Oregon focused on access mode choice behavior of riders along a suburb-to-suburb commuter rail line [2]. A study of home-based transit access trips from a 1996 Bay Area travel survey involved an analysis of transit access mode choice that concluded strong significance of built environment characteristics on mode choice to and from transit stations [1]. Airport access mode choice modeling has formalized itself as a standard component of airport practice through an Airport Cooperative Research Program (ACRP) report [25].

2.6 Accessibility Analysis

Accessibility analysis using measures of accessibility are widely-used in literature. Common analysis measures include those reviewed in [26]. While measures differ in the levels of accessibility and conceptualizations of accessibility, in some cases, accessibility measures provide quick, digestible ways to compare accessibility across points of interests in a network. One study by Guttierez [27] explores accessibility measures calculated on a macrolevel network connecting various cities in Europe. The study compares three measures of accessibility: weighted average travel time, economic potential accessibility and contour measures to evaluate expected changes as a result of a new line to be built. The findings of the study reveal very different results between accessibility measures, particularly between weighted average travel time and contour measures where the former prioritizes long distances and the latter prioritizes nearer distances. The economic potential accessibility measure prioritizes distances somewhere between these two indicators, but captures diminishing destination attraction with increasing distance from an originating point. Valuable to note from the study is that areas of high accessibility before the new line would be built would still persist as the most highly accessibility points in the network, which may attest to over prioritization of connectivity in some accessibility measures [27]. Accessibility analysis requires the delineation of a study area from which to draw measures of attraction. One study develops a methodology of determining variable service areas as opposed to static, fixed Euclieean distance service areas [28]. The study finds that service area prescriptions are largely underestimated in comparison with traveler behavior in the Montréal region and suggests further examination of transit service areas to optimize service provision. Distance-decay functions have also been estimated from travel behavior data and also present important information in calculation of certain accessibility measures [29].

2.7 Summary

Literature review reveals a plethora of procedures and concepts available to guide the development of a framework to evaluate FMLM connectivity. Informed primarily by procedures from common elements of FMLM analysis methodology, this study develops and applies a methodology framework that first investigates access mode choice to stations via discrete choice analysis. Following, the framework then investigates the spatial relationship between rail stations and demand attributes in two ways. First, by calculation and comparison of accessibility measures. Second, by visualization of spatial distribution of demand types in the study area utilizing spatial statistical analysis. Finally, this study attempts to synthesize the findings of these analyses with proposed station categories and recommended FMLM implementations.

CHAPTER 3

METHODOLOGY

This chapter discusses the overall analysis methodology employed in this thesis.

3.1 Discrete Choice Model

Problems aimed at determining the probability of certain outcomes from a finite set of choices in a situation based on the attributes of an observation typically employ discrete choice models. Discrete choice models estimate probabilities of outcomes as a function of characteristics associated with a decision-maker as well as the attractiveness of the outcome [30], [31].

Discrete choice models based on random utility theory maintain four principal assumptions, described in the context of this study. *Assumption One* states that individuals in a population act rationally, have access to all information relevant to making a choice between nonmotorized and motorized access mode, and consistently select the outcome that maximizes their personal utility. *Assumption Two* states that a discrete outcome, nonmotorized or motorized access mode exists for each individual based on a vector of measured attributes of the individual and its environment. *Assumption Three* of random utility theory recognizes that a modeler or observer does not have access to perfect or complete information influencing individuals' decision-making. Random utility thus formulates net utility per outcome per individual with the systematic components described in Equation (1) plus the addition of a stochastic term, intended to capture immeasurable or unobserved idiosyncrasies influencing individuals' decision-making. The net utility of outcome i (nonmotorized access mode choice or motorized access mode choice) for individual n is expressed as:

$$U_{in} = X_{in}\beta_i + w_{in}\delta_i + \epsilon_{in} \tag{1}$$

where:

U_{in} = net utility of outcome i (nonmotorized access mode choice or motorized access mode choice) for individual n

$X_{in}\beta_i$ = portion of systematic component describing individual-specific attributes with X_{in} representing a vector of individual-specific attributes (i.e., local built environment, income) associated with outcome i and β_i representing a vector of estimable parameters

$w_i\delta_i$ = portion of systematic component describing outcome-specific attributes with w_i representing a vector of outcome-specific attributes associated with outcome *i* and δ_i representing a vector of estimable parameters

ϵ_{in} = stochastic portion of utility function which describes unobserved influences on outcome i for individual n

Finally, *Assumption Four* suggests that an individual chooses between nonmotorized or motorized access mode to optimize their utility [30]. The distribution of the error term in a random utility model influences the form of the ultimate discrete outcome model. The binary logit model was chosen for this study, assuming the individual disturbance terms of the utility functions in Equation 1 are identically and independently distributed as extreme value and the difference in disturbance terms between two choices (used for estimate) is distributed logistic [16].

The following choice probability for an alternative i (e.g., nonmotorized mode for accessing transit station) over alternative j (e.g., motorized mode for accessing transit station) selected by individual n, represented by $P_n(i)$, is developed [16]:

$$P_n(i) = \Pr(U_{in} \geq U_{jn}) \tag{2}$$

$$P_n(i) = \frac{e^{U_{in}}}{e^{U_{in}} + e^{U_{jn}}} \tag{3}$$

For model estimation, one choice (e.g., motorized mode for accessing transit station) is set as a base outcome (i.e., the parameters of the utility function for that choice set to zero) with the parameters in the remaining utility function representing how variables increase or decrease the probability of the remaining choice compared to the base outcome.

The parameters in the binary logit model were estimated with maximum likelihood, as described in [24], [31].

3.1.1 Interpretation of Parameter Estimates

Analysis of model output includes interpretation of hypothesis tests of significance for estimated parameters associated with explanatory variables. Hypothesis testing in this study was based on a 95% confidence interval with *p*-values (probability of making a Type

I error) less than 0.05. Yet, model interpretation recognizes that omission of relevant variables may occur when valuation of variables' significance relies solely on statistical measures [32].

Log-odds are reported along with parameter estimates for the binary logit model in this thesis. A one-unit increase in the value of an explanatory variable would expect a change in a log odds of the binary outcome according to the estimated magnitude and direction of the parameter estimate [33]. Models are also reported with estimated robust standard errors, which are typically employed in logistic regression models. Robust standard error is analyzed in order to estimate the variance of maximum likelihood estimator given a model specification. The distinction between standard errors and robust standard errors lies in how robust standard errors may indicate issues related to heteroscedasticity in observations. In this study, robust standard errors are performed after running model tests using standard errors to identify significant differences in variance estimates which may reveal issues in model specification. If little variation is seen between standard and robust error estimates, robust standard error estimates may not contribute new information or conclusions about model performance [34], [35]. STATA estimates robust standard errors using the Huber-Sandwich Estimator [35].

Model results also report *odds ratios*. Odds ratio allows for an alternative to interpreting the expected effects of explanatory variables on the dependent binary outcome variable. The odds ratio is calculated as the exponentiated value of the log-odds parameter estimate, assuming a one-unit change in the explanatory variable. The odds ratio can be generalized by the following equation for a δ-sized increase [33]:

$$e^{\beta_k * \delta} \tag{4}$$

where β_k represents the parameter estimate associated with attribute x_k and δ represents the size of increase in x_k.

Another interpretation technique produces estimations of an expected percentage changes in the odds of the binary dependent variable associated with a change in the explanatory variable x_k. This percent change is calculated by the following equation for each parameter estimate in the final model specification [33]:

$$Percentage\ change = 100[e^{\beta_k \delta} - 1] \tag{5}$$

3.1.2 Specification Test

3.1.2.1 Linktest

The linktest model specification test in STATA is used to detect possible specification error. The test creates a regression on the dependent variable based on predictions and predictions squared from the specified logistic regression model. The output of the test evaluates the significance of both the prediction and predictions squared in the produced regression. If the predictions squared has significant explanatory power in the model, this indicates that the model may be misspecified due to variable omission or due to an insufficient linear combination of variables in the logit model [36], [37].

3.1.3 Goodness of Fit Tests

3.1.3.1 Hosmer-Lemeshow Test

The Hosmer-Lemeshow is a goodness of fit test developed for logistic regression models. The outcome of the tests measures the level of matching between predicted frequency and observed frequencies. The test constructs groups of observations according to their predicted probabilities, from smallest in value to largest in value. A low p-value, specified in some guides as under 0.05, indicates a poor fit. Research has found that the test may be sensitive to the number of groups specified for analysis and cause significant changes in the p-value associated with the test. While the Hosmer-Lemeshow test is widely used in logistic regression models, the level of sensitivity to the number of groups used elicits a desire to supplement analysis of goodness of fit using other techniques [38].

3.1.3.2 Pseudo R-Squared

An R-squared statistic as commonly found in ordinary least squares (OLS) regression does not exist for logistic regression. Yet, "pseudo" R-squared statistics have been developed for logistic regression. The default pseudo R-squared statistic reported in STATA is calculated using McFadden's R-Squared calculation, represented as:

$$R^2 = 1 - \frac{ln\hat{L}(M_{Full})}{ln\hat{L}(M_{intercept})} \tag{4}$$

where $\hat{L}$ represents estimated likelihood, M_{full} represents the regression model with predictors and $M_{intercept}$ represents the regression model without predictors [39].

As in conventional R-squared statistics, the range of the pseudo R-squared statistic lies between 0 and 1. However, unlike the OLS R-squared statistic, a higher R-squared value does not indicate better model fit. Rather, a value recommended as an indicator of excellent fit is 0.4. Caution is advised when interpreting the test statistic similarly to an OLS R-squared statistic [30].

3.2 Transit Station Categorization

In order to effectively categorize the transit stations, the study first employs accessibility analysis to characterize the ease or difficulty with which certain opportunities may be reached from a rail station. Following, this study explores the spatial distribution of opportunities in relation to the positions of rail stations in the UTA network.

3.2.1 Accessibility Analysis

Accessibility measures, also known as accessibility indicators, attempt to quantify accessibility as influenced by travel behavior and the spatial distribution of activities or opportunities in an area. Myriad accessibility measures exist and Geurs' [26] review of accessibility measures and the types of perspectives embodied by each category provide a foundation from which to determine key measures for analysis. The final measures adopted in this study include weighted average travel time and potential accessibility.

3.2.1.1 Weighted Average Travel Time

Weighted average travel time (WATT) measures the spatial distribution of activities according to a cost such as time or distance of travel from one origin point to all destination activities in an area, weighted by the opportunities or attractiveness of each destination point [27]. The following equation shows a mathematical representation of the WATT location-based accessibility measure:

$$T_i = \frac{\sum_{j=1}^{n}(t_{ij} \cdot M_j)}{\sum_{j=1}^{n} M_j} \quad (5)$$

where T_i represents the Weighted Average Travel Time value at origin node i, t_{ij} represents costs of traveling between origin node i to destination j in the network and M_j represents the proxy weight of attractiveness at destination j. Population at destination node j provides an example of proxy measure of destination attractiveness used in determining WATT.

Though attractiveness of destinations constitutes a consideration in WATT calculation, the accessibility measure primarily prioritizes spatial distribution of activities within a network based on travel costs and operation of transit services. Subsequently, WATT may appropriately capture accessibility between elements within a transit network, but fail to capture a comprehensive measure of accessibility representative of other components of a trip such as access and egress to origin and destination points within a transportation network. In this study, WATT serves as a macrolevel indicator of network-wide station-to-station accessibility as a means to compare overall connectivity of stations.

3.2.1.2 Potential Accessibility

Gravity-based measures of accessibility exist as commonplace in accessibility studies of transit networks. As location-based indicator of accessibility, potential accessibility derives itself from gravity-based assumptions of travel reminiscent of

Tobler's First Law of Geography which articulates diminishing relationship between one point and everything else with increasing distance [40]. Thus, gravity-based measures suggest decreased attraction of a facility with increasing distance away from a facility and increased attraction of a facility with decreasing distance away from the facility. Thus, assumptions about the degree to which attraction changes in relation to distance remain pivotal to the calculation of gravity-based measures. The following is a mathematical representation of a gravity-based measure of accessibility referred to as "gravity potential" [41]:

$$P_i = \sum_{j=1}^{n} \frac{M_j}{T_{ij}^{\alpha}} \tag{6}$$

where P_i represents the estimated degree of potential accessibility of node i, M_j represents the proxy measure of attractiveness of node j, T_{ij} represents the travel cost between node i and node j and α represents the impedance factor (or "friction factor") of travel from node i to node j.

The impedance factor, α, in gravity-based measures describes the degree of decreasing attraction with distance and may capture land-use effects and information on travelers' perception of travel with respect to distance [26]. Studies may empirically derive the impedance factor from data describing travel behavior, though in the absence of such data and depending on the level of analysis, studies may assume α equal to 1 to capture distance effects without over-prioritizing nearer destinations [27]. While this assumption finds applicability in national-level analyses, the regional and local characteristics of the transit network studied in this thesis warrant consideration of local travel behavior. Thus, this study utilizes available data on travel behavior to estimate impedance factors from distance-decay relationships among nonmotorized and motorized mode choice to and from stations. The impedance factors become integrated into the gravity model potential estimates for each station.

3.2.1.3 Distance Decay Functions

This study constructs distance decay functions to characterize walk and drive access mode behavior to rail stations. Estimated travel lengths from users' origins to first rail boarding station are used to empirically derive distance decay functions of travel access behavior to rail stations. Observations are analyzed according to categories of access mode (walk or drive). Analysis assigns travel lengths to bin categories and calculates the share of total trips taken with lengths included in those bins. Distance decay curves are constructed that model the relationship between distances and the percent of trips which belong to the aforementioned distance categories. Further analysis of the relationship involves curve-fitting to estimate a distance decay function. Data were fit according to power form using curve-fitting functions in Excel based on walk and drive access behavior. *Figure 1* provides an image of the distance-decay curve constructed for walk access mode share, with accompanying equation of the power form function.

The result illustrates an inverse relationship between trip-making frequency and distance. The impedance factor, referred to as α in the potential accessibility equation, is estimated as -0.925 in the above distance decay function for walk access.

Figure 2 presents the distance decay function constructed based on drive access estimates. The estimated α parameter from the drive distance decay function is 0.806.

The impedance factors estimated from distance decay functions for the walk and drive access modes are then used as the potential accessibility α parameter shown in Equation 6. Due to variations in travel behavior from region-to-region or city-to-city or even among trip types, discretion is encouraged in comparison of impedance parameters developed between agencies or study areas [42], [43]. The impedance factors derived in this study between walk and drive access modes may be compared with more confidence since both are based on travel behavior in the same area. Thus, the larger magnitude of the impedance factor derived from the walk distance-decay function compared with the drive distance-decay function indicates greater friction or greater diminished willingness to travel farther distances by pedestrian modes.

