Light Rail Expansion in Houston Using Viable Path Corridors and Least Cost Path: Alternatives for the Failed University and Uptown Lines

by

Jared Andrew Reid

A Thesis Presented to the
Faculty of the USC Graduate School
University of Southern California
In Partial Fulfillment of the
Requirements for the Degree
Master of Science
(Geographic Information Science and Technology)

December 2016

To Mom and Dad for giving me the world atlas for our road trips.

Table of Contents

List of Tables	vi
List of Figures	vii
List of Abbreviations	viii
Abstract	ix
Chapter 1 Introduction	1
1.1 Motivation	2
1.2 Current Light Rail System	4
1.3 Prior Failed Route	6
1.4 Outline of the Thesis	8
Chapter 2 Related Work	9
2.1 LCP for Transit	10
2.2 Classifying Rasters	13
2.3 Weighting Rasters	14
2.4 Algorithms	15
2.5 Summary	17
Chapter 3 Methods	18
3.1 Data	19
3.2 Standardization	23
3.3 Determination of VPC	26
3.4 Reclassification	28

3.5 Data Weighting 34

3.6 VPC and LCP Tools 35

Chapter 4 Results 37

4.1 Model Iterations of LCPs 37

4.2 Comparisons of the LCPs 38

4.3 Lessons Learned 48

Chapter 5 Conclusion 49

5.1 Strengths and Limitations 51

5.2 Future Work 52

REFERENCES 55

List of Tables

Table 1 Data Sources, Types, and Values 20

Table 2 Iterative Route’s Source, and Characteristics 38

List of Figures

Figure 1 Current Houston Light Rail Network and Major Business Districts ... 5
Figure 2 Congressional Districts with Current and Prior Failed Lines ... 7
Figure 3 Cost Raster Weighting Example ... 9
Figure 4 Dijkstra's Shortest Path Algorithm ... 16
Figure 5 Thesis Method Workflow ... 19
Figure 6 Highlights of HCAD Accuracy and Precision ... 21
Figure 7 Population Density by Census Block and Square Miles ... 25
Figure 8 Population Density Raster using Focal Statistics Tool ... 26
Figure 9 Individual VPCs Combined ... 28
Figure 10 FEMA Flood-zone Reclassification by Hazard ... 30
Figure 11 Major Roads Reclassification by Highway Intersection ... 31
Figure 12 Congressional Approval Avoidance Reclassification ... 32
Figure 13 Residential Roads to Avoid ... 33
Figure 14 Reclassification of Population Density Raster ... 34
Figure 15 LCP Workflow for ArcGIS 10.3 ... 35
Figure 16 Least Cost Path Iterations ... 39
Figure 17 Residential Route along Westcott Street ... 42
Figure 18 Non-Residential Route along Washington Avenue ... 43
Figure 19 Places of Interest 0.5 Miles from Routes ... 45
Figure 20 Four Potential Routes with Failed Prior Route ... 46
Figure 21 Adjusting Terminus Location to Test Route Change ... 47

List of Abbreviations

GIS	Geographic information system
USC	University of Southern California
CPU	Central processing unit
CBD	Central business district
MCDM	Multiple-criteria-decision-making
AHP	Analytic hierarchy process
LCP	Least-cost path
VPC	Viable path corridors
LRT	Light rail transit
HCAD	Harris County Appraisal District
USGS	United States Geological Survey
FEMA	Federal Emergency Management Agency
DOT	Department of Transportation
TVC	Traceable verifiable and complete
DMs	Decision Makers
TVC	Traceable, Verifiable and Complete
METRO	Metropolitan Transit Authority of Harris County

Abstract

This project provides a series of four paths for light rail between the Downtown Central Hub and the Northwest Metropolitan Transit Authority of Harris County (METRO) Transit Center in Houston, Texas. These potential light rail routes are alternatives to a failed proposal for University and Uptown routes that would still connect Houston's downtown central business district (CBD) with its largest financial district, the Uptown District. Building such an additional line would have an immediate, positive impact by promoting traffic efficiency, health benefits, environmental renewal, business growth, and commuting options. The method used builds upon prior least-cost path (LCP) research by incorporating domain specific engineering standards, lessons learned from the prior failed proposal, and viable path corridors (VPC). The results of the study are paths that follow existing light rail, freight rail, and road rights-of-way (ROW). The results include four iterations of the model: VPC only, Population, Residential Roads, and All Cost Rasters runs. Based on lessons learned from the prior DOT and METRO light rail line study and the application of the combined VPC and LPC method, the study found several feasible route options that run in areas different than the failed Uptown and University routes. These alternatives are suggested as preliminary candidate routes that will later be refined by planners, engineers, and surveyors.

Chapter 1 Introduction

This study explores the least-cost path (LCP) of building a light rail line between the Downtown Central Hub and the Northwest Metro Transit center in Houston, Texas. This addition, to the existing Red, Green, and Purple lines, would connect Houston's downtown central business district (CBD) with its largest financial district, the Uptown District. Houston is the fourth most populous city in the United States as well as the fourth fastest growing city in America (Carlyle 2014). Houston has grown rapidly in recent years, adding 35 percent to its population while the other largest U.S. cities such as New York, Los Angeles, and Chicago grew only by 4 to 7 percent (Kotkin and Gattis 2014). Many negative byproducts followed the population boom: increased traffic congestion, vehicle emissions, negative impacts to citizens' health, and burdening of existing public transportation options (Ewing and Tian 2014; Schadewald 2014; Zucker 2013; Emerson et al. 2012; HGAC 2011; Turner and Duranton 2009; Frank et al. 2004; Sanchez et al. 2003).

An additional light rail line can help to alleviate many of the issues that stem from rapid growth. With the aid of GIS tools, data, and design specifications, this LCP study determines the most viable rail line from Downtown Houston to the Uptown District. Data includes FEMA flood zones, Houston METRO parcels, congressional districts, elevation datasets, population density, existing road, light rail, and freight rail networks. Source documents informed the classification of the data from 1-Optimal to 5-Avoid. This effort differs from prior LCP studies by including light rail design specifications in the form of source technical documents that directly inform the viable path corridors (VPC) and the reclassification of cost data from 1-Optimal to 5-Avoid, which allows for transparent and traceable reclassified data.

1.1 Motivation

In past decades Houston has built larger and more highways to handle population growth and traffic congestion. Building bigger highways does not properly address traffic congestion because increased road building has been shown to increase traffic in some cases (Turner and Duranton 2014). Other studies show the direct link between light rail development and decreases in cars on the road (Ewing and Tian 2014). An additional rail line would reduce traffic congestion (HGAC 2011, 24; DOT and METRO 2010, 1:31). Building alternative commuting options is vital for a city that continues to experience incredible growth.

Also, research shows that using light rail may contribute to reduced obesity by decreased hours spent in a car. A report on obesity in Atlanta found that additional hours in a car lead directly to an increase in obesity (Frank et al. 2004, 87). Building an additional light rail line will increase ridership in Houston's light rail system and reduce hours spent in a car per day. This need is underscored by a recent report from the Texas Department of State Health Services that shows 66 percent of Texas adults were overweight or obese in 2010 (TDSHS 2012,2). Furthermore, Houston has had the dubious honor of being named the fattest city in the country in 2012 (Millado and Vigneri 2012). With health care costs expected to rise significantly in the upcoming decades, the city of Houston cannot afford to support a majority overweight or obese population.

Moreover, reduced environmental impacts due to less car traffic will have a positive effect on air and water quality for Houston. This effort's study corridor includes the important biodiverse waterways of Buffalo Bayou and White Oak Bayou. Buffalo Bayou is the main waterway flowing through Houston, and decreasing particulate pollution from automobiles will improve the environmental quality of the surrounding bayous, adjacent parks, and neighboring residential areas. In addition, researchers from the University of Utah found light rail saves an additional thirteen tons of toxic air pollutants (Ewing and Tian 2014). For a city that ranks seventh worst in the U.S. for ambient ozone pollution by the American Lung Association, the environmental improvements via a light rail extension are very desirable.

Business development opportunities from an additional light rail line would be significant. Bob Eury, the Executive Director of the Houston Downtown Management District, regards light rail as a key contributor to the current downtown building boom where numerous million dollar commercial projects are active along the Main Street rail corridor (Schadewald 2014). He also regards light rail as significant for weathering downturns in economic cycles. Moreover, economic opportunities continue to grow along the existing north-south Red Line in Houston specifically with commercial rents. Rents from 2012 in both Class A and Class B offices averaged $25.16 per square foot, in the same period in 2013, the average asking rents for both classes increased to $25.79 per square foot (Zucker 2013). Increased commercial rents brought in more tax revenues for the city. In addition, Qisheng Pan's article on light rail shows economic benefits in the form of increased property values for parcels located closer to a light rail station in cities across the United States including Houston (Pan 2013).

Finally, the proposed additions to the light rail footprint will also have a benefit for those in particular need of public transit because they do not have access to personal automobile transport. For example, a paper by the Civil Rights Project of UCLA touches on how public transportation’s ridership consists predominantly of minority groups and those with lower economic status (Sanchez et al. 2003). Building an additional line will benefit those of lower incomes and minority backgrounds. This is particularly important due to the fact that Houston is now considered the most diverse city in the United States according to a Rice University study (Emerson et al. 2012). Considering existing light rail lines are in the disadvantaged part of Houston (DOT and METRO 2010, 1:113), adding a line to the grid will provide a much needed increase in access from these areas to the two largest business districts. An additional line in Houston would improve mobility, and increase access to jobs, homes, and services (DOT and METRO 2010, 1:126). With a growing and diverse population, Houston must ensure that all groups have expanded commuting opportunities to traverse the city of Houston.

In summary, an additional line would have immediate positive impacts and promote traffic efficiency by reducing traffic; health benefits, by potentially reducing obesity levels; environmental revitalization, by reducing particulate pollution; business growth, by spurring residential and commercial development; and expanding mobility options, by enabling greater access to jobs, homes, and services.

1.2 Current Light Rail System

Construction started on Houston’s light rail system in March 13, 2001, and today consists of 27 miles of rail lines as seen in Figure 1.