Both weighted average travel time and potential accessibility measures contain an element M_j that describes the mass or degree of opportunity at a destination location [26], [27], [41]. Subsequently, the calculation of either metric requires the determination of the amount of opportunity representative of a destination. This process involves an interrogation of data resolution and means to address varying levels of data aggregation. Informed by the FMLM concept and the availability of local travel behavior data, this study delineates a catchment area or "access shed" around rail stations based on estimated travel behavior to individual stations.

3.2.1.4 Catchment Area Determination

The catchment area constitutes the principal site of analysis around rail stations in this study. Catchment areas in research and planning documents describe the extent of accessible area or opportunities from a point given a certain measure of impedance. To illustrate, the Federal Transit Administration (FTA) considers a pedestrian investment located one-half mile from a transit station as having a direct relationship with public transportation. Consequently, pedestrian investments that fit this criterion may be eligible for support from federal funds [6]. Yet, access sheds constructed based on the radial or "Euclidean, straight-line" distance may misrepresent the amount of traversable area within a given distance. Research that acknowledges insufficiencies associated with conceptualizing areas of access using straight-line distances offers alternative methods of delineating catchment area [8], [29]. Furthermore, distance thresholds recommended as generalizations of access mode choice may not reflect local travel behavior. Construction of threshold distances based on travel behavior data aims to provide distance measures more representative of local behavior.

3.2.1.5 Catchment Area Distance Thresholds

Travel behavior data from the RSG Origin-Destination Survey are used to construct catchment area distances. Of the 7,698 home-based work (HBW) and home-based school trips in the dataset, 3,756 remain after filtering data to include only those respondents for whom rail constitutes the first transit mode taken to complete their trips. The ArcGIS Network Analyst Shortest Path function is used to estimate travel lengths from users' origins to their first station boarded. Though the RSG survey does not explicitly provide the coordinates of the first station boarded, the road network dataset used for estimation of travel distances accumulates total distances traveled on nontransit traversable roadway networks.

Lengths successfully estimated for each individual respondent in ArcGIS were retained for further analysis. These lengths were categorized according to access mode (walk or drive) and the first rail station boarded by each respondent. In an effort to determine a threshold distance representative of users' travel behaviors at each station, this study calculates the 95th percentile of distances traveled to each station. In other words, the threshold distance was determined to capture an estimate of the maximum distance to which 95% of users would walk or drive to access a transit station.

3.2.1.6 Catchment Area Visualization

Construction of catchment areas utilizes the ArcGIS Network Analyst Service Area function. The Service Area function delineates accessible area from an origin point constrained by a certain travel cost threshold reachable according to navigable facilities in a roadway network. Thus, the catchment areas constructed using this function provide a more accurate representation of the amount of area accessible within a given distance of travel. In this study, the 95th percentile distances estimated for each access mode to individual rail station constitute the impedance factor inputs to generate service areas. *Figure 3* provides a visualization of the calculated 95th percentile walk catchment area lengths. *Figure 4* provides a closer look at catchment areas constructed for a few select stations.

Table 1 describes, by access mode, the distance thresholds, in meters, calculated for each rail station.

3.3 Examining Spatial Distribution of Binary Logit Attributes

This study evaluates local indicator of spatial association (LISA) statistics calculated using Spatial Statistics toolbox functions ArcGIS platform. LISA statistics test whether significant spatial patterns of attributes persist in a study area [44]. In this study, the explanatory variables found from binary logistic regression constitute the attributes investigated using LISA statistics. The result in ArcGIS produces a visualization of the spatial distribution of attributes from the final binary logit model specification. Results of LISA statistics are then used in conjunction with calculations of walk catchment areas to infer potential relationships between socio-spatial processes and the walk catchment area around rail stations. The walk catchment area is used as a means to capture the most information regarding station access at the most intimate or immediate level of nonmotorized access.

3.3.1 Hot Spot Analysis

Hot Spot analysis is a spatial statistics technique to identify spatial patterns in data. In ArcGIS, performing Hot Spot analysis involves a process of evaluating each geographic feature in a dataset to determine clusters of high-value or low-value attributes. The analysis produces a local Getis-Ord Gi* statistic that identifies areas exhibiting high or low values of a certain attribute. More technically, the Getis-Ord Gi* statistic tests the null hypothesis that attributes exhibit complete spatial randomness. A significant statistical result in favor of rejecting the null hypothesis suggests the occurrence of a spatial cluster or the presence of spatially auto-correlated data [45], [46]. ArcGIS presents the Getis-Ord Gi* statistic for each geographic feature in the form of a Z-score and p-value. A low p-value, defined by a certain threshold level of significance, indicates a significant spatial clustering. A high positive or negative magnitude of the Z-score indicates whether the cluster is of high or low values or “hot spots” and “cold spots,” respectively. The following presents the mathematical form of the Getis-Ord Gi* statistic and its components [45]:

$$G_i^* = \frac{\sum_{j=1}^{n} w_{i,j} x_j - \bar{X} \sum_{j=1}^{n} w_{i,j}}{S \sqrt{\frac{[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2]}{n-1}}} \tag{7}$$

$$\bar{X} = \frac{\sum_{j=1}^{n} x_j}{n} \tag{8}$$

$$S = \sqrt{\frac{\sum_{j=1}^{n} x_j^2}{n} - (\bar{X})^2} \tag{9}$$

where x_j represents the attribute value for feature j, $w_{i,j}$ represents the spatial weight between feature i and j and n represents the total number of features evaluated.

Hot spots and cold spots identified in this study serve additionally as proxy features of high or low demand to rail stations.

3.4 Summary of Methodological Framework

This section outlines the general methodological framework for analysis employed in this thesis. A visualization of the steps described is presented in *Figure 5.*

The first step, which involves discrete choice analysis, identifies attributes of access mode choice to transit. In an effort to expand the scope of FMLM analysis from focus on built environment characteristics, modeling efforts include deliberate determination of other types of influences on access mode choice. The second step, performing accessibility analysis, quantifies the degree to which rail stations exhibit accessibility to the attribute demand types explored in discrete choice modeling. The last step involving hot spot analysis investigates the spatial distribution of attribute demand types to identify spatial relationships between demand and rail stations to inform prioritization of certain strategies of FMLM development.

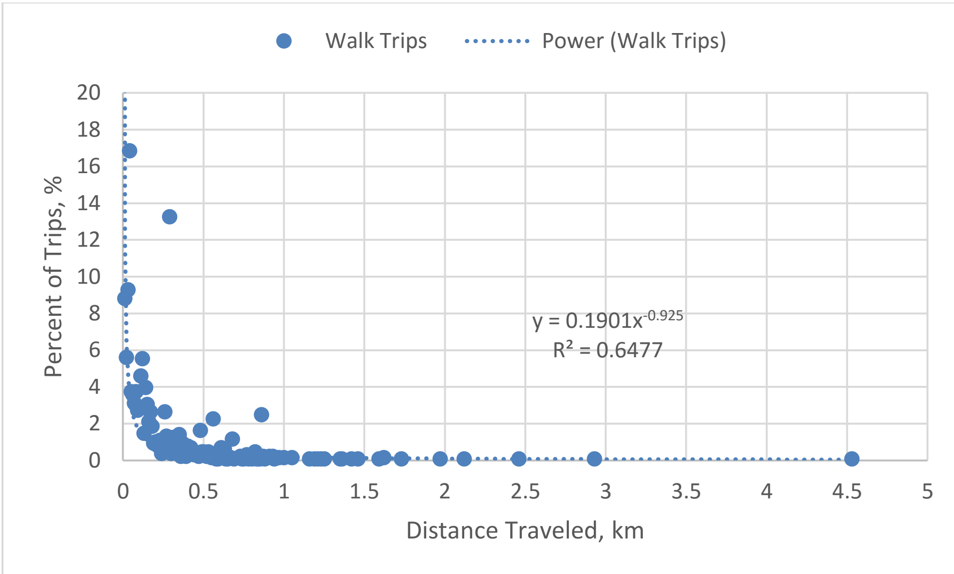

Figure 1 Distance Decay Function for Walk Trips to Stations

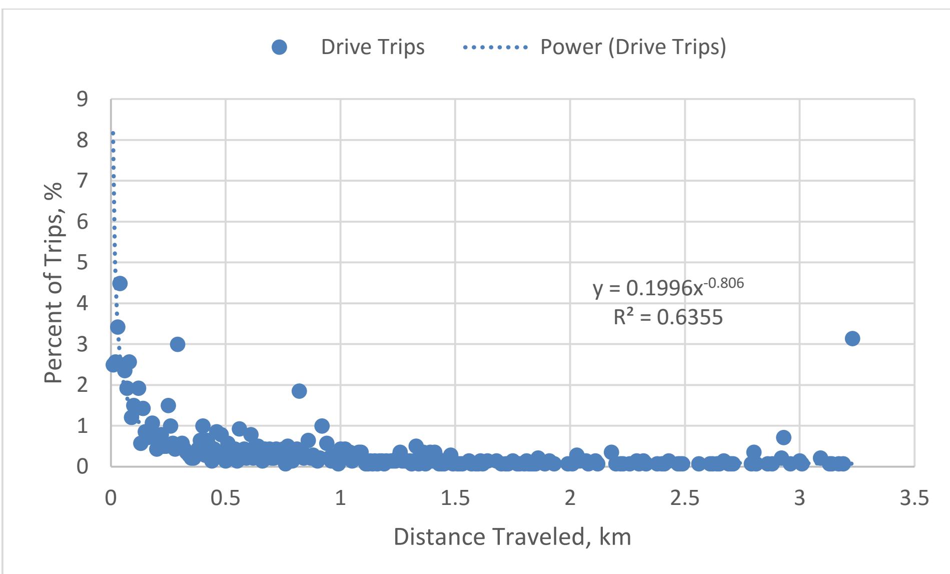

Figure 2 Distance Decay Function for Drive Trips to Stations

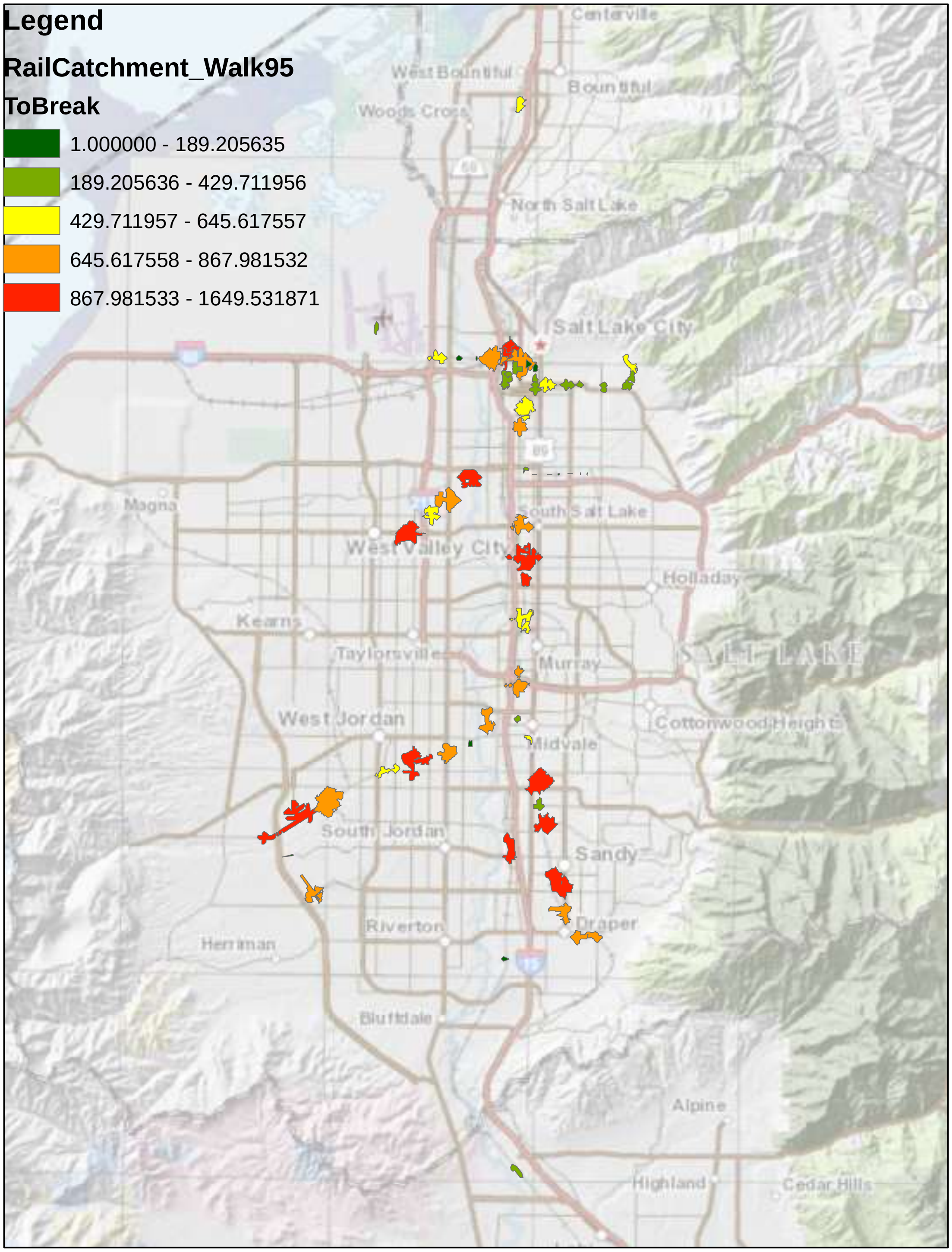

Figure 3 Walk Catchment Areas Based on 95th Percentile of Walk Distances

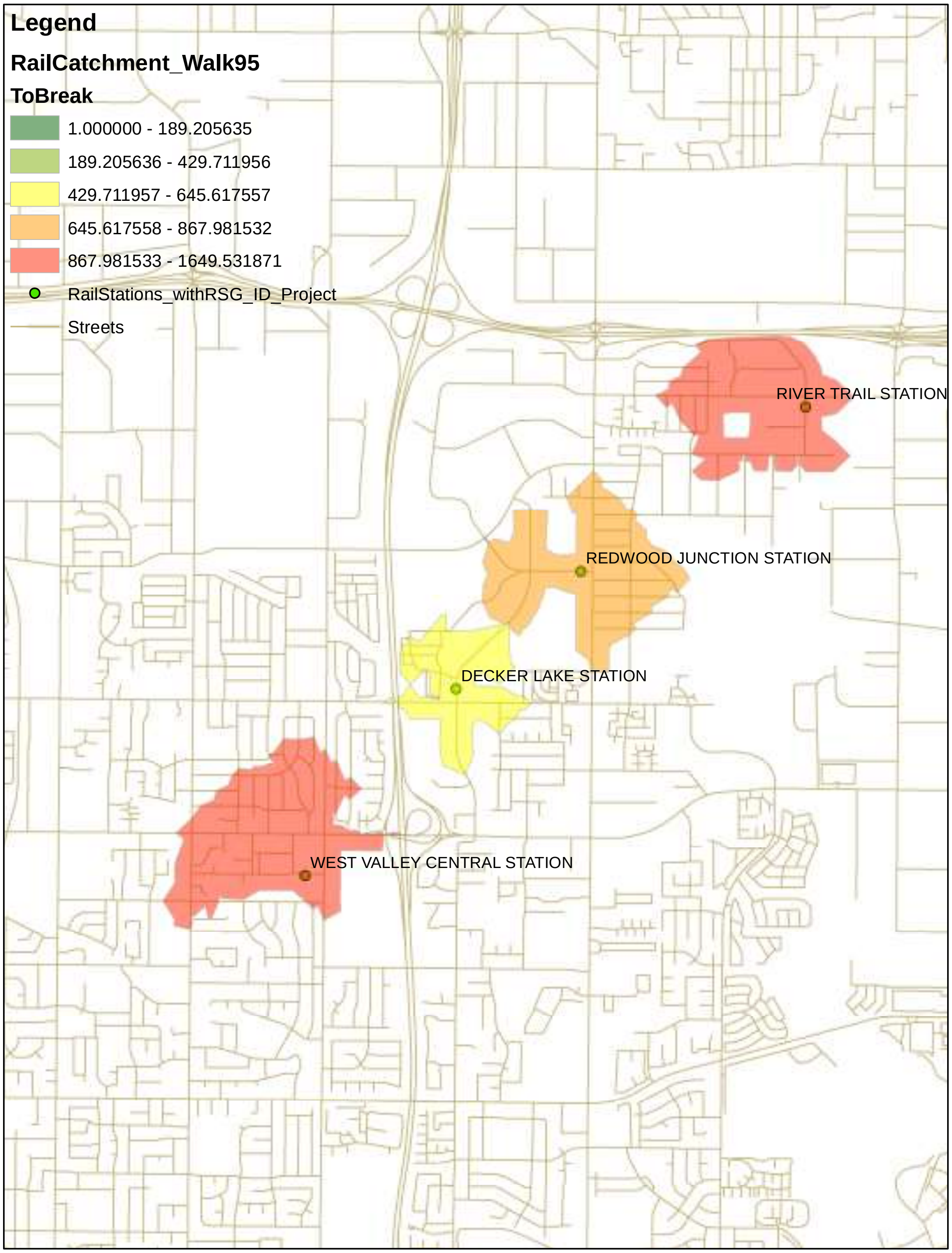

Figure 4 Walk Catchment Areas Visualized with Underlying Street Network

Table 1 Distance Thresholds for Each Rail Station by Access Mode (in meters)

Rail Station	Walk	Bike	Drive
1940 W North Temple Station	476.29	21.27	237.45
2700 W. Sugar Factory Rd Station	926.17	0.00	1469.51
4800 W. Old Bingham Hwy Station	848.28	51.34	2932.57
5600 W. Old Bingham Hwy Station	1649.53	2412.68	7771.65
900 East Station	201.07	145.63	37.78
900 South Station	602.95	232.29	354.09
Airport Station	279.91	92.72	148.37
American Fork Station	0.00	1275.37	4585.09
Arena Station	867.98	0.00	1022.81
Ballpark Station	714.27	2.08	1114.98
Bingham Junction Station	674.47	510.82	686.51
Central Pointe Station	824.21	43.67	2064.63
City Center Station	189.21	97.05	188.21
Clearfield Station	64.27	933.78	2587.15
Courthouse Station	376.69	160.92	1996.34
Crescent View Station	1230.13	429.71	3492.32
Daybreak Parkway Station	822.81	207.87	2383.01
Decker Lake Station	529.49	0.00	2446.42
Draper Station	107.84	0.00	5030.65
Draper Town Center Station	789.70	1360.61	5250.46
Fairpark Station	31.24	0.00	0.00
Farmington Station	48.16	1236.08	2033.86
Fashion Place West Station	765.57	492.71	1291.48
Fort Douglas Station	294.16	93.50	278.38
Gallivan Plaza Station	207.35	257.11	149.65
Historic Gardner Station	1.87	14.19	786.37
Historic Sandy Station	904.73	172.99	1130.76
Jackson/Euclid Station	685.75	32.73	223.21
Jordan Valley Station	645.62	385.87	1824.08
Kimballs Lane Station	744.80	594.96	2050.27
Layton Station	468.02	224.08	2226.11
Lehi Station	419.59	106.19	7994.44
Library Station	448.47	144.67	2031.67
Meadowbrook Station	893.39	25.23	1399.36
Midvale Center Station	466.29	48.06	1261.60
Midvale Fort Union Station	410.56	25.55	195.13
Millcreek Station	663.50	16.15	615.96
Murray Central Station	613.25	67.66	2509.02
Murray Central Station (Frntrnr)	613.25	67.66	2509.02

Table 1 Continued

Rail Station	Walk	Bike	Drive
Murray North Station	928.18	48.22	2118.27
North Temple Bridge/Guadalupe	868.43	68.05	3556.24
North Temple Station	868.43	68.05	3556.24
Ogden Station	684.02	49.80	12160.08
Old Greektown Station	198.03	0.00	98.11
Orem Central Station	531.13	0.38	1313.97
Planetarium Station	398.81	0.00	379.36
Pleasant View Station	0.00	0.00	0.00
Power Station	164.70	547.04	157.96
Provo Central Station	707.42	154.48	2988.40
Redwood Junction Station	679.12	1120.73	437.65
River Trail Station	977.47	462.76	765.11
Roy Station	0.00	6289.53	5938.23
Salt Lake Central Station	429.71	141.16	7103.21
Salt Lake Central Station (Frntrnr)	429.71	141.16	7103.21
Sandy Civic Center Station	918.20	703.27	1613.81
Sandy Expo Station	340.44	0.00	439.39
South Jordan Parkway Station	34.39	38.60	1329.20
South Jordan Station	951.54	281.97	1287.52
Stadium Station	293.84	252.48	293.84
Temple Square Station	141.34	0.00	0.00
Trolley Station	368.15	143.21	32.80
University Medical Center	569.41	9.95	569.41
University South Campus Station	293.58	79.04	293.58
West Jordan City Center Station	866.58	115.14	2050.46
West Valley Central Station	1026.31	59.98	998.82
Woods Cross Station	429.93	650.02	2180.52

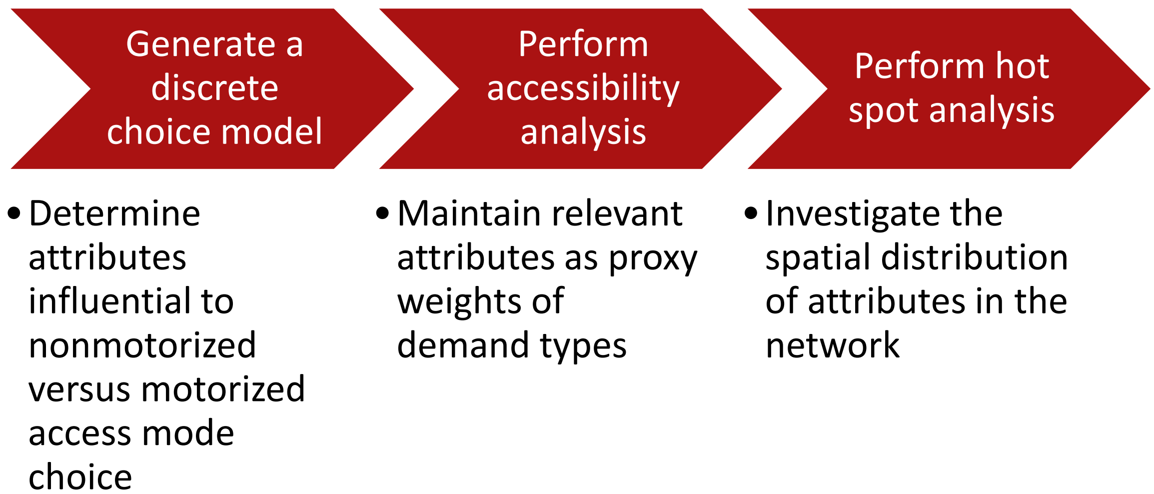

Figure 5 General Outline of Analysis Framework

CHAPTER 4

EMPIRICAL SETTING

Data involved in this study originated from several sources in an attempt to draw on a comprehensive body of characteristics to inform development of a methodology for station categorization.

4.1 Network Overview

The network examined in this study consists of 50 light rail (TRAX) stations, 15 commuter rail (FrontRunner) stations, 46 BRT stations, and 7 streetcar (S-Line) stations. *Figure 6* shows the coverage of this current transit network. TRAX is comprised of three separate lines, named the blue line, red line, and green line, with connections extending to different reaches within the Salt Lake County area. One end of the blue line begins in the heart of downtown Salt Lake City and terminates 19.3 miles south in the city of Draper, on the southern end of Salt Lake County. The red line has one end that originates at the University of Utah Medical Center and extends a length that terminates in the city of Daybreak, located in the southwest section of Salt Lake County. The green line is the newest of the three TRAX lines and connects West Valley City in the western end of Salt Lake County to downtown Salt Lake City and then to the Salt Lake City International Airport. FrontRunner, the commuter rail, travels up to 50 miles per hour and covers a length of 88 miles, traversing three Utah counties (from north to south): Davis County, Salt Lake County and Utah County. UTA's BRT system, referred to as "MAX," currently comprises one BRT service in operation. The service, 3500 South MAX line, connects the city of Magna, located near the westernmost edge of Salt Lake County, West Valley City, and the city of South Salt Lake. Finally, the S-Line streetcar network is UTA's most recently developed line which originates in South Salt Lake and, after approximately 2 miles of travel, terminates in a neighborhood area commonly known as Sugarhouse. The UTA network described traverses various land use types and densities and thus presents unique FMLM challenges throughout its system. The rail network comprised by the TRAX and FrontRunner routes constitutes the primary routes and stations for analysis in this study.

4.2 Analysis Dataset

4.2.1 RSG Survey Data

The primary dataset involved in this analysis constitutes an origin-destination survey of transit users conducted by Research Systems Group, Inc. (RSG) for the UTA, the primary provider of public transportation services within the State of Utah. The RSG study consists of two phases. The first phase was considered a "before" study which surveyed travelers on the TRAX Blue line and bus routes in the vicinity of the expected extension of the Blue Line to the city of Draper, Utah in August 2013. The second phase of the study, from which data in this study originate, developed as part of a system-wide study of all rail lines and most bus routes, doubling as a survey of travel behavior also following the Red Line mid-Jordan extension in August 2011.

The survey, administered between September 10th, 2013 and February 13th, 2014 utilized an origin-destination questionnaire available in English and in Spanish and also available for completion in the presence of the surveyor, online or returned via mail. The questionnaire collected data detailing traveler characteristics such as income level, educational level and residence; trip characteristics such the type of mode used to access transit station, the type of transit utilized, history of transit use and destination; and attitudinal data on whether users would recommend certain types of transit services provided by UTA. Sampling considerations for surveying administration intended to gather approximately 10% of average weekday boardings for each rail line and bus route surveyed. Bus surveys reached 76 bus routes, which included the 35MAX BRT and express bus routes, all three light rail lines and the FrontRunner commuter rail line. Paratransit, ski bus and FLEX route services were omitted from data collection since those services have less frequency and higher costs associated with obtaining data.

The RSG produced 13,168 amount of final, useable records. Several modeling and analysis constraints in this study led to further exclusion of observations. Of the 13,168 observations in the RSG survey, 7,698 remained as HBW trips. HBW trips in this study refer to those trips in which an individual's home constitutes one end of the trip (origin or destination) and the individual's workplace or school constitutes the other end of the trip (origin or destination). To avoid ambiguity in model results, data were further filtered to only include those observations whose origin is home. The final dataset was then limited to 3,756 observations. Access modes to transit stations reported in the RSG survey are grouped into a binary variable describing nonmotorized access modes (walk/wheelchair and bike) versus motorized access modes (drove alone, drove with someone who parked, rode with someone else who dropped off).

4.2.2 American Community Survey (ACS) 2009-2013 Data

The U.S. Census Bureau administers the mandatory ACS survey to a sample of the U.S. population every year to help inform decision-making from the local level to the national level. The ACS provides demographic data on individuals according to different levels of analysis. In this project, the ACS 2009-2013 survey data used pertain to information at the Census block group level. Data were downloaded in the form of a file geodatabase from the U.S. Census Bureau website. Data from the survey used in this project relate to mode choice response in block groups [47].

4.2.3 Smart Location Database (SLD) Data

The Smart Location Database constitutes the source for most information related to built environment characteristics in this study. The Environmental Protection Agency (EPA) compiled the SLD for all block groups in the United States as defined by the United States Census Bureau to serve as a part of a series of tools available for scenario planning, demand modeling and studying the relative location efficiency of block groups within metropolitan areas of the U.S. [48]. SLD data for Utah were downloaded in the form of a file geodatabase for visualization and manipulation using the ArcGIS platform. Tools in ArcGIS were used to add information from the SLD at the aggregate Census block group level on built environment characteristics to the reported origin points of individual observations in the RSG survey data for home based work trips. Variables related to network density and percentage of zero-auto ownership households were extracted from this dataset for analysis in this study.

4.2.4 General Transit Feed Specification (GTFS) Data

GTFS data refer to a standardized publication format for public transit agencies to publicly present data on their public transportation systems. Information in the data include transit network layout (i.e., stops, routes, geometry) as well as scheduling (i.e., stop times, days of operation). The standardized format is intended to facilitate analysis of public transportation data from agency to agency [49]. UTA compiled their public transportation data in GTFS format and made them publicly available. Environmental Systems Research Institute published a tool for reading GTFS data for analysis in ArcGIS. The tool was used to create the roadway and transit network used for analysis of travel behavior based on available 2014 road network data and GTFS data from January 28, 2014. More information about the tool can be found in [50]. Distances traveled from users' origins to first boarding station were estimated using the published GTFS tool in conjunction with the Network Analyst toolbox in ArcGIS. In order to estimate travel lengths, the transit road network dataset constructed via the GTFS network development tool was set to accumulate distances traveled on nontransit networks. The results estimated thus served as estimates of travel lengths taken to user's first boarding station. Determined origin to first boarding station travel lengths were then added to each HBW trip observation in the RSG survey data. In some cases, travel lengths were not generated for a number of observations due in part to differences in stop identification between RSG survey data and GTFS UTA data or else due to invalid geocoded origins and ending points. Simulating travel lengths in ArcGIS using the ESRI GTFS data tool follows the exact schedule determined by UTA in the GTFS files. Thus, output transit travel times include waiting times associated with transit scheduling as well as station-to-station travel times for trips with transfers.