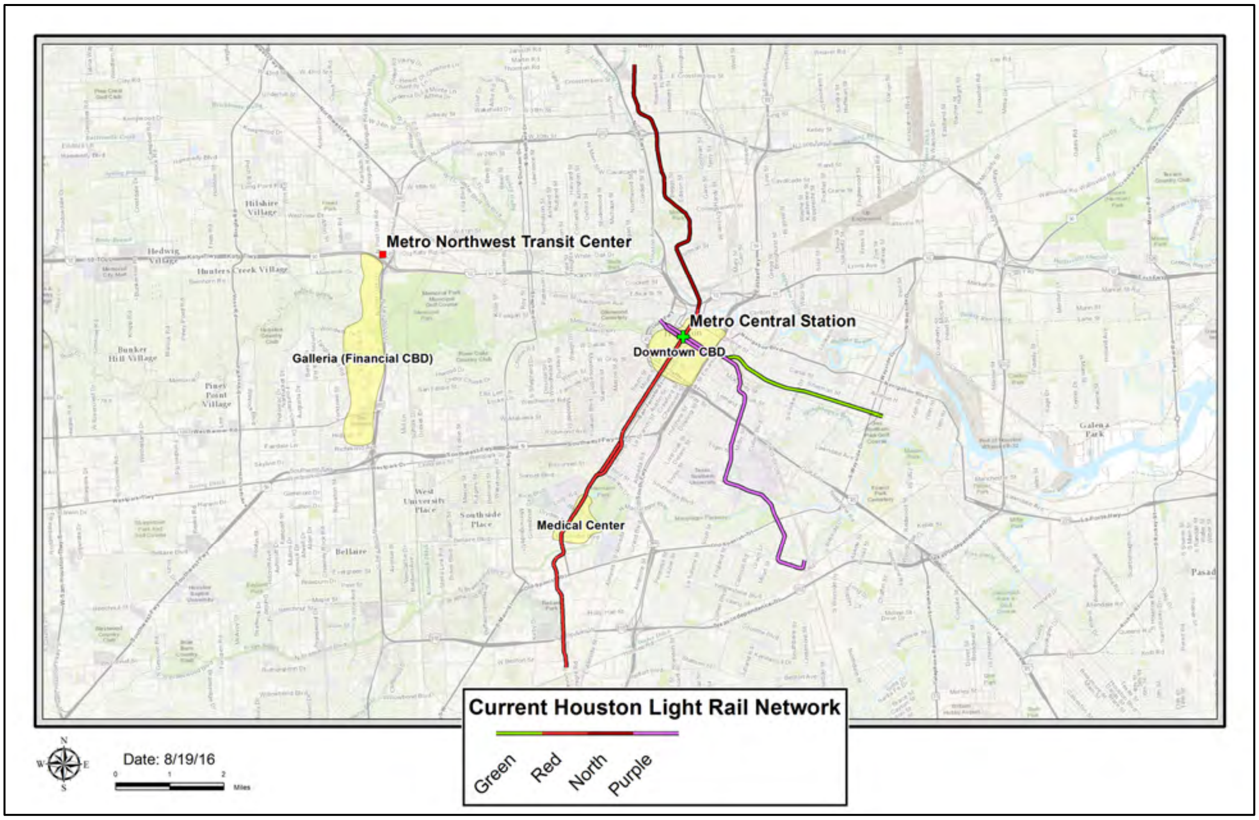

Figure 1 Current Houston Light Rail Network and Major Business Districts

Success of a Houston light rail system depends on adding an additional line that connects Metro Central Station to the Metro Northwest Transit center to the current light rail network as the city's infrastructure was built around a hub-and-spoke model. The existing networks consist of the Red Line, Purple Line, and Green Line. The Red Line connects the largest medical center in the world with Rice University the top-ranked university in Texas, and downtown Houston's Central Business District (CBD). Houston has 24 Fortune 500 companies, which is the third most in the United States ahead of Dallas, Los Angeles, and San Francisco, and the CBD is home to many of them (Forbes 2016, GHP 2015). The Purple Line connects the Southeast Transit Center with the University of Houston, Texas Southern University, the downtown CBD, and the Theater

District. The Green Line connects the Magnolia Park Transit Center with the Convention Center, the downtown CBD, and the Theater District. It is important to note there currently is no ability to travel by light rail between Houston’s downtown CBD and its largest financial district, known as the “Uptown District” or the “Galleria,” approximately fourteen miles west of downtown.

1.3 Prior Failed Route

It is important to consider lessons learned from prior failed lines for this study. A previous proposal failed primarily due to political reasons. Homeowners of Afton Oaks, an upper income subdivision, adamantly opposed the proposed routing of a line to the Uptown District along the Richmond Road ROW out of fear that their property values would be negatively affected (Stiles 2006).

The prior line also failed due to the political opposition led by 7th District Republican Congressman John Culberson. The initial proposed route passed through Culberson’s district as shown in Figure 2, and he publicly stated that the failed lines were unaffordable, unnecessary, and unapproved by voters, even though voters approved the line by ballot initiative (METRO 2003). Culberson’s political opposition was also strengthened due to gerrymandering as seen in Figure 2. This gerrymandering is illustrated by Culberson’s snaking district encompassing a majority of suburban and exurban areas and voters, who in some cases are located as many as twenty miles away from the initial failed proposed light rail route and have historically voted against light rail expansion.

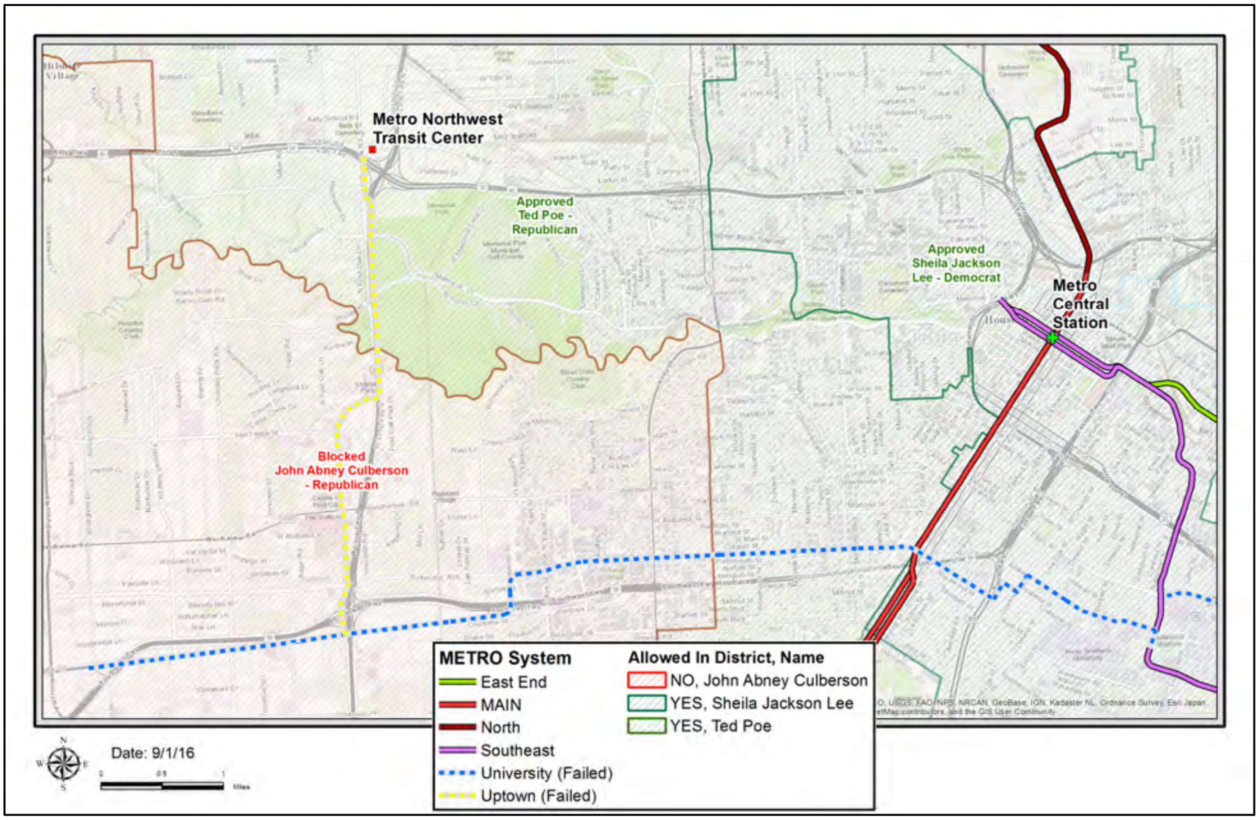

Figure 2 Congressional Districts with Current and Prior Failed Lines

Fortunately, the study corridor also includes the Congressional Districts of Democrat Shelia Jackson Lee and Republican Ted Poe, both of whom are in favor of light rail as shown in Figure 2. Both congressional members currently have light rail in their districts and publicly support light rail. This study learns from the failed attempts by using model iterations that exclude congressional districts from possible rail paths if they do not support light rail. The failed routes encountered political roadblocks that ultimately doomed the lines. Using a GIS method that accounted for acceptable corridors of travel and possible spatial roadblocks could have saved many working hours and funds. The prior failed routes did not use GIS analysis for their routing.

Although this study does not build from exactly the same routing priorities as the plans for the failed University and Uptown lines, it does use the METRO Northwest Transit Center as the terminus. The METRO Northwest Transit Center was the original terminus for the prior failed lines, a major public transit hub, and the proposed transit center for the Texas high-speed train from Dallas to Houston (Texas Central 2015, 22).

1.4 Outline of the Thesis

Chapter-by-chapter content for the thesis includes related work, methodology, results, and conclusion chapters. The related work chapter reviews LCP modeling in general and specifically for light rail projects. It describes how the project is built upon prior methodologies. This section is organized by the following topics: An explanation of LCP, lessons learned from prior LCP studies, discussion about reclassification based on domain-specific documents, an overview of LCP algorithms, and a justification of the selected algorithm. The methodology chapter documents the data collection, their sources, and metadata; standardization of the data to get it into an acceptable data type to run geospatial processing; reclassification of the data that is traceable to domain specific technical documents such as the Track Design Handbook, a prior METRO feasibility study, and Siemens light railcar specifications (Siemens 2014; FTA 2012; DOT and METRO 2010); and the justification of building the VPC. Additionally, the tools and software used to accomplish each step in the methodology are discussed. The results chapter presents the results of the determination of LCP based on the VPC for several LCP iterations. It includes descriptions of the resulting paths along with maps, comparisons of the iterations, and lessons learned. The conclusion chapter summarizes lessons learned from the study’s method, limitations, strengths, and opportunities for future work.

Chapter 2 Related Work

Least-cost path (LCP) is a methodology commonly used in GIS to determine the most efficient path from a beginning location to an end location. This chapter explains LCP and reviews generally how it has been used in GIS and transit, including the classification process, weighting process, and algorithms. LCP can be defined as two fixed points and the calculation of the cost of movement including distance from one location to another (John et al. 2015). Examples of costs for building an urban light rail path include economic, environmental, physical, and political costs. Describing costs, Wang et al. (2009, 1366) state: “[t]hese ‘costs’ generally reflect some understanding of resistance or mobility through a landscape.” These movement costs are usually associated with individual grids or cells in a raster data type. Several rasters using a common measurement scale are then weighted by importance to create an accumulative cost raster as shown in Figure 3.

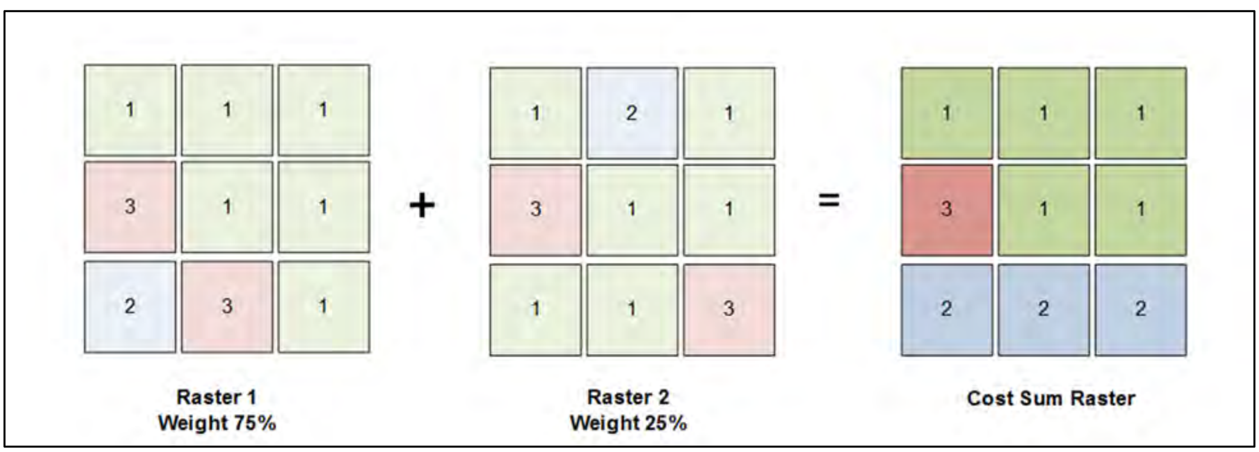

Figure 3 Cost Raster Weighting Example

After an accumulated cost raster is generated, movement cost is calculated by connecting the lowest cost cell to the next lowest cost cell or, as Thomas Pingel of the University of California Santa Barbara describes, a raster layer is created where the LCP can be solved using shortest-path algorithms (Pingel 2010). In ArcGIS, LCP analysis views eight raster cell neighbors that are evaluated and the path moves to cells with the lowest cost. This is repeated multiple times until the source and destination are connected. The final completed path is the smallest sum of raster cell values between the two points.

2.1 LCP for Transit

After thorough research, insufficient LCP studies for light rail lines were found. Therefore, this study looked to find LCP studies in broader domains such as general transit. Prior transit LCP studies focused on many different topics such as employing domain-specific documents, applying GIS processes, and utilizing spatial algorithms.

Cowen et al. (2009) applied traceable and documented economic construction costs to LIDAR data in the form of slope values for new railroad tracks. Additionally, the prior study incorporated off-the-shelf data whenever possible including USGS data. Cowen et al. (2009) noted that not all factors could be taken into account for the study, only potential routes based on the data present. This current study similarly utilized off-the-shelf data as the budget for the study was limited. Furthermore, traceable and documented values for the reclassification of elevation’s slope data were incorporated. The current study also similarly makes the limitations of existing data known when evident.

McCoy et al.’s (1994) study on applying electrical utility least-cost has lessons for transportation in its consideration of efficiency, socioeconomic, and environmental factors in the evaluation process. It was also found that the study facilitated internal communication between the stakeholders of their project. Furthermore, the prior study explicitly addressed its uncertainties. The inclusion of a diverse range of factors was critical for this current study by incorporating FEMA flood, elevation, and protected parcel data, while also making known any limitations of the study or data when warranted.

Bagli et al.'s (2010) study on electrical line routing discovered that small changes in the start and terminus locations can result in significantly different route paths. It was also noted that even in dense urban environments, where space is limited for placing stations and building electric paths between destinations, LCP can offer great flexibility and generate multiple options for end users like planners and engineers. Finally, the prior study explored identifying corridors where the path could travel. This discovery is important and was investigated as the end point could possibly enter anywhere in the METRO Northwest transit center's parcel polygon, additional paths were also explored based Bagli et al.'s (2010) recommendations.

Shrestha et al.'s (2005) study on the least-cost planning of environmentally sensitive public transportation options in Beijing focused primarily on environmental factors that would reduce nitrogen oxide emissions. This study model included hard costs such as existing and candidate transport options, total cost, and emission factors. Including environmental factors such as flood zones was an important part of the current study. Shrestha et al. (2005) also self-admittedly wished to include freight transportation corridors as options in its analysis, which were included in the author's study. The methodology also did not consider the cost of travel time or traffic congestion. Similarly this study did include those costs as well in order to keep the scope focused.

Pingel (2010) integrated design specifications for raster classification in the mountainous road route selection. Pingel's (2010) study specifically modeled slope as a contributor to route selection. The author's study also included multiple endpoints to establish likely travel corridors. While this study does not include multiple endpoints to determine corridors, it does apply existing light rail design specifications and also created a unique method of determining and creating corridors called viable path corridors (VPC), which are specifically defined later in the study. Light rail design specification sources included studies from METRO and the Department of Transportation, the Siemens Corporation, and The National Research Council Transportation Board.

The DOT and METRO's Final Environmental Impact Statement (FEIS) study for the failed route in Houston did not utilize LCP but did provide a plethora of information for the reclassification and VCP portions of this study (DOT and METRO 2010). Information of significant importance included single and bi-direct widths for rail corridors, minimum overhead, and spans for catenary requirements, preferred ROWs, avoided ROWs, and other data pertinent to the classification of cost rasters. Catenary requirements refer to maximum allowed vertical clearance need for power polls. While the aforementioned study did not use GIS and LCP, this thesis project finds that supplementing the prior failed light rail study data, and recommendations with GIS, VPC, and LCP will strengthen the case for future light rail in Houston.

2.1.1 GIS for Light Rail

To reiterate, an exhaustive search revealed a lack of specific guidance on LCP and light rail. The aforementioned METRO FEIS study used static maps made with GIS as a communication method for public meetings and hearings. Additionally, the METRO FEIS study used GIS data from the Harris County Appraisal District (HCAD) to analyze potential socioeconomic effects and generate an inventory of community facilities, services, and land uses within a half-mile of the proposed route.

Denver's Regional Transportation District (RTD) successfully utilized GIS for Title VI Compliance (Washington 2015). Maps and analysis were used to insure compliance with the Title VI of the Civil Rights Act of 1964, which prohibits discrimination on the grounds of race, color, and national origin. RTD planners determined through GIS analysis that service additions did not have significant service changes, which the Federal Transit Administration (FTA) defines as a 25 percent decline in service hours for a particular community for twelve or more months. If an agency was found to be in violation of the law, they would have lost federal funding. The FTA now recommends maps in all Title VI reporting nationwide (Washington 2015).

The abovementioned lessons learned from related work were applied to this effort through an exhaustive literature review on LCP for Light Rail, LCP for transportation, and GIS for light rail. Though specific direction on LCP for light rail was unavailable, lessons learned from the literature review did allow for guidance into the collection, reclassification, and weighing of the data, as well as the GIS process utilized to determine VPC and LCP. The process of VPC was developed independently for this study and is discussed in detail later in the study.

2.2 Classifying Rasters

Classification of rasters involves assigning numeric values for existing quantitative and qualitative data. LCP studies often utilize expert rankings, for example, Reeves (2015) used multi-criteria evaluation for path modeling, but admitted concerns about experts' opinions and misinterpretations of attributes. Hochmair (2004) offers a classification for route selection criteria for a public transportation route. The author classified best route criteria from survey participants in which they were asked to give the criteria they would consider for a preferred route choice. Specific choices included routes that traversed restaurants, parks, and cafes. The participants scored the value of each criterion between 1 (quite unimportant) and 4 (very important).

This thesis creates informal classifications by applying domain specific verifiable classifications, much like Thomas Pingel's approach. Pingel (2010) applied classification to slope based on the California Department of Transportation (DOT) design guidelines in his paper. This study's raster's attribute cost ranking is taken directly from existing light rail design specifications from the National Research Council Transportation Research Board (FTA 2012), Metro Houston's and Department of Transportation's design study for the failed route (DOT and METRO 2010), and Siemens railcar design specifics (Siemens 2014). These and other traceable and verifiable sources leave less ambiguity in the classification of the rasters than in some LCP models.

2.3 Weighting Rasters

Weighting rasters in LCP for GIS is the means in which one classified data set is prioritized over another. LCP study methodologies require the application of a defendable process in order to build an accumulative cost raster layer. Assigning defendable weights for costs values is lacking in some prior LCP studies. Other LCP studies addressed this by utilizing an Analytic Hierarchy Process (Yakar et al. 2014; Effat et al. 2013; Banai's 2006; Jankowski 1995). Due to time and resource constraints, in this study's methodology the data cost rankings were assigned an equal weight. However, iterations were run that included or ignored subsets of cost rasters, which gives a clear idea of paths that might emerge given weighting for different decision makers (DMs) or stakeholder interests.