4.2.5 Longitudinal Employer-Household Dynamics (LEHD) Origin-Destination Employment Statistics (LODES)

LEHD LODES data provide employment statistics for many states within the United States based on origin-destination, workplace location or residence location of workers. The employment statistics are compiled at the Census Block level and include attributes such as number of jobs. This total number of jobs is further stratified by employment industry type, wage level, race of worker and educational attainment. Workplace area statistics refer to those statistics at workplace destinations whereas residence location statistics refer to statistics of workers at home locations [51]. This study extracts employment data at workplace as well as residence.

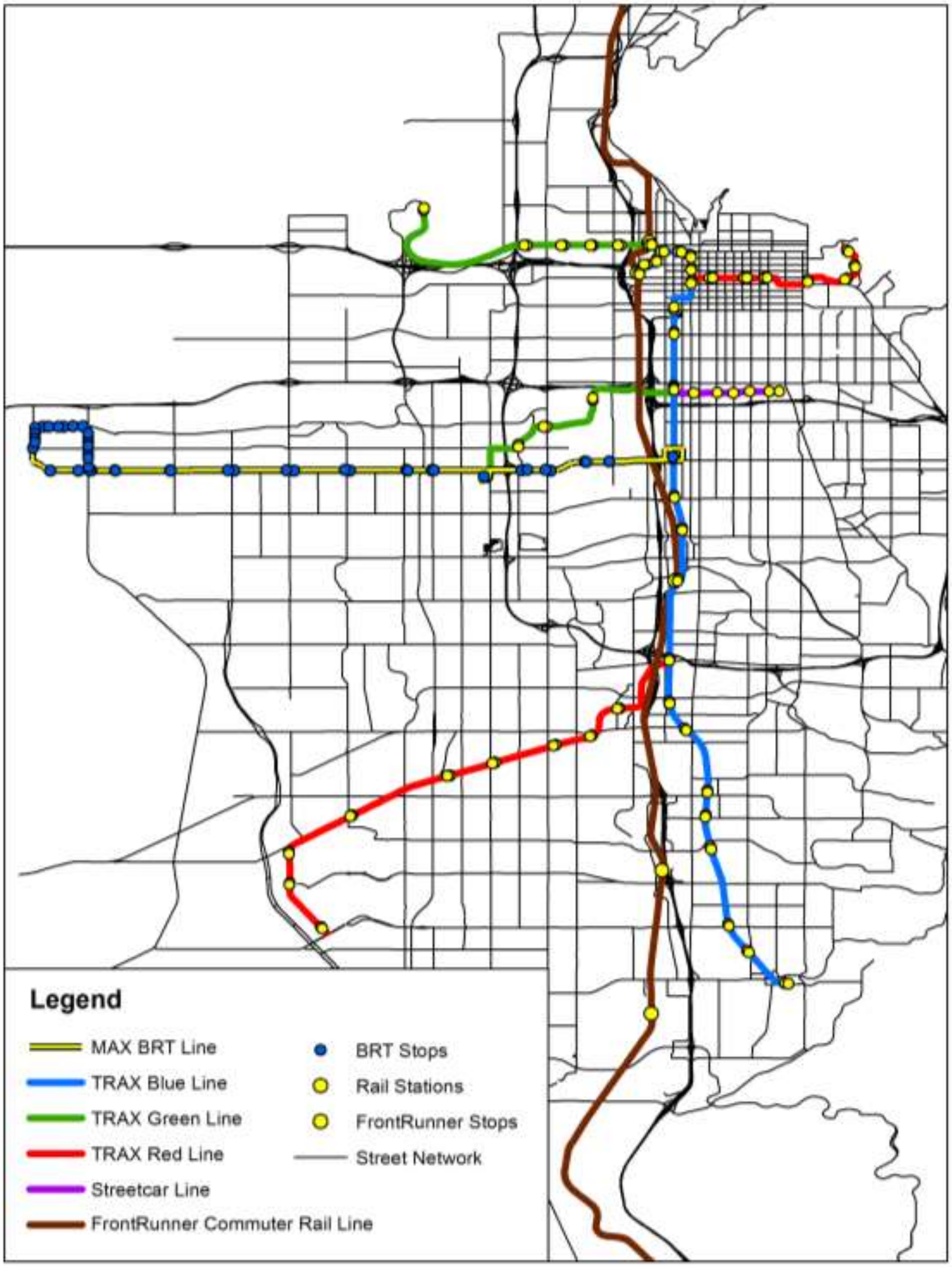

Figure 6 Existing UTA Transit Network

CHAPTER 5

RESULTS AND ANALYSIS

5.1 Discrete Choice Model on Transit Access Mode

Mode choice models discussed in the literature review informed the selection of explanatory variables for the specification of the model in this study. Variable selection involved an iterative process of performing binary logit regressions on many variations of model specifications and observing the influence of explanatory variables on access mode choice. Inferences relied in part on statistical tests for significance with thresholds previously described. Additionally, diagnostic tests for possible specification error as well as multicollinearity were conducted for each model output. The attributes were classified into three categories: traveler trip characteristics, traveler characteristics and land use and built environment characteristics. Traveler characteristics were further broken down into variables derived at an individual level and those derived at the Census block as well as Census block group levels. *Table 2* summarizes descriptive statistics of explanatory variables included in the sample to produce the final model specification.

Several interaction variables were constructed and included in the final model specification. These include the *drvlic_altmod* and *employ1_HigherEd* variables. Each of these interaction terms was constructed as the product of dummy, dichotomous variables. Coding each interaction term aimed to capture observations in which both dummy variables were present and subsequently led to an ultimate score of "1" for the variable. In this study, the *drvlic_altmod* variable seeks to capture the quality of possessing a driver's license as well as having access to an alternative means of movement apart from UTA services. The *employ1_HigherEd* variables seeks to capture the effects of interaction between full-time employment and possessing a bachelor's degree or higher.

5.2 Model Results

Table 3 summarizes the estimation results of the binary logit model of nonmotorized versus motorized mode choice for accessing transit stations. Estimated odds ratios, estimated parameter coefficients, robust standard error estimates, z-statistics and p-values are reported for each explanatory variable included in the final model specification.

5.2.1 Interpretation of Coefficient Estimates

5.2.1.1 Traveler Trip Characteristics

The model estimates a negative and highly significant parameter coefficient for *Length_OtoB,* describing the distance from a user's home origin to first boarding station. The result suggests that increases in travel distances is associated with greater propensity for choosing a motorized mode to access a transit station.

The parameter estimate for the variable *busfirst* has a positive, highly significant relationship in the model. This outcome suggests that the quality of a user first using a bus transit mode to complete their journey via transit is associated with greater propensity for choosing a nonmotorized mode to access transit from a home origin.

The estimated influence of the *FRNT_Use* variable as a negative and highly significant parameter coefficient suggests use of FrontRunner as a significant influence on greater propensity for accessing a station using a motorized mode. This estimate appears consistent with findings in regions with rail service and especially suburban commuter services that find access mode preferences in favor of motorized modes and reinforced by the availability of parking lots at these stations [2], [29].

The parameter estimate for *transfers* indicates that the variable has a significant, positive relationship in the model. Research has shown that an increased number of transfers in a user's trip decreases the average walk access distance threshold for travelers [29]. In conjunction with the parameter estimate for *transfers*, greater propensity for accessing stations via a nonmotorized mode may be associated with increases in number of transfers by relationship with diminished travel thresholds to access transit.

5.2.1.2 Traveler Characteristics

The *subfare* parameter estimate yields a significant, negative relationship for the variable in the model. This result suggests that access to or utilization of a subsidized fare payment type is associated with greater propensity for choosing a motorized mode to access transit stations. Subsidized fare payment encompasses discounted fare plans that meet different needs, most of which are geared toward employment entities to mitigate pollution from vehicular HBW trips. For example, UTA provides a company-sponsored EcoPass to encourage employees to utilize transit for HBW trips. The negative parameter might allude to the home locations of pass holders in auto-oriented suburban areas that have historically received the most subsidies, incentives and amenities (i.e., discounted fares, park-and-ride facilities) to travel by transit [3].

The *gender* variable is estimated to have a significant, negative relationship in the model. This suggests a greater propensity for choosing a motorized mode to access transit among female-identified respondents in comparison with male-identified respondents. This result may mirror studies which discuss increased number of responsibilities for female-identified people at home and at work, necessitating travel time savings that may take the form of motorized access to transit stations [52].

Model estimates yield a highly significant, positive parameter coefficient for the *hhveh_0* variable. The estimate suggests that users with households that have access or ownership over zero vehicles have greater propensity for choosing nonmotorized modes to access transit. This result aligns with [53], [54].

The model estimates a significant, positive parameter coefficient for the *age_25to34* variable. The result suggests greater propensity for using a nonmotorized mode to access stations associated with an age between 25 years old and 34 years old.

The *hhinc_1to4* variable is estimated with a significant, positive parameter coefficient. This suggests that having an income below $49,999 is associated with greater propensity for using a nonmotorized mode to access stations. The value $49,999 lies below the 2009-2013 estimates for median income in the State of Utah. The parameter estimates may reflect potential financial constraints that influence or limit travel options, including travel access to stations.

The model estimates a highly significant, negative parameter coefficient for the *drvlic_altmod* variable. The parameter estimate suggests that the qualities of possessing a driver’s license in addition to having access to alternative means of transportation apart from UTA services is associated with greater propensity for choosing a motorized mode to access transit stations. This mirrors an implicit relationship between possession of a driver's license and access to a vehicle.

The model estimates a statistically insignificant, positive parameter coefficient for the e*mploy1_HigherEd* variable. This indicates a positive relationship between full-time employed persons in possession of a bachelor's degree or higher. While not statistically significant, this parameter was retained in the final model specification in order to characterize relationships between proxy measures of economic security and travel behavior. In this case, the estimated results suggest greater propensity towards using a nonmotorized mode to access stations for an individual who embodies the attributes of this variable.

5.2.1.3 Block Group Characteristics

The final model yields a significant, positive parameter coefficient for the *PublicTransit* variable. This results suggests that, for an increase in the percentage of workers who use public transportation to reach work, there is a greater propensity in the associated block group for individuals to use a nonmotorized access mode to stations. Conversely, the model estimates a significant, negative parameter coefficient for the *DriveAlone* variable which suggests that an increase in the block group population of workers who drive alone to work is associated with diminished propensity for choosing a nonmotorized access mode to reach stations.

The model estimates a significant, positive parameter coefficient for the *MinoritizedPop* variable. This result suggests that among individuals in areas of high occurrences of ethnic, nonwhite populations, there is an associated greater propensity for choosing nonmotorized modes to access stations [3], [53].

Model estimates for *PCT_AO0* produce a significant, positive coefficient for the parameter. This result suggests that, for increase in the percent of households with no vehicle ownership, a user has greater propensity for travel to stations by a nonmotorized mode [55]

The final model specification produced a significant, positive parameter estimate for the *D3apo* variable. The variable intends to capture the number of facility miles that are pedestrian-oriented compared with the number of total facility miles. The positive parameter estimate for this variable suggests that increase in pedestrian-oriented network density is associated with greater propensity towards nonmotorized access modes to stations.

The parameter estimates for *WorkDensity* produce a significant, negative coefficient. This suggests that an increase in employment density at an individual's destination is associated with diminished propensity towards nonmotorized access mode choice in favor of greater propensity towards motorized access mode choice. This variable may be capturing spatial effects or patterns of travel between suburbs and more urbanized areas.

5.3 Reduced Model Specification

Analysis explored further model estimation based on the findings of the aforementioned model specification in an effort to isolate a select few variables with salient influence on access mode choice. This procedure maintained variables from the three variable types considered in the previous exploratory binary logit model specification. Descriptive statistics of the dataset associated with estimations of the reduced model form are presented in *Table 4* and results of the reduced model specification are presented in *Table 5*.

5.3.1 Interpretation of Coefficient and Odds Ratio Estimates for Reduced Model Form

Results of the reduced binary logit model specification identify 11 variables as having salient influence on access mode choice. Each variable maintained in the reduced model specification exhibits statistical significance at a 95% confidence level and mirrors conclusions found in literature concerning their individual influences on mode choice decisions.

The directions of coefficient estimates for each variable reflect those described in the exploratory binary logit model, though the magnitudes of influence and values of significance for each variable in the two models differ.

The reported percent change in the odds that y=1 reveals several factors as having a large magnitude of influence on the odds of the dependent variable predicting nonmotorized access mode choice. These variables include the *busfirst* attribute and the *hhveh0* attribute. Comparing strengths of predictors from the model estimate may be helpful in determining which attributes to prioritize in FMLM strategy development.

5.4 Accessibility Analysis Results

Accessibility analysis in this study comprises two parts: accessibility measures characterizing accessibility at each rail station and the spatial distribution of attributes in relation to rail stations evaluated through hot spot analysis.

5.4.1 Weighted Average Travel Time

The WATT location indicator was constructed to compare accessibility among all rail stations on the basis of prioritizing those stations that exhibit most minimal-time routes. Stations with the lowest WATT values may be interpreted as those with the least travel time to all other destinations and their associated opportunities in the network. Opportunities at destination stations were determined according to employment density (jobs per acre per Census block) provided in the LODES LEHD 2013 dataset for all blocks encompassed by the walk and drive catchment areas. *Table 6* presents a ranking of the top 10 stations with lowest values of WATT for destination opportunities.

With the exception of Murray Central Station, the top 10 stations are all located within or in close proximity to downtown Salt Lake City. From a network design perspective, this may be attributed, in part, to the radial layout of the rail network in Salt Lake City. A radial network refers to one which links suburbs to a central business district (downtown Salt Lake City) [3], [56]. The nature of the central business district as a common destination for all connecting rail routes in the network lends stations in this area a high degree of connectivity to all other stations. Additionally, weighted attributes such as employment density tend to be high in downtown areas, lending additional prioritization for these stations among other nearby, low-WATT stations. Murray Central

Station is a major transfer point between FrontRunner commuter rail, red line TRAX and blue line TRAX routes. As a point in the network with connections to three other rail routes, Murray Central Station demonstrates a high degree of connectivity to other stations.