2.4 Algorithms

Algorithms are also a crucial part of the LCP process. The simplest LCP path algorithm is the Euclidean Distance algorithm, also commonly known as the "as the crow flies" path. The algorithm works by calculating the shortest distance between two cells. This algorithm's uses are extremely limited, such as for finding a hospital for an emergency helicopter flight. Stahl's (2005) writing on autonomous ground vehicle navigation discusses use of a different LCP algorithm, the Best First Search (BFS). This algorithm searches for a path with processing speed as a priority. There is a tradeoff in the quality of the solution for faster run times. BFS uses an idea of how far away the start point is to the end point. Because of this estimate, the algorithm selects cells closer to the end point for accumulation before it selects the cells near the start point. In this manner fewer cells are accumulated before it finds a solution resulting in fast calculations, but it does not guarantee the optimal result. Processing time is not a priority and computation power is not a key limitation given the scope of this study, so such a trade-off is not necessary.

In place of the Euclidean Distance and Best First Search algorithm, this study utilizes Dijkstra's shortest path algorithm (Cormen et al. 2001). Dijkstra's algorithm finds the shortest path from a start location to an end location by traveling from neighboring cells to the lowest cost neighboring cells until the end location is reached as shown in Figure 4. In this study, these cells will be the accumulative cost sum raster cells.

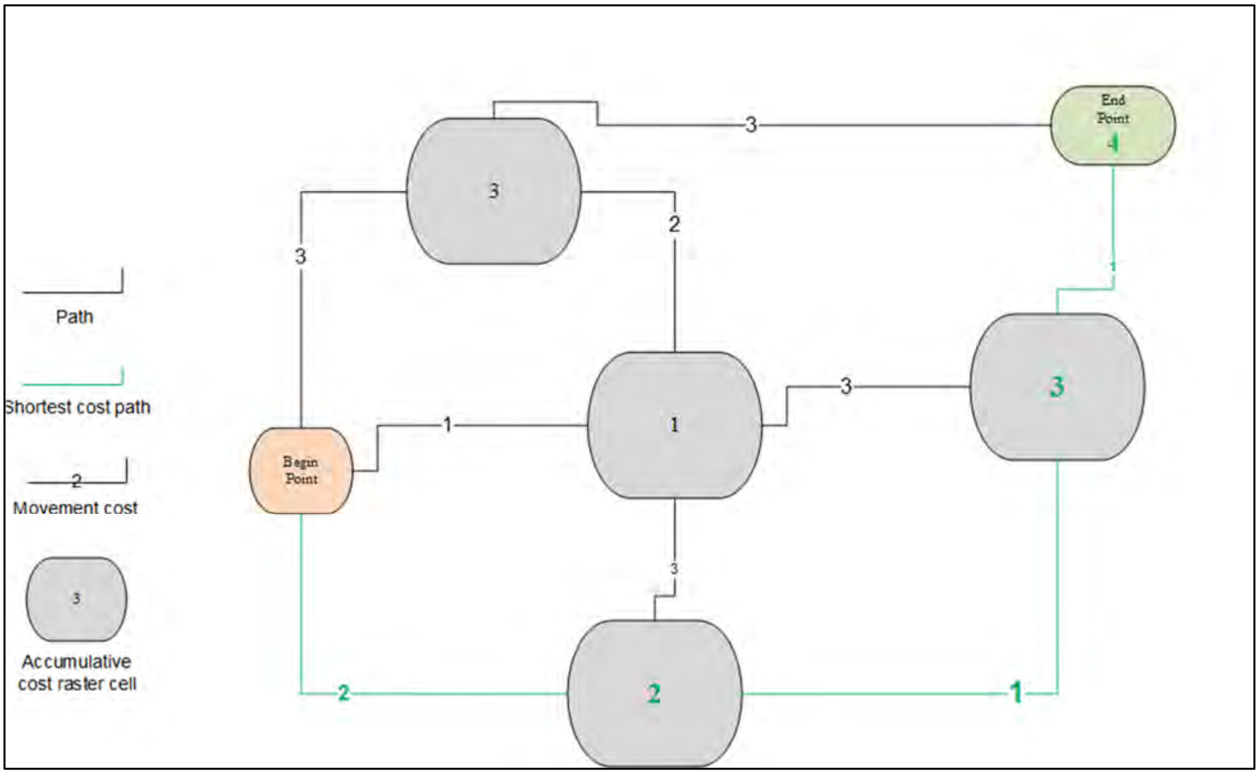

Figure 4 Dijkstra's Shortest Path Algorithm

Another method of finding LCP for light rail, developed independently for this study, was the use of viable path corridors (VPC) in conjunction with Dijkstra’s LCP algorithm. VPC are acceptable right-of-way (ROW) corridors a LCP route can travel along. This process was developed from prior Houston METRO rail design specification’s corridor requirements and restrictions. This VPC method is more computationally efficient because fewer rasters are processed in the LCP model than would be if all possible rasters in the study area were included in the model.

2.5 Summary

In summary, this thesis codifies prior transportation LCP studies into a LCP for light rail study by applying existing light rail design specifications, using research into failed attempts, and relying on design specifications to standardize, reclassify, and weight data. Furthermore, the aforementioned methodology is traceable by each dataset having a source to reference that directly informs the reclassification. Interestingly, LCP has been underused for light rail line planning possibly because of data accuracy and precision constraints since no LCP for light rail studies were found. To mitigate concerns about data accuracy and precision, VPC were designed and implemented for this project. This VPC methodology is discussed in greater detail in Chapter 3.

Chapter 3 Methods

This chapter documents the data collected to create each raster layer along with the way data was standardized, included in the viable path corridors (VPC), reclassified, weighted, and the tools used. The data is cataloged here by source, last update, type, accuracy, precision, the reason why it was collected, and standardization methods. Viable path corridors are defined and documented as well. Reclassification values are authoritatively cited to design specification sources. Finally, weighting procedures and VPC and LCP geoprocessing tools are discussed.

The steps and tools needed to accomplish each methodology step are detailed below in Figure 5. The first step was the application of lessons learned from the literature review to the selection and collection of required data based on prior LCP studies for transit, and engineering design specifications. The second step was the conversion and geoprocessing of data, which was done with ArcGIS 10.3. All data was reprojected to State Plane South Texas NAD 83. All non-ESRI data was converted to an ESRI format. All polylines were converted to polygons corridors, and then polygon corridors were converted to rasters. The third step was the reclassification of data based on light rail design specifications in order to create a simplified ranking for the raster cells 1-5, 1 being the most optimal, and 5 being avoid. The fourth step was building VPC of acceptable light rail corridors based on light rail design specifications. The fifth step was the addition of cost factors to the VPC to generate an accumulated cost raster. The Extract by Mask tool was used to input the cost factors raster and feature mask of VPC raster, then the result was an accumulated cost factor raster clipped by VPC. The final step was the identification of criteria for the four model runs and use of LCP tools of Cost Distance and Cost path tools to generate iterative LCP runs.

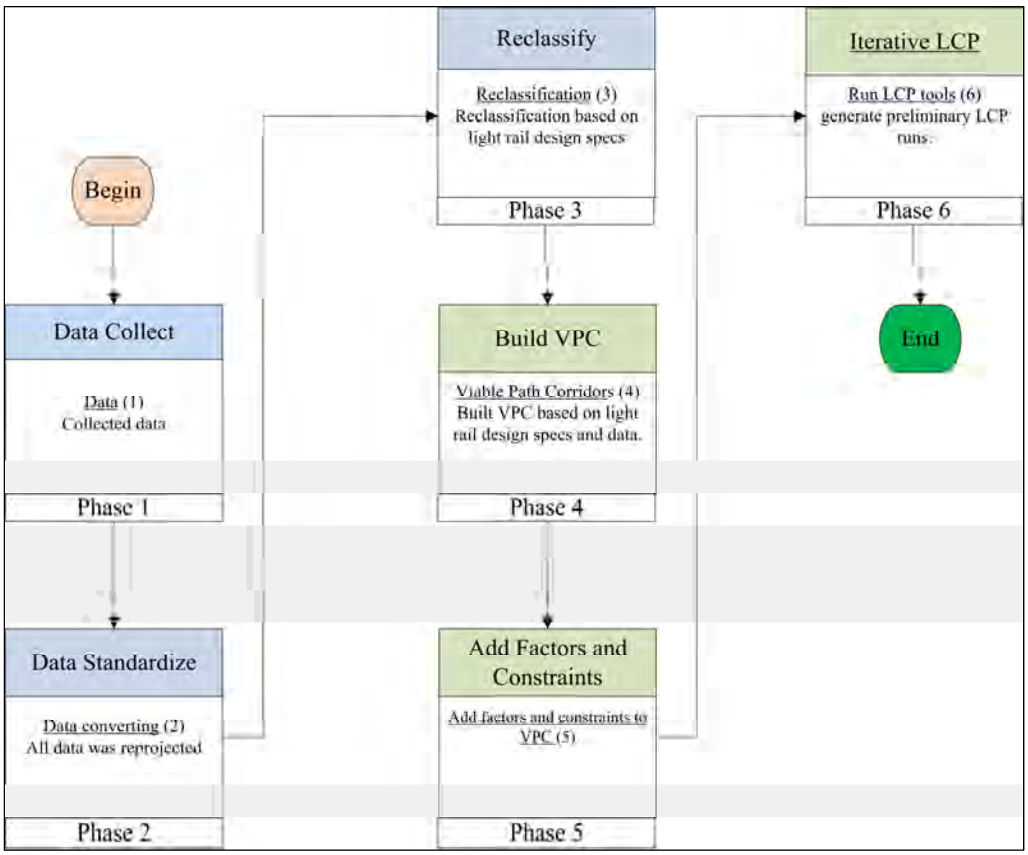

Figure 5 Thesis Method Workflow

3.1 Data

The following data was acquired for the study corridor: parcels owned by the Metropolitan Transit Authority of Harris County (METRO), residential, secondary, and tertiary roads, interstates, congressional districts, existing light rail lines, freight rail lines, flood zones, elevation, population, and places of interest. The data sources and types are detailed in Table 1.

These variables are vital as they serve as the basis for the VPC as well as the constraints for the LCP between the Downtown Central Hub and the Northwest METRO Transit center.

Table 1 Data Sources, Types, and Values

Name	**Source**	**Data type**	**Values**
Metro Parcels	Harris County Appraisal District	Polygon	Ownership name
Roads	Open Street Map	Polyline	Road type and name
Freight Rail	National Transportation Atlas Database	Polyline	Rail status and owner
Existing Light Rail	City of Houston	Polyline	Name
Flood Zones	Federal Emergency Management Agency	Polygon	Type
Elevation	United States Geological Survey	Raster	Elevation
Congressional Districts	United States Census	Polygon	Name and Party
Population	United States Census	Polygon	Population and Area
Places of Interest	City of Houston	Point	Type

Data from Harris County Appraisal District (HCAD 2016) is comprised of parcel ownership data. HCAD provides the data free, it is updated quarterly and was last updated in 2016. The data is in polygon and polyline shapefile format. The accuracy of data and precision of data is intentionally kept hidden by the GIS department at HCAD. A visual comparison of the known accuracy and precision of Open Street Map data and aerial imagery show no observable topology errors and similar levels of detail as seen in Figure 6. Topology concerns of overlaps and intersections were not present. The data is used to determine interstates, lands owned by the

City of Houston, METRO, and the protected parcels. Protected parcels include uses that would not be taken away for a light rail line. METRO has designated protected parcels as: churches, schools, fire stations, police stations, and hospitals (DOT and METRO 2010, 1:41).

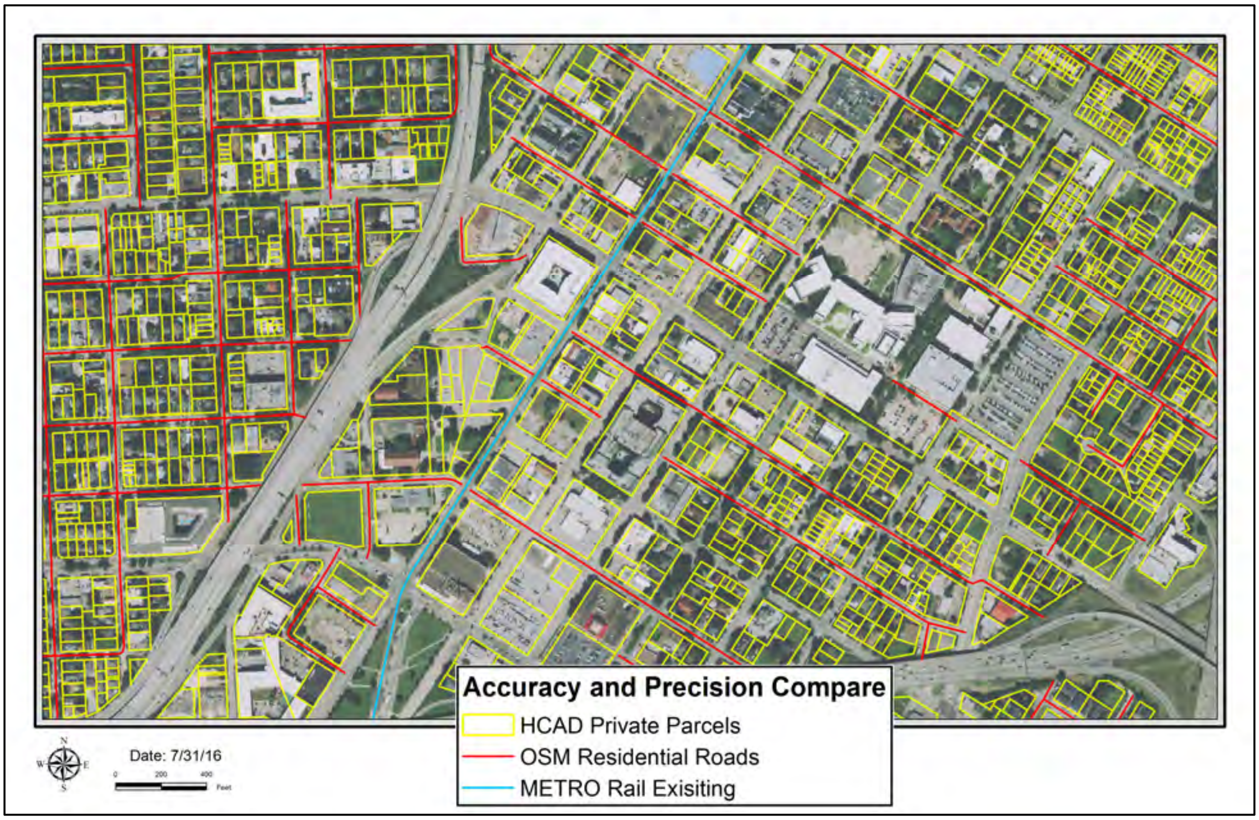

Figure 6 Highlights of HCAD Accuracy and Precision

Data for 113th U.S. Congressional District consists of congressional districts divided by name and party affiliation. ArcGIS Online provides the data free, collected through the United States Census Bureau, and it was last updated December 1, 2015. The data is provided by Esri as a web service and in polygon format. The accuracy of the data is an average of 25-feet, and the precision of the data is to six decimal places or sub-foot (Congressional District 2010, 3). The data is used to determine cooperative and oppositional congressional districts.

Data from the City of Houston is comprised of Houston METRO rail lines, rail stations, transit centers, and places of interest. The City of Houston provides the data free, and it was last updated in 2015. The data is in shapefile and KMZ format. The ArcGIS Toolbox > KML to Feature Class tool was used to standardize the data. The exact accuracy and precision of the data is unknown, although a visual comparison to the known accuracy and precision of the Open Street Map data show no observable topology errors and similar levels of precision as seen in Figure 6. These topology errors included overlaps and intersections of roads and parcels. In this study the data is used to determine existing light rail lines and light rail stations.

Data from the Federal Emergency Management Agency (FEMA) consists of flood zones and flood boundary data. FEMA provides the data for free, and it is updated on a monthly basis. The data is disseminated in polygon format. The accuracy of data is better than 10-meters or 33-feet, and the precision is not given though updates to the dataset require a 1-foot change. In this study, the data is used to determine flood zones.

Data from the United States Geological Survey (USGS) consists of elevation data. USGS provides the data free, and it was last updated in 2008. The data is available in raster format. Data conversion was accomplished by clipping the DEM Raster to the study corridor to reduce file size and processing time. The accuracy of the data is 1.64-meters or 5.38-feet, and the precision is 3-meters or 9.85-feet. In this study, the data is used to determine slope grade.

Data from National Transportation Atlas Database, a service of the United States Department of Transportation, consists of freight railway networks. The data is free, and was last updated in 2016. The data is in polyline format. The accuracy of the data is 1:2,400 or 6.67-feet and precision is 4-feet. In this study, the data is used for existing railway network ROWs.

Data from Open Street Map consists of primary, secondary, tertiary, and residential roads. The data is free, and was last updated in 2016. The data is in polyline format. The accuracy is 2-3-meters or 7-10-feet and the precision is 1 centimeter. This data used in this study includes residential roads, secondary roads, secondary road links, tertiary roads, and tertiary road links.

Data from the United States Census Bureau consists of census blocks and their population. The United States Census Bureau provides the data free, and last updated in 2010. The data is in polygon format. The precision is less than 7.5-meters or 24-feet. In this study, the census data is used to determine population density.

3.2 Standardization

After the data was gathered, a standardization process was needed to transform the data into an appropriate type format for GIS analysis. In order for the data to be standardized, the following geoprocessing jobs were performed.

First, data in a non-Esri format was converted. City of Houston Light Rail data was in KMZ format and was converted to a feature class. Second, re-projecting data to the local projected coordinate system of NAD 83 South Central Texas was needed for the distance calculation. This was accomplished using the ArcGIS Toolbox > Data Management Tools > Projections and Transformations > Feature > Project tool. Polyline data was buffered to give corridors of roads and railroads based on aerial imagery. The ArcGIS Toolbox > Proximity > Buffer tool was used for this task. All remaining data in polygon format was converted to a raster, using ArcGIS Toolbox > Conversions Tools > To Raster > Polygon to Raster tool. Fourth, converting raster elevation data to slope grade percent was accomplished using the ArcGIS Toolbox > Spatial

Analyst > Surface > Slope tool. Next, the cell size or level of detail for each conversion from polygon to raster was determined based on each individual data source's level of detail at a minimum of one-fourth the size of the polygon's resolution to preserve accuracy during the conversion. Piwowar (1988) and Congalton (1997) suggest that the optimum grid cell size should be at least one-fourth the size of a minimum polygon to maintain the integrity of the data (Congalton 1997; Piwowar 1988). As there were different raster resolutions all individual rasters and accumulated rasters used for geospatial calculations for VPC were then converted to at a 10-feet cell size, and LCP cost rasters converted to a 30-feet cell size in accordance to the largest raster cell size using Mosaic to New Raster Data Management tool. Then the LCP cost rasters were resampled from 30-feet to 10-feet cell size; it should be noted that this did not improve the quality of the LCP cost rasters but rather created more pixels to represent cost rasters at 30-feet resolution. This method preserved the needed higher resolution of the viable path corridors rasters while allowing for the desired standard cell size for geospatial LCP calculations.

Additionally, to convert population data from U.S. Census Blocks to population density, an area field was needed, so one was added and the area calculated. A square mile field was also needed, so one was added and next the field was calculated by area divided by the population of the block. Next the polygon estimates of population density for U.S. Census Blocks were converted to raster using the previously describe standardization method as seen in Figure 7.

Figure 7 Population Density by Census Block and Square Miles

Then, using the Focal Statistics tool in ArcGIS, cell values for population density were related to a cell location neighborhood by a geodesic buffer of 0.5-miles, as seen in Figure 8 (i.e., a circle with a radius of 0.5-miles) (Schlossberg and Brown 2004). The Focal Statistics tool calculated the weighted average of the population density based on a circular neighborhood with the given radius. In other words, the population 10-feet cells were averaged by its neighbors in a 0.5-mile radius.