5.4.2 Potential Accessibility

The potential accessibility measure was constructed to take into account the effects of diminishing influence of opportunities with increasing distance away from a rail station. As with WATT calculations, potential accessibility was calculated according to walk and drive catchment areas. Additionally, it is also calculated for bike catchment areas around stations with observed bike access.

The results of potential accessibility calculations are presented by catchment area type as well as variable type in the Appendix. Stations were ranked from highest to lowest degree of potential accessibility. As described in the methodology section, higher values of potential accessibility indicate greater potential accessibility for the node studied. In this study, this means that stations ranked as number “1” produced the highest measures of potential accessibility to the demand type specified by the attribute evaluated. In other words, higher values of potential accessibility in this study may be interpreted as greater ease of access to reach certain attributes. *Table 7* is presented as an example of station ranks determined from results of potential accessibility.

For example, in *Table 7* (Ranking Potential Accessibility of Walk Catchment Area Trip Characteristics), Fairpark Station has the highest level of potential accessibility calculated according to opportunities for reaching *busfirst* demand in the station catchment area. Subsequently, a station like Fairpark may be able to leverage resources to support nonmotorized access characteristics of *busfirst* users in the area through improved connections to bus stops through multimodal facilities or improved bus service reliability.

5.4.3 Hot Spot Analysis

Maps were generated in ArcGIS to identify hot spots as well as cold spots of each attribute presented in the binary logit final model specification in Chapter 5. An example of one such map which describes hot spots of minority populations is presented in *Figure 7*. As indicated in the legend, areas of deep red signify areas of high, statistically significant incidence rates of the *MinoritizedPop* attribute, which describes the percentage of ethnic, nonwhite population in a Census Block Group

The following map in *Figure 8* visualizes the estimated walk catchment area for each rail station in the network in relation to the hot spot analysis map presented in *Figure 7*. Comparing the two layers allows for visualization of walk catchment areas coincident with hot spot areas of a certain attribute. Such analysis may consider these coincident areas as those warranting higher priority for considering station improvements that accommodate the attributes investigated.

The result in *Figure 8* exhibits coincident walk catchment area with hot spot analysis areas. The coincident area suggests the presence of socio-spatial processes that elicit the particular attribute (*MinoritizedPop*). Following this line of reasoning, West Valley Central Station is one such station that may warrant recommendations or implementations that specifically accommodate the significant *MinoritizedPop* local population.

Table 2 Summary of Descriptive Statistics on Selected Variables (number of observations = 3160)

Variable	Description of Variable	Mean	Std. Dev.	Min	Max
Dependent Variable					
NonMoto_Moto	Nonmotorized access mode =1, Motorized access mode =0	0.583	0.493	0.000	1.000
Traveler Trip Characteristics					
Length_OtoB	Estimated travel length from origin to first boarding station	1102.879	1737.152	0.000	41057.000
busfirst	User used bus as first transit mode on trip	0.452	0.498	0.000	1.000
FRNT_use	User used FrontRunner as part of trip	0.206	0.405	0.000	1.000
transfers	Number of transfers	0.495	0.630	0.000	2.000
Traveler Characteristics, Individual					
subfare	User makes trip using subsidized fare payment	0.607	0.488	0.000	1.000
gender	Gender of user according to gender binary	0.414	0.493	0.000	1.000
hhveh_0	Household vehicle ownership 0	0.167	0.373	0.000	1.000
age_25to34	Age of user from 25-34	0.301	0.459	0.000	1.000
hhinc_1to4	Household income below $49,999	0.549	0.498	0.000	1.000
drvlic_altmod	Interaction term for users with a driver's license and access to an alternative mode to transit	0.528	0.499	0.000	1.000
employ1_HigherEd	User in possession of bachelor's degree or higher and employed full-time	0.271	0.444	0.000	1.000
Traveler Characteristics, Block Group					
PublicTransit	Population at home origin who use public transit to work, %	4.160	4.854	0.000	33.640
DriveAlone	Population at home origin who drive alone to work, %	73.820	11.823	0.000	100.000
PCT_AO0	Households with 0 vehicle ownership at home origin, %	6.743	8.894	0.000	54.320
MinoritizedPop	Population at home origin ethnic, nonwhite, %	15.203	12.100	0.000	74.774
Land Use and Built Environment Characteristics					
D3apo	Pedestrian-oriented facility miles per square mile	12.987	5.586	0.248	31.511
WorkDensity	Gross employment density (jobs/acre) at destination	16.715	11.950	0.000	50.933

Table 3 Exploratory Binary Logit of Nonmotorized Access Mode Choice Mode (versus Base Outcome of Motorized Mode Choice)

Variable	Coefficient	Odds Ratio	Std. Err.	z	P
Traveler Trip Characteristics					
Length_OtoB	-0.001	0.999	0.000	-7.690	>0.00
busfirst	2.145	8.546	0.130	16.490	>0.00
FRNT_use	-1.382	0.251	0.171	-8.090	>0.00
transfers	0.462	1.587	0.110	4.210	>0.00
Traveler Characteristics					
Individual					
subfare	-0.575	0.563	0.126	-4.550	>0.00
gender	-0.581	0.559	0.119	-4.890	>0.00
hhveh_0	2.681	14.607	0.399	6.720	>0.00
age_25to34	0.487	1.628	0.129	3.760	>0.00
hhinc_1to4	0.598	1.818	0.124	4.830	>0.00
drvlic_altmod	-1.067	0.344	0.126	-8.450	>0.00
employ1_HigherEd	0.335	1.398	0.138	2.430	0.015
Block Group					
PublicTransit	0.079	1.082	0.017	4.670	>0.00
DriveAlone	-0.010	0.990	0.006	-1.610	0.108
PCT_AO0	0.032	1.032	0.009	3.640	>0.00
MinoritizedPop	0.020	1.021	0.006	3.540	>0.00
Land Use and Built Environment Characteristics					
D3apo	0.039	1.040	0.011	3.560	>0.00
WorkDensity	-0.015	0.986	0.005	-2.880	0.004
Summary Statistics					
Number of Observations	3160				
Log pseudolikelihood at zero	-2147.0323				
Log pseudolikelihood at convergence	-1013.875				
McFadden’s Pseudo R-squared	0.5278				

Table 4 Summary of Descriptive Statistics on Reduced Model Form Variables

Variable	Mean	Std. Dev.	Min	Max
Dependent Variable				
NonMoto_Moto	0.584	0.493	0.000	1.000
Traveler Trip Characteristics				
Length_OtoB	1089.008	1715.725	0.000	41057.000
busfirst	0.449	0.497	0.000	1.000
FRNT_use	0.205	0.404	0.000	1.000
Traveler Characteristics				
Individual				
subfare	0.604	0.489	0.000	1.000
gender	0.414	0.493	0.000	1.000
hhveh_0	0.169	0.375	0.000	1.000
hhinc_1to4	0.551	0.497	0.000	1.000
drvlic_altmod	0.527	0.499	0.000	1.000
Block Group				
PublicTransit	4.161	4.852	0.000	33.640
MinoritizedPop	15.225	12.118	0.000	74.774
Land Use and Built Environment Characteristics				
WorkDensity	16.722	12.002	0.000	78.490
Number of Observations	3264			

Table 5 Reduced Binary Logit of Nonmotorized Access Mode Choice Mode (versus Base Outcome of Motorized Mode Choice)

Variable	Coefficient	Odds Ratio	Robust Std. Err.	z	P	Percent Change in Odds that y=1
Traveler Trip Characteristics						
Length_OtoB	-0.001	0.999	0.000	-7.670	>0.000	-0.0598
busfirst	2.191	8.947	0.123	17.790	>0.000	794.663
FRNT_use	-0.978	0.376	0.137	-7.120	>0.000	-62.405
Traveler Characteristics						
Individual						
subfare	-0.620	0.538	0.123	-5.030	>0.000	-46.187
gender	-0.607	0.545	0.110	-5.510	>0.000	-45.5025
hhveh_0	2.802	16.480	0.393	7.140	>0.000	1547.988
hhinc_1to4	0.583	1.792	0.111	5.260	>0.000	79.229
drvlic_altmod	-1.024	0.359	0.122	-8.390	>0.000	-64.090
Block Group						
PublicTransit	0.105	1.111	0.015	6.860	>0.000	11.1244
MinoritizedPop	0.032	1.033	0.005	6.060	>0.000	3.2839
Land Use and Built Environment Characteristics						
WorkDensity	-0.015	0.985	0.005	-3.100	0.002	-1.483
constant	0.469	1.598	0.213	2.200	0.028	59.845
Summary Statistics						
Number of Observations	3264					
Log pseudolikelihood at zero	-2216.5497					
Log pseudolikelihood at convergence	-1082.964					
McFadden's Pseudo R-squared	0.5114					

Table 6 Select Rankings Based on WATT Weighted by Employment Density

Rank	Walk Catchment Area	Drive Catchment Area
1	Arena Station	Arena Station
2	Temple Square Station	Temple Square Station
3	Planetarium Station	Planetarium Station
4	North Temple Bridge/Guadalupe Station	Courthouse Station
5	Courthouse Station	900 South Station
6	900 South Station	Old Greektown Station
7	City Center Station	Salt Lake Central Station
8	Old Greektown Station	Gallivan Plaza Station
9	Gallivan Plaza Station	City Center Station
10	Salt Lake Central Station	Murray Central Station

Table 7 Potential Accessibility Table for Walk Catchment Areas, Trip Characteristics

Ranks	W_BusFirst	W_FRNTUse	W_transfers
1	Fairpark Station	Farmington Station	Fairpark Station
2	Farmington Station	Clearfield Station	Clearfield Station
3	Temple Square Station	Temple Square Station	Farmington Station
4	Clearfield Station	Draper Station	Temple Square Station
5	City Center Station	Layton Station	South Jordan Parkway Station
6	Old Greektown Station	City Center Station	Old Greektown Station
7	Gallivan Plaza Station	Old Greektown Station	City Center Station
8	Central Pointe Station	Central Pointe Station	Gallivan Plaza Station
9	Library Station	Gallivan Plaza Station	900 East Station
10	Salt Lake Central Station	Provo Central Station	Salt Lake Central Station