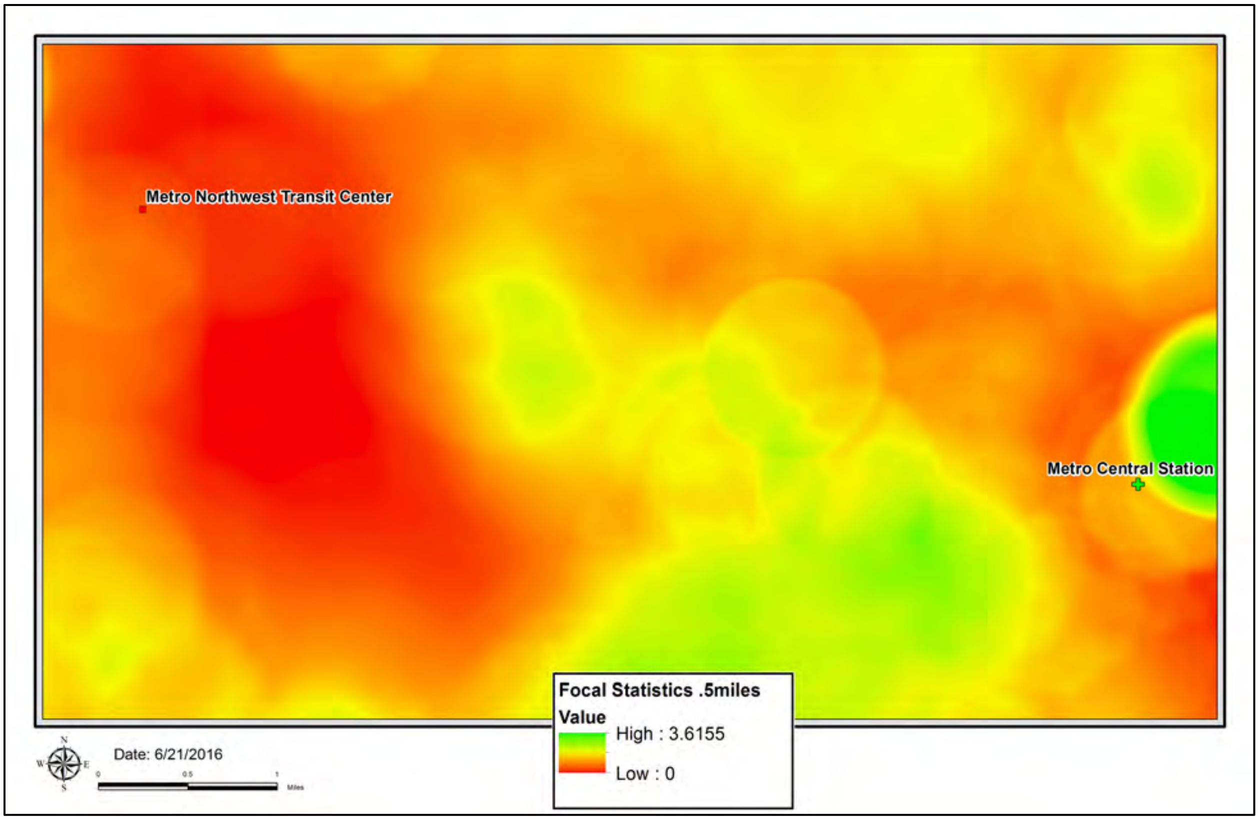

Figure 8 Population Density Raster using Focal Statistics Tool

3.3 Determination of VPC

The building of viable path corridors was based on minimum width requirements for a bi-direction line. It was determined that 25-feet corridors were needed for bi-directional light rail lines (DOT and METRO 2010, 3:110) and 10-feet 8-inches for single directional light rail (DOT and METRO 2010, 3:107). The VPC follows existing Freight Rail, Optimal Streets, and Existing Light Rail corridors that are greater than 60-feet wide. Each VPC was validated with first person site analysis, in addition to ESRI, and Bing aerial imagery. Residential streets were not included because their ROW widths of 30-feet would not be acceptable to accommodate both the bi-directional line and vehicle traffic. Also, the use of residential streets would more likely give rise to not in my back yard (NIMBY) opposition (DOT and METRO 2010, 3:107). However, it is important to note that residential streets were used as a cost factor for iterative runs when they intersect the VPC, as described below and in the LCP iterations discussed in Chapter 4.

Existing rail corridors are of critical importance for the study as this type of ROW is extremely suitable for light rail construction. FTA design specifications state that one of the most common ROWs for new light rail construction in urban areas is existing or abandoned freight railway lines (FTA 2012, 84) Additionally, METRO called for increased transit routes using existing railroad corridors (DOT and METRO 2010, 1:126). There was no data available to gauge the economic impact of using one freight right-of-way over another, so no finer grain scoring was performed here.

Harris County Appraisal District (HCAD) METRO parcels and existing light rail lines were also included in the VPC, as METRO owns the land and ROW.

Secondary and Tertiary Roads from Open Street Map were also included in the VPC based on METRO's prior route design study and the increased ROW width of secondary roads over tertiary roads. In an attempt to reduce the cost of purchasing ROW, METRO used existing major street rights of way (DOT and METRO 2010, 1:60).

All combined path segments for VPC, Existing METRO light rail ROW, Freight rail ROW, and secondary and tertiary streets are shown in Figure 9.

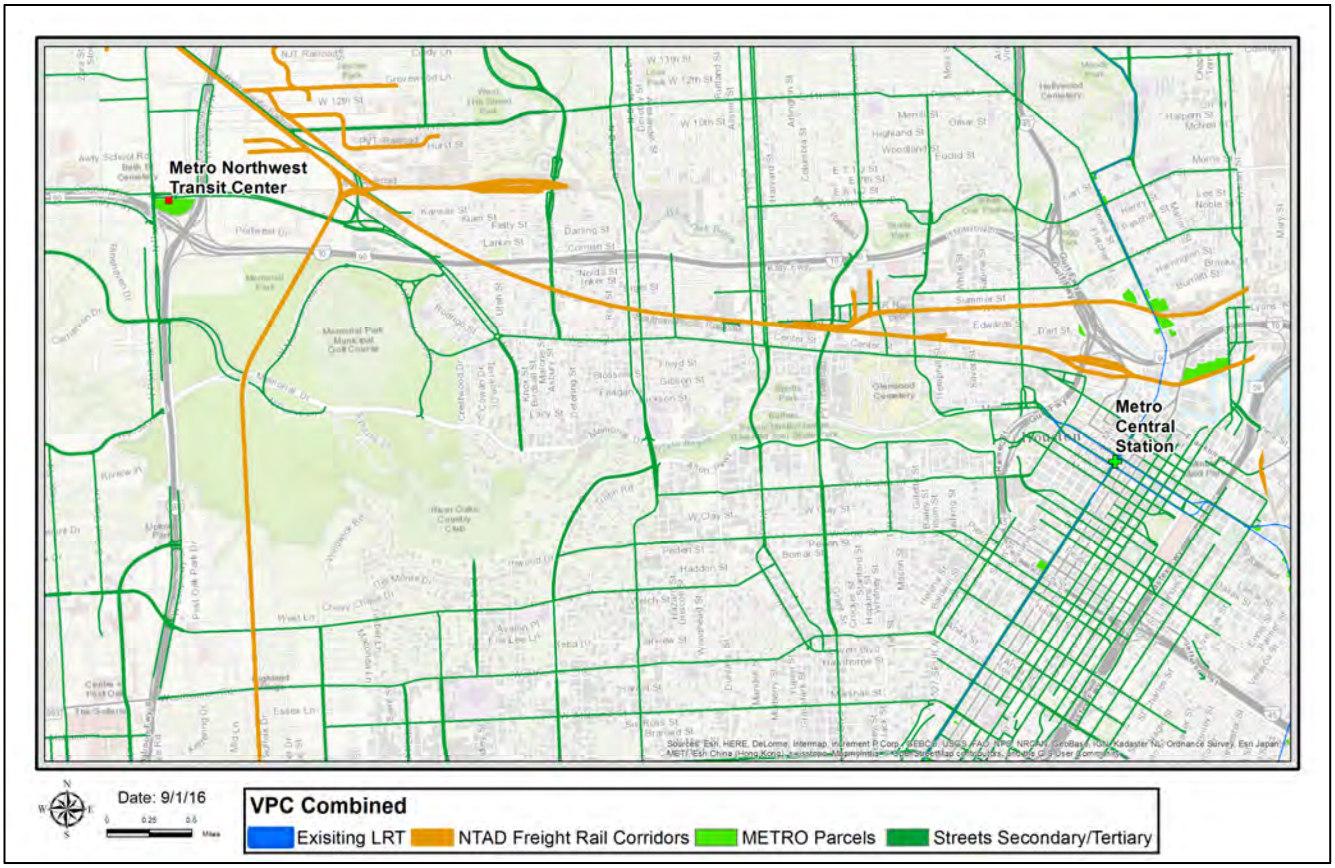

Figure 9 Individual VPCs Combined

3.4 Reclassification

Reclassification of the standardized data is required to simplify and to create a priority for the cost raster cells. An appropriate reclassification range had to be established that was simple and logical. For this study, the following was chosen: 1 – Optimal, 2 – Acceptable, 3 – Neutral, 4 – Sub-optimal, 5 – Avoid. These values were assigned by applying light rail design engineering specifications from The *Track Design Handbook for Light Rail Transit* from the Federal Transit Administration (FTA), Siemens vehicle data sheet, the prior failed METRO engineering design study, as well as detailed background research on the failed light rail project (Siemens 2014; FTA 2012; DOT and METRO 2010).

The Siemens data sheet describes Houston Metro's current S70 Low-floor Light Rail Vehicle's maximum operational gradient as 7 percent (Siemens 2014). The slope grade data was reclassified based on the following design specifications: Slope grade values between 0-7 percent are reclassified as 1-Optimal, and slope grade values 7, and greater are reclassified as 5-Avoid.

Flood data is of critical importance for a construction project and especially so in Houston. Downtown Houston is only 60-feet above sea level and intersected by large ravines of flowing water called bayous that are prone to flooding. The FTA states the importance of planning for flood zones, because operations can be halted if water levels get above the rail. They go on to discuss how debris from floodwater can block vital systems and become a fire hazard (FTA 2012-694).

FEMA Flood zones that are located in FEMA's minimal flood hazard zone have a less strict permit required by County Engineer of Harris County Floodplain Management Regulations (HCPID-ED 2011). FEMA describes the minimum flood hazard zone as areas higher than the elevation of the 0.2-percent-annual-chance flood. These minimal flood hazard zones will be reclassified as 1–Optimal. FEMA describes the 100-500-year flood zones as the area having a 1 to 0.2 percent chance of flooding annually. It is suggested that one hundred to five-hundred-year flood zones be avoided when possible, but these are not strictly prohibited and so were reclassified as 3-Neutral. Unfortunately, the data would not allow for a separation of 500 or 100 from the 100-500-year flood zone. FEMA describes a Regulatory Floodway as the channel of a river and the adjacent land needed to discharge the floodwaters. A regulatory floodway has an even higher danger of flooding due to weather events and will be reclassified as 4–Sub-optimal as an elevated support could be built or an existing bridge could be present. The following reclassified FEMA flood zones are illustrated in Figure 10.

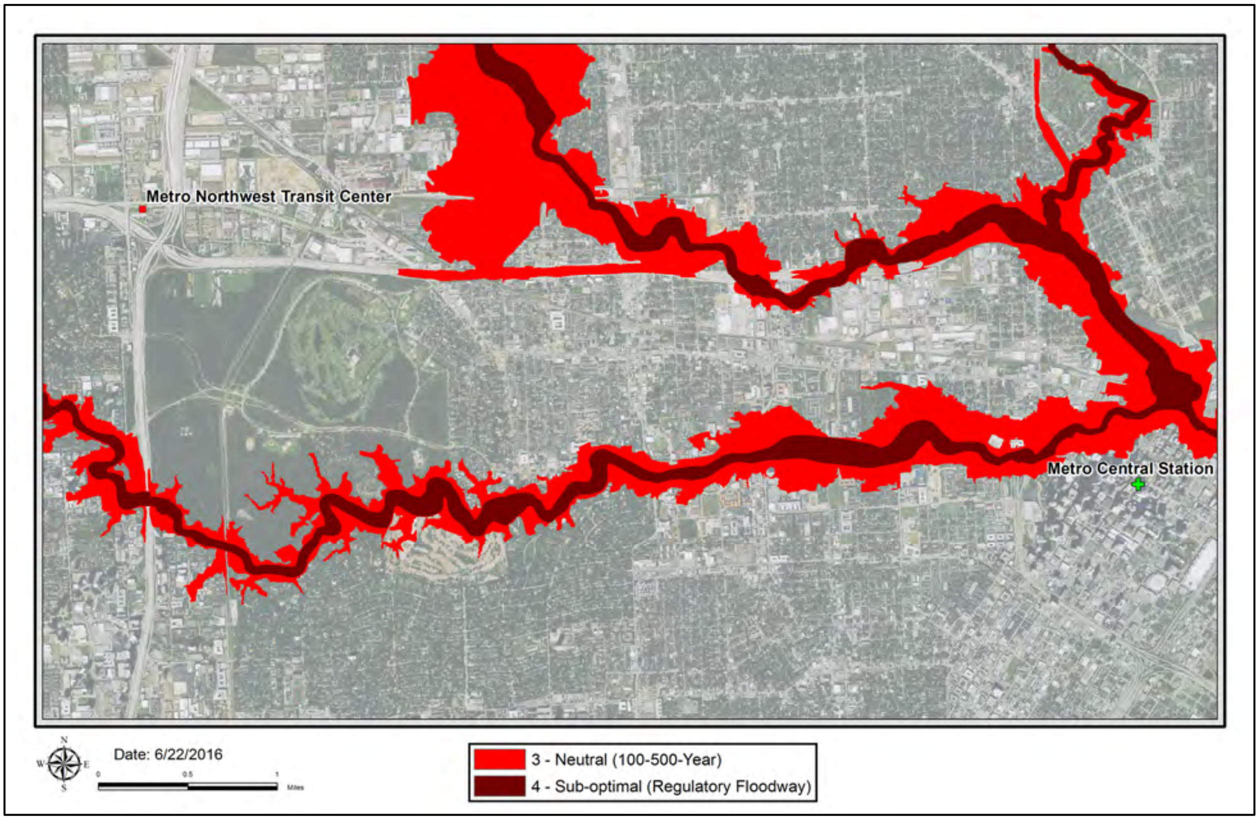

Figure 10 FEMA Flood-zone Reclassification by Hazard

Extra coordination is required for interstate crossings as they must be coordinated carefully with designers of light rail systems specifically regarding signal and crossing warning systems (FTA 2012, 560). On the other hand, no prohibitive modifications to interstate structures will be required for lines that cross underneath (DOT and METRO 2010, 1:51). Vertical clearance issues regarding catenary poles and wires underneath interstate crossings can be alleviated. As much as 1-mile stretches of the prior failed route went without catenary (DOT and METRO 2010, 2:189). Catenary in this context is vertical poles and wires that provide the power needed for the light rail vehicle to operate. While the need for coordination exists, crossings have not been a prohibitive issue for previous Houston light rail routes. For example, METRO crosses underneath Major Highways where existing secondary and tertiary roads are present (DOT and METRO 2010, 2:116). Major Highways were reclassified as 2–Acceptable, as seen in Figure 11.

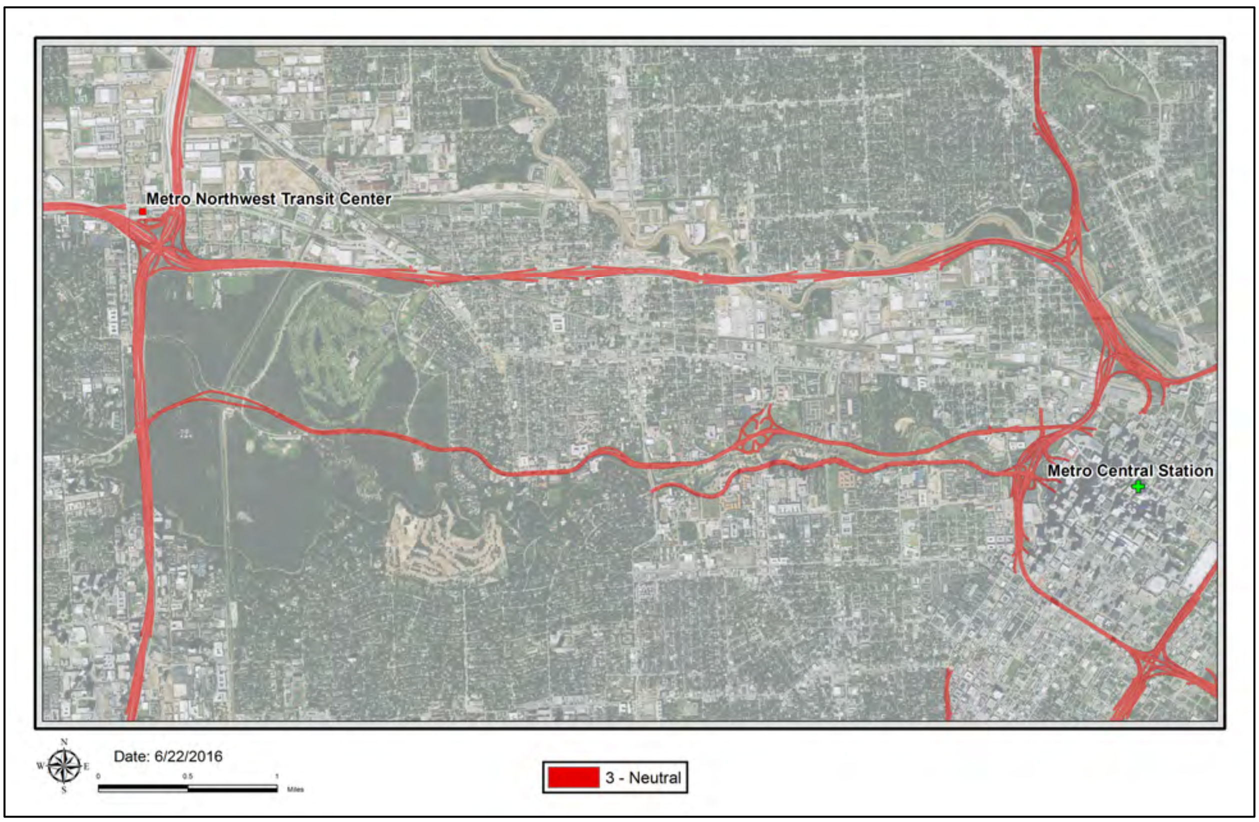

Figure 11 Major Roads Reclassification by Highway Intersection

USA 113th Congressional District data was reclassified based on prior and current support of the congressional district members in the study area. Reclassification value of 5–Avoid was given to land in Congressional Districts where members are against light rail (Culberson 2014) as illustrated in Figure 12.