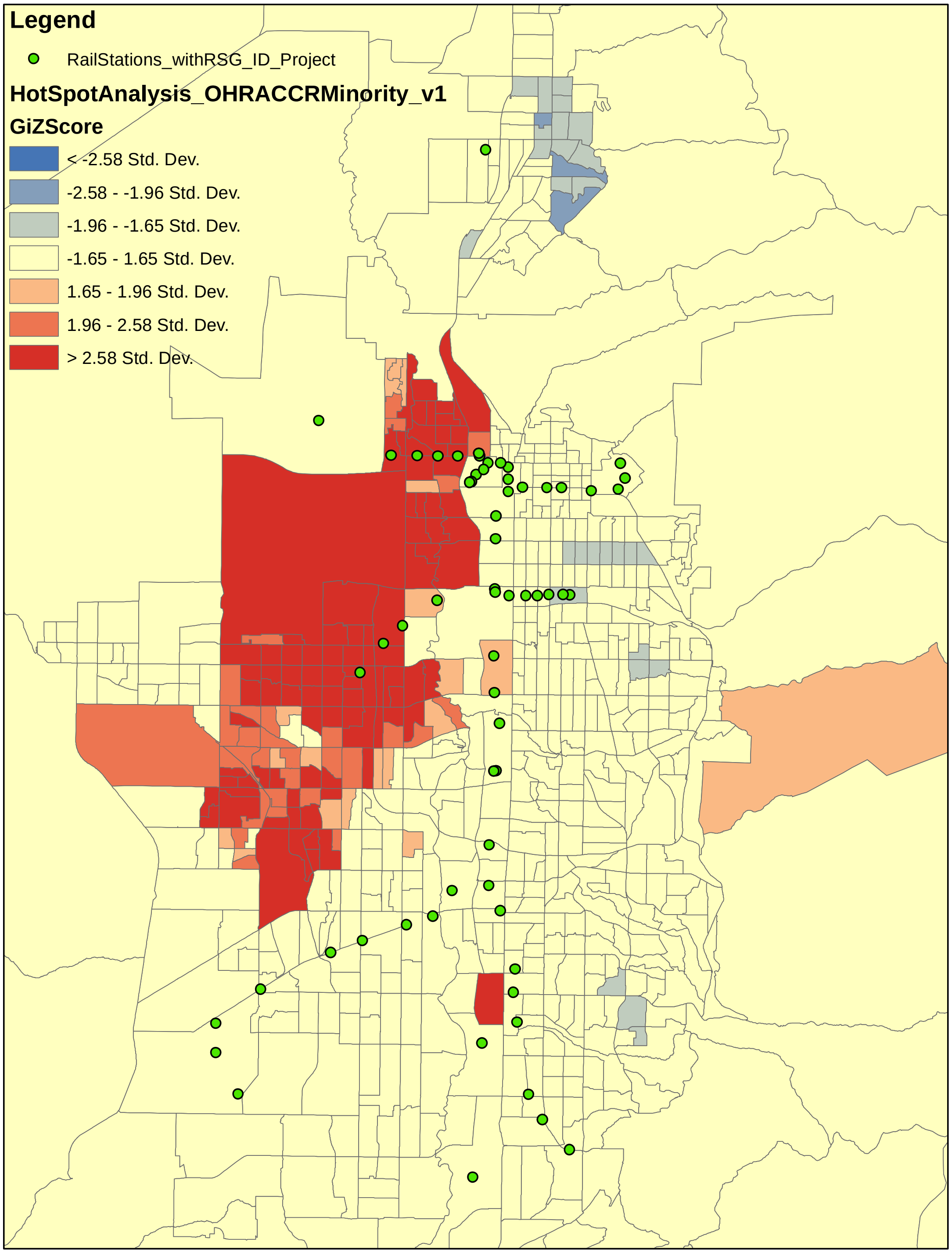

Figure 7 Hot Spot Analysis Results for MinoritizedPop Attribute

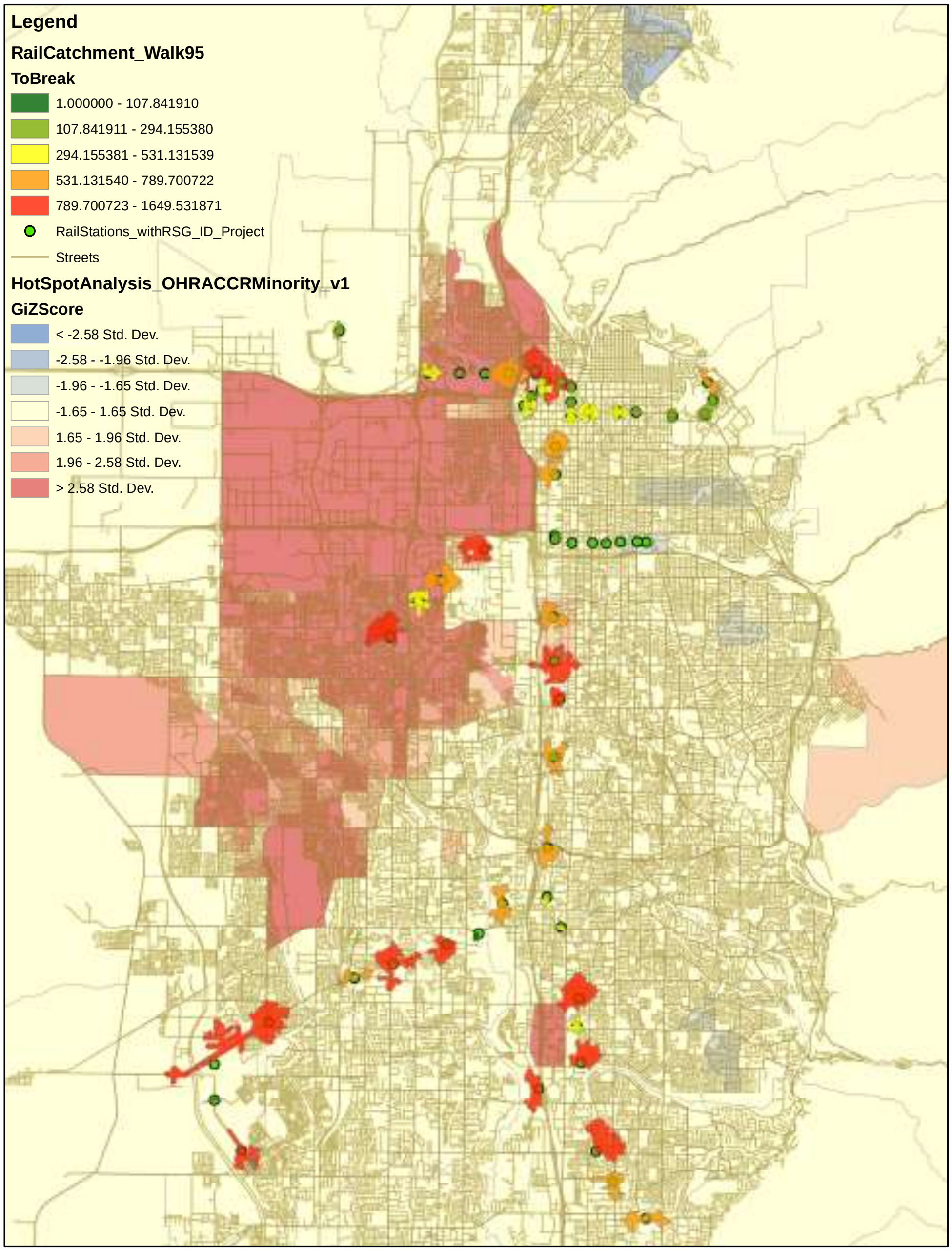

Figure 8 Walk Catchment Areas Overlay on MinoritizedPop Attribute Hot Spot Analysis

CHAPTER 6

RELATING RESULTS TO FMLM ANALYSIS FRAMEWORK

This section presents a discussion of analysis results and the role of these results in the formulation of a proposed set of station typologies.

6.1 Review of Analysis Procedure

The analysis in this study followed a framework to evaluate facets of accessibility to fixed station rail transit network of the Utah Transit Authority to inform the development of station categories to facilitate FMLM strategy development and implementation in the network.

To begin, this study limited analysis to interrogate factors related to travelers' decisions to choose a nonmotorized versus motorized mode to reach a transit station. To identify factors influential to transit access mode choice decisions, this study employed discrete choice modeling via binary logit modeling on data describing trip, individual, block group and land use characteristics. This study first developed an exploratory binary logit model then developed a reduced form of the exploratory model in order to isolate factors with strong and easily interpretable influence on transit access mode choice. The attributes identified in the reduced form of the binary logit model were maintained as proxy demand types for evaluation in accessibility analysis.

Accessibility analysis employed in this study aimed in one part to quantify the level of accessibility from each fixed rail transit station to a demand type surrounding the station. Two measures to quantify accessibility were calculated: weighted average travel time and potential accessibility. The demand types determined from attributes of the reduced binary logit model factored into calculations of these measures as weights of attraction characteristic of the catchment area surrounding each transit station.

The catchment area component of accessibility analysis constitutes another critical piece of accessibility analysis employed in this study. The catchment area delineated an area characterizing an assumed extent of influence around each rail station. The catchment area also played a critical role in spatial analysis, the second method of quantifying accessibility characteristics in this study.

Spatial analysis relied on hot spot analysis spatial statistical technique in order to identify the clustering of high and low incidences and rates of the reduced binary logit model attributes in space. The motivation behind conducting this type of analysis was to infer relationships between the physical distribution of demand types in space and the location of rail transit stations.

Accessibility analysis subsequently comprised three quantitative methods to explore rail transit accessibility within the context of nonmotorized versus motorized access mode choice. Evaluation of results from the analysis framework employed in this study intended to support a means to characterize transit stations based on travel behavior, traveler behavior and land use characteristics. Leveraging associations or characteristics of these attributes asserted an important role in the rationale for developing station typologies using FMLM as the primary lens of analysis.

6.2 Assessing Quality of Information from Accessibility Analysis

The results of the weighted average travel time measurement provided limited nuanced information about access to certain demand types on a system-wide level. This may be due to the nature of the indicator as a macrolevel evaluation of the physical distribution of activities in space, constrained to the operational characteristics of the entire UTA rail network. Consequently, results of weighted average travel time provided more information about the connectivity of one station in relations to all other stations in the network primarily from an operational perspective. Despite changing demand types to weigh attraction at each station, the same few stations nearest or within the central business district were consistently ranked with highest accessibility.

The results of potential accessibility calculations provided limited information about levels of access to certain demand types between rail stations. As in the case of weighted average travel time, the metric consistently ranked stations within or near the central business district of the study area. Yet, while weighted average travel time estimated the connectivity of stations on a network level the potential accessibility metric was developed to evaluate accessibility from the rail transit station to demand within the catchment area of that station. The results of potential accessibility elicited suggestions of central business district areas as those areas exhibiting greater diversity of demand types as a result of dense land use and built environment characteristics.

Moving away from the central business district accompanied diminishing strength in conclusions drawn from the accessibility metrics. The metrics were very useful in determining quickly which stations exhibited high accessibility to various demand types.

Hot Spot Analysis provided an easily interpretable characterization method of the spatial relationship between a certain demand type and the location of a rail station based on proximity. While characterizing access to demand via spatial proximity in this section of the analysis suffers from a perspective of proximity that lacks consideration for distances in the road network in the study area, the visualization technique provided digestible visualizations of the distribution of demand types.

6.3 Associations with Demand Attributes of the Reduced Binary Logit Model

Associations with proxy demand types were noted in the interpretation of variable coefficients of the exploratory binary logit model developed in this study. Characterizing accessibility according to demand types warranted the interpretation of what it means to have the demand type either present or absent, or in other words, characteristic or uncharacteristic of a certain transit station based off of analysis results. This section provides an example of the associations made with demand attributes and how those associations could be interpreted within a FMLM lens. This step served as an essential component to bridge analysis results with the FMLM motivations of this thesis. Moreover, evaluating these associations with attribute demand types constitutes an important step in justifying and interrogating how characteristics of attributes may be leveraged or addressed to improve FMLM connectivity.

6.3.1 Associations with the MinoritizedPop Attribute

The discrete choice models yielded a modeling result for the *MinoritizedPop* attribute that suggests greater propensity for nonmotorized access mode choice to rail stations among users who come from areas with high rates of the attribute. The *MinoritizedPop* attribute was maintained as a statistically significant and informative independent variable to predict nonmotorized versus motorized access mode choice in both the exploratory binary logit model and reduced binary logit model form developed in this study. Statistical significance aside, the attribute also finds significant support in mode choice literature as well as literature discussing the equitable or inequitable distribution of transportation infrastructure and funding. In mode choice literature, minoritized populations that are particularly concentrated in a metropolitan area are commonly described as having some form disadvantage in accessibility to transit and other transportation services. The lack of access is often framed within discussion of the strain experienced from transportation costs and therefore, financial inaccessibility of certain transportation services or modes [54], [57], [58]. In other cases, discussion of transportation infrastructure discuss how minoritized populations are often situated in areas which experience divestment in transit service those communities rely on in favor of funding other transit expenditures such as rail service to attract economic development and a demography of riders who may not be limited to only traveling by public transportation [3].

As a component of the analysis in this study, the *MinoritizedPop* attribute lends important information into first orienting planners to where a historically vulnerable population in literature and in the study area exists. Familiarizing planners with the locations aids in determining a category of rail stations in close proximity or exhibiting high potential accessibility to this attribute. From there, planning may be organized or focused deliberately on the needs and opportunities of the people and communities who constitute this demand type.

Within a lens of FMLM analysis, the *MinoritizedPop* provides critical information from which to glean or further investigate the travel behavior associated with this population. Further investigation may yield information about the nonmotorized travel behaviors of individuals within areas of high rates of minoritized populations to inform the development of FMLM strategies in these locations. For example, studies show the prevalence of bike mode choice among minoritized populations [54]. This consideration may be evaluated in the context of the study area to see if the same travel behavior apply and if so, next steps may include consideration of the types of implementations that would be useful in facilitating or improving the safety of this type of travel for this population. The location of the attribute may also lend important information to establishing an order of resource prioritization among rail stations.

Associations with demand attributes are discussed more generally in the process of proposing station categories in the next chapter.

CHAPTER 7

PROPOSED STATION CATEGORIES

Based on the accessibility analysis results described, the following categories were constructed to guide strategy development to increase ridership in tandem with FMLM goals put forth by UTA. Station categories were created according to perceived variations in the level of transit-integrated, reliance or discretionary use surrounding each individual station. Transit-integrated comprises rail stations perceived as well-used and inherent components of transportation infrastructure in an area. Markers of integration associate high connectivity and access to a diverse set of demand attributes. Thus, the transit-integrated category includes stations with low WATT values and consistent high ranking for walk potential accessibility calculated for each attribute defined. The transit-reliant/transit-beneficiary category attempts to identify rail stations serving populations who may rely on transit or for whom greater economic and physical accessibility could ameliorate financial burdens accrued from transportation costs. Studies such as equity analyses of transportation networks have included similar categories as in [59], [60]. This category comprises stations in near proximity of areas with significant hot spots of zero-vehicle owning households, minoritized populations and block group public transit use to work. Transit discretionary rail stations comprise those in close proximity to hot spot areas of drive alone to work behavior, possession of a driver's license and access to an alternative transportation mode to UTA services, status of employment and possession of higher education level of education, areas with high rail-use and cold spots of nonmotorized access to transit [3].

After identifying overarching station categories based on perceived integration and use, stations were further separated according to perceived nuances which might have resonant effects in prioritizing the type of connectivity strategies and planning. Transit-integrated stations are divided into “Central Business District,” “University” and “Public Resource.” “Central Business District” stations include those with highest network connectivity determined via WATT values and geographic placement in the Salt Lake City downtown area. “University” stations include stations that connect directly to University of Utah facilities, including the University Medical Station. Transit-reliant stations are divided into subcategories consisting of “Vulnerable” and “Diverse Demand Set.”

“Vulnerable” includes those stations in close proximity of hot spots of nonmotorized access mode to transit, minority population, zero-vehicle households and below-median incomes. Additionally, these stations exhibit cold spots of public transit use. Based on the number of indicators in these categories signalizing transit-reliance or potential economic benefit from transit use, the contrast between high drive alone and high transit-need indicators suggests further investigation of surrounding characteristics and travel behavior at these stations. These stations are determined “vulnerable” following research which discuss disparities in transit amenities and travel behavior related to racial and class composition of transit areas served [3], [61]. Furthermore, stations in the transit reliance/transit beneficiary category are geographically located in areas with histories of being coded as “low-income” and “racially-diverse” spaces [62]. Transit discretionary rail stations are further categorized into “City Connection,” “Rural/Residential,” “High Potential Diverse Demand.” “City Connection” stations comprise those in near proximity to a downtown center which exhibits a diverse set of demands. Diverse demands are assumed by the presence of hot spots and cold spots of several attributes explored from logistic regression. “Rural/Residential” stations refer to those for which significant hot spots and cold spots which show no close proximity to employment centers and primarily exhibit characteristics of auto-dependence. “High Potential Diverse Demand” refers to stations with high potential accessibility values for multiple attributes, indicating significant opportunity to meet diverse demand at these stations from expansion of station access sheds.

Table 8 presents the proposed set of station categories.

7.1 Station Categories and Preliminary Recommendations for Improving FMLM Connectivity

7.1.1 Transit Integrated—Central Business District

The central business district in the study area evaluated in this thesis has bike share and car share programs in place, GreenBike and Enterprise CarShare, respectively. Both programs have been undergoing strategic expansion to improve travel options for individuals, especially those individuals who lack access to a car in the case of the CarShare program. The GreenBike program benefits connectivity in the area by providing an alternative means of transportation and has kiosks located near transit stations to bridge FMLM connectivity with transit.

Central business district rail stations are also close to downtown traffic calming improvements which help to improve safety of nonmotorized travelers and slow down vehicular traffic. Multimodal intersection design in conjunction with these traffic calming improvements helps to encourage a multimodal transportation infrastructure in the central business district. As part of building a multimodal network, the last component of an enhanced bike land and pedestrian network would help to bring that infrastructure into fruition.

7.1.2 Transit Integrated—University

Rail stations directly serving the University of Utah are located along the periphery of the university's main campus. Facilities management have been involved in improving ADA accessibility on campus and the on-campus bike collective has advocated for safer bike lanes and shared corridors with pedestrians and other travelers.

7.1.3 Transit Integrated—Airport

The Airport category comprises only the airport rail station. Accessibility analysis revealed very little information to guide planning for the airport rail station because the location of the airport station and connection of the airport station solely to the airport produce a catchment area that encompasses a negligible area in this study. The only FMLM implementation suggested for this categories includes improved wayfinding.

7.1.4 Transit-Reliant/Transit-Beneficiary—Vulnerable

This category comprises stations with significant clusters of variables which suggest reliance on transit and subsequently, greatest opportunity to receive the most benefits to improved transit infrastructure. The stations in this category are also located near offices, which poses possibility for a joint effort with surrounding entities to support FMLM strategy implementation.

7.1.5 Transit-Reliant/Transit-Beneficiary—Diverse Demand

Diverse demand stations in this category include those in close proximity to various types of demand but are not located within the central business district. These stations comprise several trunk stations along the rail network, which serve as key connection or transfer points. As such, these stations could benefit from analysis of service frequencies, reliability and spans to accommodate perceptions of access to these stations. As connection points, these facilities could benefit from increased visibility as a way to attract riders, improved bus amenities and improved multimodal integration from travelways to the stations. Traffic calming implementations could also be used to facilitate safe nonmotorized movement to these facilities which tend to be in auto-oriented areas. In several cases, these rail stations exhibit close proximity to demand types which suggest vulnerability and greater propensity to access transit by nonmotorized modes. Such stations may be prime sites of interest for local community to engage in discussions and planning to suit the needs of the communities these stations primarily serve or are located next to.

7.1.6 Transit Discretionary—City Connection

This category includes rail stations near two major cities enters along the Wasatch Front and are located in close proximity to their respective downtown centers. The dense land use of the downtown centers could be leveraged in such a way by joint partnerships between cities, employment centers and local transit agencies to further develop density and make use of that density to improve accessibility to public transit in these areas. Such FMLM strategies that might fit these conditions include a bike share program or vanpool program.

7.1.7 Transit Discretionary—Rural/Residential

This category comprises stations in low-density suburban areas. In literature, these areas are commonly described as auto-dependent and assume that the majority of the travelers in these areas have access to a private vehicle and commute to work or other activities primarily by car [3]. The results of spatial analysis mirror these results in literature. Subsequently, the methods of attracting riders onto transit who meet these conditions may differ significantly in comparison to a potential rider in a central business district, for example. FMLM considerations to improve connectivity at the stations may require community coordination, education around air quality, congestion and transportation option and wayfinding improvements.

7.1.8 Transit Discretionary—High Potential

Diverse Demand

These stations exhibit small walk catchment areas in close proximity to areas with diverse demand types. FMLM implementations at these stations might benefit from a concerted effort to understand how to expand the existing, estimated catchment area so as to derive or access more of the demand types surrounding these stations. FMLM considerations thus may include land use development and coordination to enhance density and accessibility to economic opportunities and stations in the area. Bike and pedestrian connectivity improvements may also provide some attraction to potential riders. Wayfinding improvements may attract riders by bringing attention to the transit station.

Table 8 Proposed Station Categories

Transit-Integrated		
Subcategory	Stations	Recommended Improvements
Central Business District ➢ Low WATT ➢ High connectivity ➢ High potential accessibility to diverse demand set	900 South Station Courthouse Station Gallivan Plaza Station City Center Station Temple Square Station Arena Station North Temple Bridge/Guadalupe Station Old Greektown Planetarium Library Station Trolley Station	➢ Expanded bike share program ➢ Improved literacy for CarShare programs ➢ Traffic calming improvements ➢ Multimodal intersection design ➢ Enhanced bike lane and pedestrian network
University ➢ Low WATT ➢ High connectivity ➢ High potential accessibility to diverse demand set ➢ Service to public institution ➢ Service to hospital	Stadium Station South Campus Station Fort Douglas Station University Medical Station	➢ Bike share development ➢ Improved pedestrian network connectivity ➢ Bike path network ➢ Improved ADA accessibility
Airport ➢ Service to public resource	Airport Station	➢ Improved wayfinding
Transit-Reliant/Transit-Beneficiary		
Vulnerable ➢ Significant cluster of zero-auto ownership households or individuals ➢ Significant cluster of minority communities ➢ Significant cluster of nonmotorized access ➢ Significant cluster of public transit use ➢ Connection to employment centers	Redwood Junction Station Decker Lake Station River Trail Station West Valley Central Station Midvale Center	➢ Coordination with local community ➢ Aesthetic enhancements to environment ➢ Multimodal network design to station ➢ Coordination with nearby offices and employment centers

Table 8 Continued

Subcategory	Stations	Recommended Improvements
Diverse Demand ➢ Significant cluster of zero-auto ownership households or individuals ➢ Significant cluster of minority communities ➢ Significant cluster of nonmotorized access ➢ Significant cluster of public transit use ➢ Significant cluster of drive alone use ➢ Significant cluster of subsidized fare users ➢ Significant cluster of individuals in possession of driver's license ➢ Transfer areas in network ➢ Access to employment center	900 East Ballpark Station Meadowbrook Station Millcreek Station Murray North Station Murray Central Station Power Station Fairpark Station Jackson/Euclid Station 1940 W. North Temple Station North Temple Bridge/Guadalupe Station Central Pointe Station Salt Lake Central Station North Temple Station	➢ Coordination with local community ➢ Enhanced and aesthetically integrated multimodal accommodations to stations ➢ Improved service reliability/frequency/ time span of bus services ➢ Improved bus shelters ➢ Bike path network development ➢ Traffic calming implementations
Transit-Discretionary		
City Connection ➢ Proximity to downtown ➢ Proximity to diverse demand types ➢ Proximity to significant cluster of zero-vehicle auto-ownership households	Ogden Station Provo Central Station	➢ Joint partnerships with cities and employment centers for FMLM enhancements ➢ Vanpool ➢ Bike share development

Table 8 Continued

Subcategory	Stations	Recommended Improvements
Rural/Residential ➢ Significant clusters of attributes that indicate auto-dependency or access to a private vehicle	American Fork Station Roy Station Crescent View Station Jordan Valley Station 2700 W. Sugar Factory Road Station 4800 W. Old Bingham HWY station 5600 W. Old Bingham HWY Station Bingham Junction Station Sandy Civic Center Station Kimballs Lane Station Draper Town Center Station Orem Station Lehi Station Pleasant View Station	➢ Community coordination ➢ Community-driven vanpool or carpooling program ➢ Bike and pedestrian network development for improved connectivity ➢ Community awareness or engagement around air quality, congestion and transportation options ➢ Wayfinding improvements
High Potential Diverse Demand ➢ Small walk catchment area connected to area with diverse demand types	Clearfield Station Farmington Station Draper Station South Jordan Parkway Station Historic Gardner Station Sandy Expo Station Daybreak Parkway Station	➢ Land-use development coordination to enhance accessibility to economic opportunities around stations ➢ Improved bike and pedestrian network connectivity ➢ Wayfinding improvements

CHAPTER 8

CONCLUSIONS

UTA faces concerns about air quality, congestion and increasing population along the Wasatch Front in Utah, which has prompted planning to focus on elements to ensure ridership gains. As has been well-explored in literature and alluded to in this study, railways have constituted an essential element in attracting transit riders beyond city cores and into suburban and rural areas. Yet, single occupancy vehicles still persist as the predominant mode choice for travelers in these areas. Planning within these conditions merits myriad methods to evaluate gaps in access and potential opportunities to bridge those gaps. The FMLM concept is one framework through which UTA and other agencies have attempted to examine ridership potential to address barriers to transit use.

This study applied the FMLM concept to the evaluation of rail station accessibility in the UTA network. A primary objective of this work aimed to develop a methodology centered around FMLM to characterize rail stations and facilitate planning efforts to enhance connectivity at rail stations. Data on travel behavior of UTA transit riders informed the development of basic elements of visual analysis using FMLM. Individual-level data were also analyzed in conjunction with aggregate-level data to examine relationships between characteristics of surrounding environment on individual travel behavior to stations. The findings of this analysis laid the foundation for determination of key demand types that warrant different types of recruitment efforts and incentives to ride transit.

Research findings from this study provide a supplemental perspective to dominant land-use-based station categorization methodologies by offering a more intimate perspective informed heavily by local demography and characteristics of travelers. The framework applied in this study provides valuable guidance to identify factors that influence nonmotorized mode choice access to transit stations, the delineation of accessible area from rail stations and the spatial distribution of factors to serve as visualizations of demand types in an area. Key findings of this study identify trip characteristics such as bus use or commuter rail use as influential factors in access mode choice to stations. Traveler characteristics such as possession of a driver's license as well as lack of access to a private vehicle both at an individual and local level also maintain significance as predictors of access mode choice. The WATT accessibility provided easily interpretable information on the level of connectivity exhibited by certain stations in the UTA network and confirmed high levels of connectivity in downtown/central business district areas. Potential accessibility measures in this study provided less interpretable or informative information regarding accessibility at stations, though the metric did confirm high levels of accessibility to various demand types expected of stations characterized by low WATT values. The insufficient findings from the potential accessibility metric may be the result of inadequate data resolution since individual data were aggregated to the block group-level. Hot spot analysis in this study communicated salient information about the geographic distribution of certain demand types. In particular, the results of cluster analysis mirrored polarization of demography and resource access between city-centers and suburban areas articulated in literature. On a more local level, the results also reaffirmed the fact surrounding an east-west dichotomy persistent in the Salt Lake County area that has been found to have a role in the distribution of resources related to school-year education [62].

The station categories developed represent an attempt to bring to light indispensable indicators of social-spatial processes that may have significant bearing on approaches to planning for FMLM infrastructural strategies to optimize accessibility, mobility, economic benefit and context-sensitivity.

APPENDIX

Table 9 Walk Catchment Area Potential Accessibility for Trip Characteristics

Ranks	W_BusFirst	W_Brbeg	W_Rbbeg	W_FRNTUse	W_transfers
1	Fairpark Station	Fairpark Station	Farmington Station	Farmington Station	Fairpark Station
2	Farmington Station	Temple Square Station	Clearfield Station	Clearfield Station	Clearfield Station
3	Temple Square Station	Clearfield Station	South Jordan Parkway Station	Temple Square Station	Farmington Station
4	Clearfield Station	City Center Station	Temple Square Station	Draper Station	Temple Square Station
5	City Center Station	Old Greektown Station	Old Greektown Station	Layton Station	South Jordan Parkway Station
6	Old Greektown Station	Gallivan Plaza Station	City Center Station	City Center Station	Old Greektown Station
7	Gallivan Plaza Station	Salt Lake Central Station	Draper Station	Old Greektown Station	City Center Station
8	Central Pointe Station	Stadium Station	Gallivan Plaza Station	Central Pointe Station	Gallivan Plaza Station
9	Library Station	Central Pointe Station	Salt Lake Central Station	Gallivan Plaza Station	900 East Station
10	Salt Lake Central Station	Library Station	Layton Station	Provo Central Station	Salt Lake Central Station
11	Courthouse Station	Murray Central Station	900 East Station	Lehi Station	Central Pointe Station
12	900 East Station	Jackson/Euclid Station	Central Pointe Station	Power Station	Draper Station

Table 9 Continued

Ranks	W_BusFirst	W_Brbeg	W_Rbbeg	W_FRNTUse	W_transfers
13	Planetarium Station	Courthouse Station	Planetarium Station	Ogden Station	Planetarium Station
14	Stadium Station	Planetarium Station	Sandy Expo Station	Sandy Expo Station	Library Station
15	Power Station	University South Campus Station	Power Station	Salt Lake Central Station	Jackson/Euclid Station

Table 10 Walk Catchment Area Potential Accessibility for Individual-Level Traveler Characteristics

Ranks	W_Subfare	W_hhdrive4	W_Gender	W_hhveh0	W_hhinc1to4	W_disabilityaltmod	W_drvlicaltmod	W_employ1highed	W_latinx	W_age3
1	Historic Gardner Station	Clearfield Station	Historic Gardner Station	Fairpark Station	Historic Gardner Station	Temple Square Station	Historic Gardner Station	Historic Gardner Station	Historic Gardner Station	Historic Gardner Station
2	South Jordan Parkway Station	Fairpark Station	South Jordan Parkway Station	Temple Square Station	Fairpark Station	Old Greektown Station	South Jordan Parkway Station	South Jordan Parkway Station	Fairpark Station	South Jordan Parkway Station
3	Farmington Station	South Jordan Parkway Station	Fairpark Station	City Center Station	Temple Square Station	900 East Station	Farmington Station	Farmington Station	Temple Square Station	Fairpark Station
4	Fairpark Station	Temple Square Station	Temple Square Station	Old Greektown Station	South Jordan Parkway Station	Planetarium Station	Fairpark Station	Fairpark Station	South Jordan Parkway Station	Farmington Station
5	Temple Square Station	Central Pointe Station	Clearfield Station	Gallivan Plaza Station	Clearfield Station	Salt Lake Central Station	Clearfield Station	Clearfield Station	Clearfield Station	Temple Square Station
6	Clearfield Station	City Center Station	Farmington Station	Central Pointe Station	City Center Station	University South Campus Station	Temple Square Station	Temple Square Station	City Center Station	Clearfield Station
7	City Center Station	900 East Station	City Center Station	Library Station	Old Greektown Station	Stadium Station	City Center Station	City Center Station	Gallivan Plaza Station	City Center Station
8	Old Greektown Station	Gallivan Plaza Station	Gallivan Plaza Station	Salt Lake Central Station	Gallivan Plaza Station	Fort Douglas Station	Old Greektown Station	Gallivan Plaza Station	Central Pointe Station	Old Greektown Station

Table 10 Continued

Ranks	W_Subfare	W_hhdrive4	W_Gender	W_hhveh0	W_hhinc1to4	W_disabilityaltmod	W_drvlicaltmod	W_employ1highed	W_latinx	W_age3
9	Gallivan Plaza Station	Old Greektown Station	Old Greektown Station	Courthouse Station	Central Pointe Station	Trolley Station	Gallivan Plaza Station	Old Greektown Station	Library Station	Gallivan Plaza Station
10	Library Station	Draper Station	Central Pointe Station	900 East Station	Farmington Station	Jackson/Euclid Station	900 East Station	900 East Station	Old Greektown Station	Central Pointe Station
11	Central Pointe Station	Trolley Station	Salt Lake Central Station	Clearfield Station	Library Station	Midvale Center Station	Library Station	Library Station	Courthouse Station	900 East Station
12	Salt Lake Central Station	Stadium Station	900 East Station	Planetarium Station	Salt Lake Central Station	Layton Station	Trolley Station	Draper Station	Salt Lake Central Station	Salt Lake Central Station
13	900 East Station	Library Station	Library Station	Trolley Station	Courthouse Station	University Medical Center	Salt Lake Central Station	Salt Lake Central Station	900 East Station	Library Station
14	Trolley Station	Murray Central Station	Courthouse Station	Power Station	900 East Station	Arena Station	Courthouse Station	Trolley Station	Trolley Station	Trolley Station
15	Stadium Station	Jordan Valley Station	Trolley Station	Jackson/Euclid Station	Trolley Station	North Temple Bridge/Guadalupe	University South Campus Station	Central Pointe Station	900 South Station	Stadium Station

Table 11 Walk Catchment Area Potential Accessibility for Block Group Level Traveler Characteristics

Ranks	W_PCTAO0	W_ORACcrMinority	W_ORACcd04	W_OPubTran	W_ODriveAlone
1	Temple Square Station	Fairpark Station	South Jordan Parkway Station	Historic Gardner Station	Historic Gardner Station
2	Fairpark Station	Clearfield Station	Fairpark Station	Fairpark Station	Fairpark Station
3	City Center Station	South Jordan Parkway Station	Clearfield Station	Temple Square Station	South Jordan Parkway Station
4	Clearfield Station	North Temple Bridge/Guadalupe	Farmington Station	Stadium Station	Farmington Station
5	Library Station	Farmington Station	Temple Square Station	Farmington Station	Clearfield Station
6	Gallivan Plaza Station	Salt Lake Central Station	Salt Lake Central Station	900 East Station	Temple Square Station
7	Old Greektown Station	Temple Square Station	North Temple Bridge/Guadalupe	City Center Station	Draper Station
8	Courthouse Station	Power Station	City Center Station	Trolley Station	City Center Station
9	Stadium Station	Old Greektown Station	Old Greektown Station	Library Station	Power Station
10	Salt Lake Central Station	City Center Station	Draper Station	Draper Station	900 East Station
11	Farmington Station	Central Pointe Station	Gallivan Plaza Station	Gallivan Plaza Station	Stadium Station
12	Power Station	Jackson/Euclid Station	Arena Station	Courthouse Station	Trolley Station
13	Trolley Station	Decker Lake Station	900 East Station	University South Campus Station	Jordan Valley Station
14	Planetarium Station	Murray Central Station	Murray Central Station	Old Greektown Station	Old Greektown Station
15	Arena Station	Sandy Expo Station	Stadium Station	North Temple Bridge/Guadalupe	Library Station

Table 12 Walk Catchment Area Potential Accessibility for Built Environment Characteristics

Ranks	W_D3apo	W_DWACc000
1	Historic Gardner Station	Historic Gardner Station
2	Fairpark Station	Stadium Station
3	Temple Square Station	University South Campus Station
4	Clearfield Station	Fort Douglas Station
5	City Center Station	Temple Square Station
6	South Jordan Parkway Station	Clearfield Station
7	Stadium Station	Draper Station
8	Power Station	Fairpark Station
9	900 East Station	University Medical Center
10	Farmington Station	Airport Station
11	Trolley Station	City Center Station
12	Library Station	Power Station
13	Old Greektown Station	Old Greektown Station
14	Gallivan Plaza Station	Gallivan Plaza Station
15	Draper Station	Farmington Station

REFERENCES

[1] M. Reilly and J. Landis, “The influence of built-form and land use on mode choice,” *Development*, vol. 4, no. 1, pp. 1–51, 2002.

[2] A. Bergman, J. Gliebe, and J. Strathman, “Modeling access mode choice for inter-suburban commuter rail,” *J. Public Transp.*, vol. 14, pp. 23–42, 2011.

[3] M. Garrett and B. Taylor, “Reconsidering social equity in public transit,” *Berkeley Plan. J.*, vol. 13, pp. 6–27, 1999.

[4] E. Guerra, R. Cervero, and D. Tischler, “The half-mile circle: does it best represent transit station catchments?,” *Work. Pap. UCB-ITS-VWP-2011-5 UC Berkeley*, no. July, 2011.

[5] A. El-Geneidy, M. Grimsrud, R. Wasfi, P. Tétreault, and J. Surprenant-Legault, “New evidence on walking distances to transit stops: Identifying redundancies and gaps using variable service areas,” *Transportation (Amst).*, vol. 41, no. 1, pp. 193–210, 2014.

[6] P. M. Rogoff, “52046,” *Fed. Regist.*, vol. 76, no. 161, pp. 52046–52053, 2011.

[7] K. Parker *et al.*, "Transit capacity and quality of service manual," Transportation Research Board, Washington D.C. Rep. 165, 2014.

[8] J. Gutiérrez and J. C. García-Palomares, “Distance-measure impacts on the calculation of transport service areas using GIS,” *Environ. Plan. B Plan. Des.*, vol. 35, no. 3, pp. 480–503, 2008.

[9] M. Kuby, A. Barranda, and C. Upchurch, “Factors influencing light-rail station boardings in the United States,” *Transp. Res. Part A Policy Pract.*, vol. 38, no. 3, pp. 223–247, 2004.

[10] K. Haldeman, “Metrorail Bicycle & Pedestrian Access Improvements Study,” Washington D.C.: Washington Metropolitan Area Transit Authority, 2010.

[11] M. M. B. Hancock, D. S. Shepherd, D. J. Faatz, D. P. D. Lopez, D. P. Lehmann, A. Burns, K. Iverson, A. Johnston, A. Jones, S. Nunnally, J. Romine, and B. Duffany, “Transit oriented development strategic plan ,” City of Denver, 2014.

[12] "Partnership for Active Transportation," in *Rails-to-Trails Conservancy (RTC)*, 2015. [Online]. Available: http://www.partnership4at.org/.

[13] Los Angeles County Metropolitan Transportation Authority, "First last mile strategic plan path planning guidelines," Los Angeles: Metro, 2013.

[14] F. Rojas, "Intermodal connectivity to BRT: a comparative analysis of Bogota and Curitiba," *J. Public Transp.*, vol. 15, no. 2010, pp. 1–18, 2012.

[15] B. Flamm and C. Rivasplata, "Perceptions of bicycle-friendly policy impacts on accessibility to transit services: the first and last mile bridge," Mineta Transportation Institute, San Jose, Rep. 12-10, W2014.

[16] M. Ben-Akiva and S. Lerman, *Discrete choice analysis: theory and application to travel demand*. Cambridge, MA, MIT Press, 1985.

[17] P. Clarke, "NIH public access," *Soc. Sci.*, vol. 69, no. 6, pp. 964–970, 2010.

[18] D. a. Rodríguez and J. Joo, "The relationship between non-motorized mode choice and the local physical environment," *Transp. Res. Part D Transp. Environ.*, vol. 9, no. 2, pp. 151–173, 2004.

[19] C. B. Frank S. Koppelman, "A self instructing course in mode choice modeling: multinomial and nested logit models," Federal Transit Administration, New Jersey, 2006.

[20] R. Cervero, "Built environments and mode choice: Toward a normative framework," *Transp. Res. Part D Transp. Environ.*, vol. 7, no. 4, pp. 265–284, 2002.

[21] R. Ewing and R. Cervero, "Travel and the built environment: a synthesis," *Transp. Res. Rec.*, vol. 1780, no. 1, pp. 87–114, 2001.

[22] S. D. P. Sanches and F. Serra de Arruda, "Incorporating nonmotorized modes in a mode choice model," *Transp. Res. Rec.*, vol. 1818, no. 1, pp. 89–93, 2002.

[23] H. Guan, Y. Yin, H. Yan, Y. Han, and H. Qin, "Urban railway accessibility," *Tsinghua Sci. Technol.*, vol. 12, no. 2, pp. 192–197, 2007.

[24] G. Debrezion, E. Pels, and P. Rietveld, "Modelling the joint access mode and railway station choice," *Transp. Res. Part E Logist. Transp. Rev.*, vol. 45, no. 1, pp. 270–283, 2009.

[25] G. D. Gosling, *Airport Cooperative Highway Research Program (ACRP) Synthesis 5: Airport ground Access Mode Choice Models*. Transportation Research Board Airport Cooperative Research Program, 2008.

[26] K. T. Geurs and B. van Wee, "Accessibility evaluation of land-use and transport

strategies: Review and research directions," *J. Transp. Geogr.*, vol. 12, no. 2, pp. 127–140, 2004.

[27] J. Gutiérrez, "Location, economic potential and daily accessibility: An analysis of the accessibility impact of the high-speed line Madrid-Barcelona-French border," *J. Transp. Geogr.*, vol. 9, no. 4, pp. 229–242, 2001.

[28] A. M. El-Geneidy, P. Tétreault, and J. Surprenant-Legault, "Pedestrian access to transit: identifying redundancies and gaps using a variable service area analysis," *89th Transp. Res. Board Annu. Meet.*, pp. 1–19, 2010.

[29] M. Iacono, K. Krizek, and A. El-Geneidy, "Access to destinations: how close is close enough? estimating accurate distance decay functions for multiple modes and different purposes," p. 76, 2008.

[30] J. Ortúzar and L. Willumsen, *Modelling Transport*. 4th ed., Wiley, Chichester, UK. 2011.

[31] S. Washington, M. Karlaftis, and F. Mannering, *Statistical and Econometric Methods for Transportation Data Analysis*. Taylor and Franci Group, LLC., 2011.

[32] E. Hauer, "The harm done by tests of significance," *Accid. Anal. Prev.*, vol. 36, no. 3, pp. 495–500, 2004.

[33] J. S. Long, "Regression models for categorical and limited dependent variables," *SAGE Publ. Inc.*, 1997.

[34] D. A. Freedman, "On the so-called 'Huber sandwich estimator' and 'Robust Standard Errors,'" *Am. Stat.*, vol. 60, no. 4, pp. 299–302, 2006.

[35] UCLA: Statistical Consulting Group. (2015). *Regression with Stata chapter four: beyond OLS*. [Online]. Available: http://www.ats.ucla.edu/stat/stata/webbooks/reg/chapter4/statareg4.htm.

[36] UCLA: Statistical Consulting Group. (2015). *Regression with Stata chapter 2: regression diagnostics*. [Online]. Available: http://www.ats.ucla.edu/stat/stata/webbooks/reg/chapter2/statareg2.htm

[37] StataCorp. (2013). *Linktest: specification linktest for single-equation models*. [Online]. Available: http://www.stata.com/manuals13/rlinktest.pdf.

[38] G. Rodriguez. (2015). *Generalized linear models*. [Online]. Available: http://data.princeton.edu/wws509/stata/c3s8.html.

[39] UCLA: Statistical Consulting Group. (2015). *FAQ: what are pseudo R-squareds?* [Online]. Available: http://www.ats.ucla.edu/stat/mult_pkg/faq/general/Psuedo_RSquareds.htm.

[40] W. R. Tobler, "A computer movie simulating urban growth in the Detroit region," *Econ. Geogr.*, vol. 46, pp. 234–240, 1970.

[41] E. Talen and L. Anselin, "Assessing spatial equity: an evaluation of measures of accessibility to public playgrounds," *Environ. Plan. A*, vol. 30, no. 4, pp. 595–613, 1998.

[42] C. Bhat, K. Kockelman, Q. Chen, S. Handy, H. Mahmassani, and L. Weston, "Urban Accessibility Index: Literature Review," Texas Department of Transportation., Austin, TX, Rep. TX-01/7-4938-1, May 2000.

[43] H. Skov-Petersen, "Estimation of distance-decay parameters - GIS-based indicators of recreational accessibility." Danish Forest and Landscape Res. Inst., Denmark, Norway, 2001.

[44] L. Anselin, "Local indicators of spatial association — LISA.," *Geogr. Anal.*, vol. 27, no. 2, pp. 93–115, 1995.

[45] Environment Systems Research Institute. (2015). *How hot spot analysis: Getis-Ord Gi* (spatial statistics) works*. [Online]. Available: http://resources.esri.com/help/9.3/arcgisengine/java/gp_toolref/spatial_statistics_tools/how_hot_spot_analysis_colon_getis_ord_gi_star_spatial_statistics_works.htm.

[46] J. K. Ord and A. Getis, "Local Spatial Autocorrelation Statistics: Distributional Issues and an Application," *Geogr. Anal.*, vol. 27, no. 4, pp. 286–306, 1995.

[47] U.S. Census Bureau. (2015). *What is the American Community Survey?* [Online]. Available: https://www.census.gov/programs-surveys/acs/about.html.

[48] K. Ramsey and A. Bell. (2014). *Smart Location Database*. [Online]. Available: https://www.epa.gov/sites/production/files/2014-03/documents/sld_userguide.pdf

[49] Google Developers. (2015). *Static transit*. [Online]. Available: https://developers.google.com/transit/gtfs/?hl=en.

[50] M. Morang, (2014). *Add GTFS to a network dataset user's guide*. [Online]. Available: http://transit.melindamorang.com/UsersGuides/AddGTFStoaNetworkDataset/AddGTFStoND_UsersGuide.html

[51] U.S. Census Bureau. (2015). *LEHD origin-destination employment statistics (LODES) dataset structure format version 7.1*. [Online]. Available http://lehd.ces.census.gov/data/lodes/LODES7/LODESTechDoc7.1.pdf

[52] P. L. Mokhtarian, "The effects of gender on commuter behavior changes in the context of a major freeway reconstruction," in *Proc. Transportation Research Board Conf.*, Washington D.C., 2010, pp. 1–16.

[53] E. Blumenberg and M. Smart, “Travel in the ’hood: ethnic neighborhoods and mode choice,” *Univ. Calif. Transp. Cent.*, 2009.

[54] A. Agrawal, E. Blumenberg, and S. Abel, “Getting around when you’re just getting by: the travel behavior and transportation expenditures of low-income adults,” Mineta Transportation Institute, San Jose, CA, Rep. 10-02, 2011.

[55] A. Tomer, “Transit Access and Zero Vehicle Households,” *Metropolitan Policy Program at Brookings*, 2010.

[56] V. R. Vuhic, *Urban Transit Systems and Technology*. Wiley, 2007.

[57] R. Bullard, G. Johnson, and A. Torres, *Highway Robbery: Transportation Racism and New Routes to Equity*. Brooklyn, NY: South End Press, 2004.

[58] J. Lee, “Perceived Neighborhood Environment and Transit Use in Low-Income Populations,” in *Transportation Res. Rec.*, issue 2397, 2013, pp. 125–134.

[59] “San Francisco transportation plan 2040 (final report),” San Francisco County Transportation Authority, 2013.

[60] Victoria Transport Policy Institute. (2014). *Equity evaluation: perspectives and methods for evaluating the equity impacts of transportation decisions*. [Online]. Available: http://www.vtpi.org/tdm/tdm13.htm.

[61] R. D. Bullard, “Addressing urban transportation equity in the United States,” *Fordham Urban Law J.*, vol. 31, no. 5, 2003.

62] E. Buendia, N. Ares, B. G. Juarez, and M. Peercy, “The geographies of difference: the production of the east side,west side, and central city school,” *Am. Educ. Res. J.*, vol. 41, no. 4, pp. 833–863, 2004.