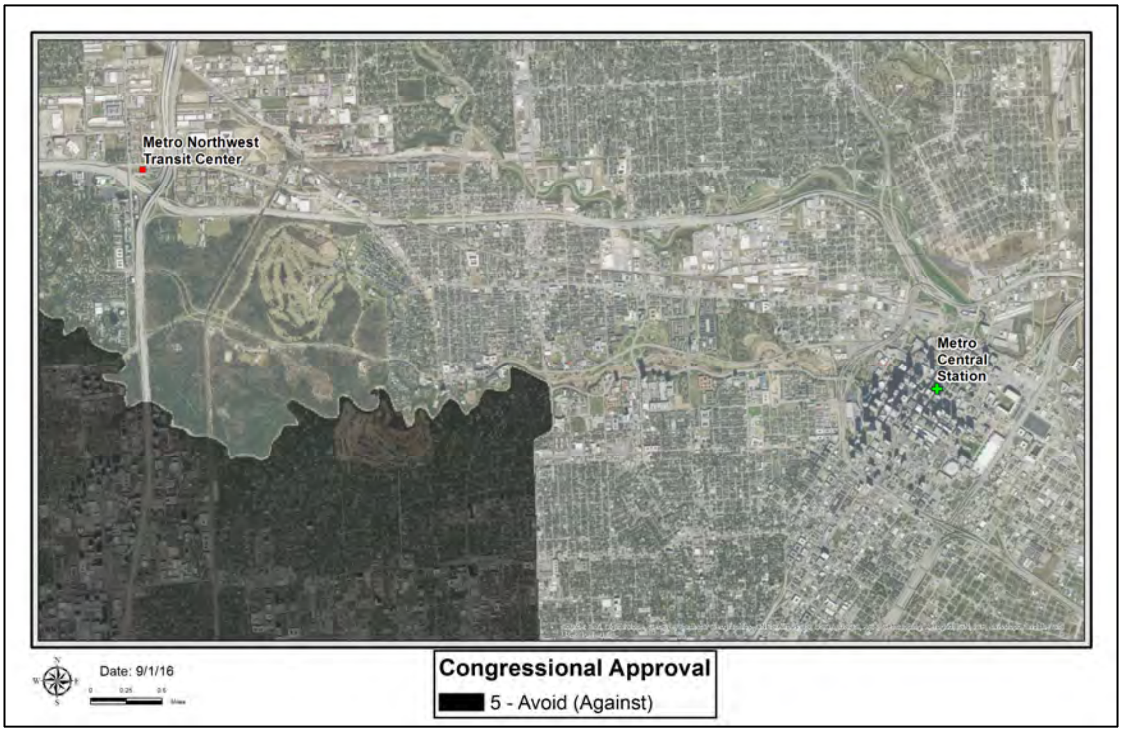

Figure 12 Congressional Approval Avoidance Reclassification

Residential Roads from Open Street Map as seen in Figure 13 were reclassified as 4–sub-optimal based on the indication of proximity to residential neighborhoods and their corresponding concerns with crossing traffic and noise. Additionally, negative feedback from neighborhoods received during the prior failed attempt to build influenced the reclassification (DOT AND METRO 2010, 4:83; Stiles 2006).

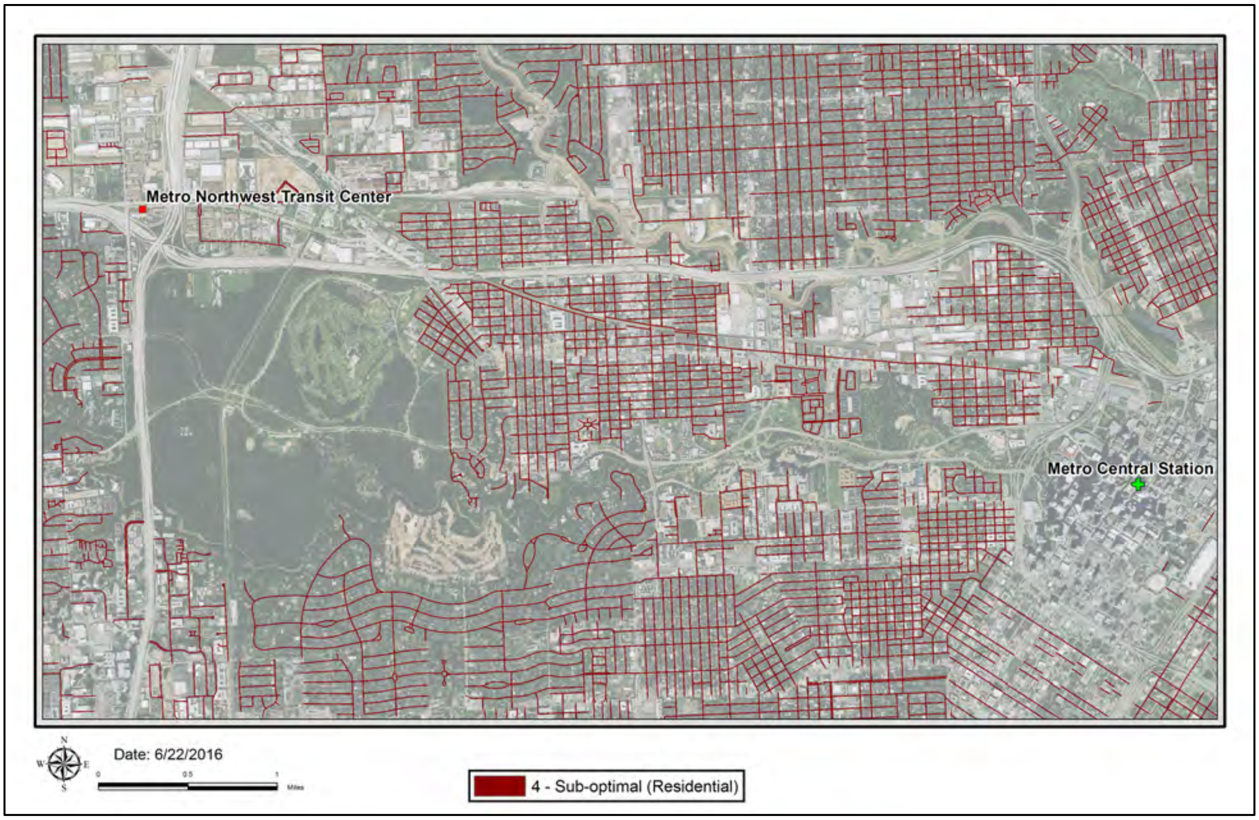

Figure 13 Residential Roads to Avoid

Population density data from the United States Census Bureau as seen in Figure 14 was reclassified as to 1, 2, 3, 4, 5 by Natural Breaks (Jenks) in reversed order, so greater density was given 1–optimal ranking. The Jenks methods was chosen to reduce the variance within classes and maximize the variance between classes (Jenks 1967).

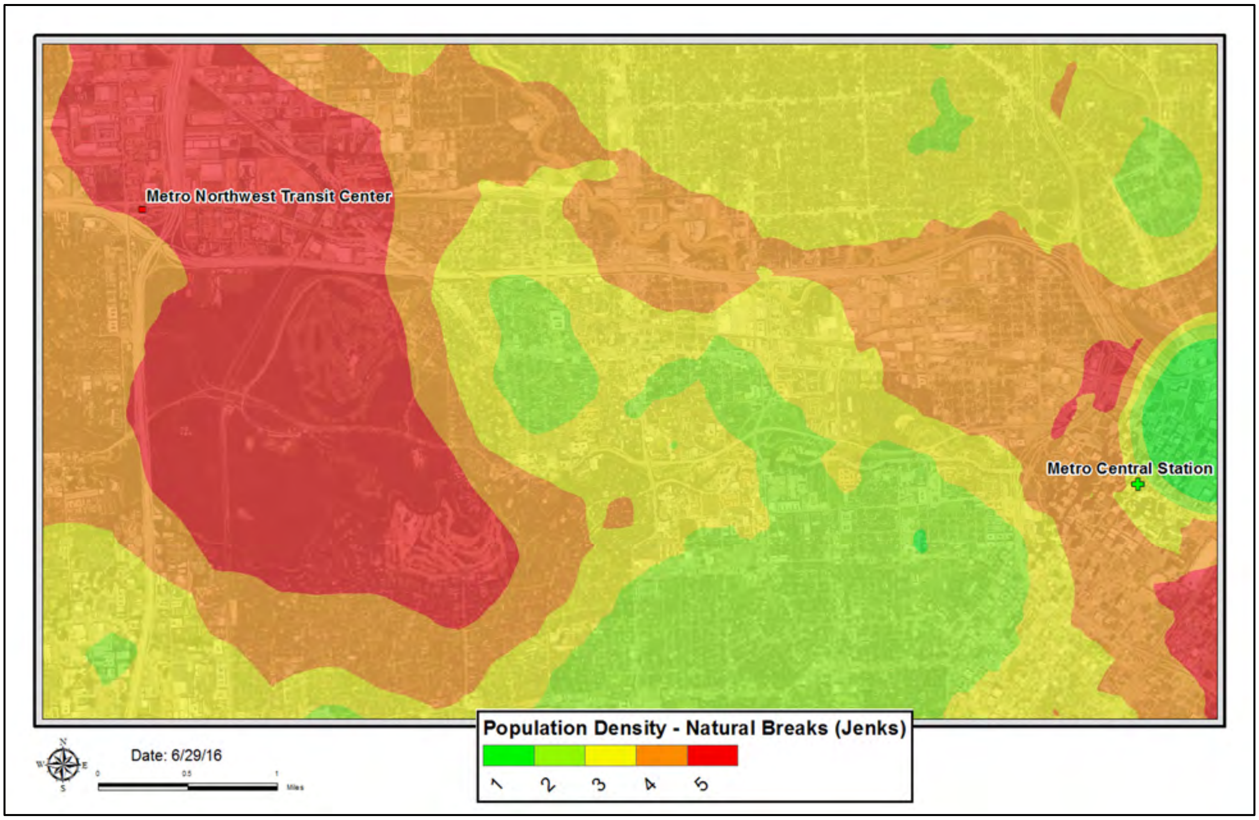

Figure 14 Reclassification of Population Density Raster

3.5 Data Weighting

For this study's methodology, ranking was assigned equally to the reclassified data. Weighting rasters in LCP for GIS is the means in which one classified data set is prioritized over another. The ArcGIS Weighted Overlay tool applies ranking to the reclassified data accessed at ArcGIS Toolbox > Spatial Analyst > Overlay > Weighted Overlay. In this study, each reclassified cost raster dataset had an equal weight totaling one hundred percent. However, as outlined in Chapter 4, various scenarios were run that either entirely included or excluded given layers

.3.6 VPC and LCP Tools

The ArcGIS Mosaic to New Raster tool was used to merge the VPC rasters by the Mosaic operator 'Mean' to create one master VPC. The cost factor rasters also used the Mosaic to New Raster tool by the Mosaic operator 'Mean' to create one master cost raster. Next, the Extract by Mask tool was used to input the Cost Factors Raster and the feature mask of VPC raster. The result was Cost Factor Rasters that were clipped by the VPC suitable for the final LCP tools. The final LCP tools used were the Cost Distance and Cost Path spatial analyst tools in ArcGIS 10.3 as shown in Figure 15.

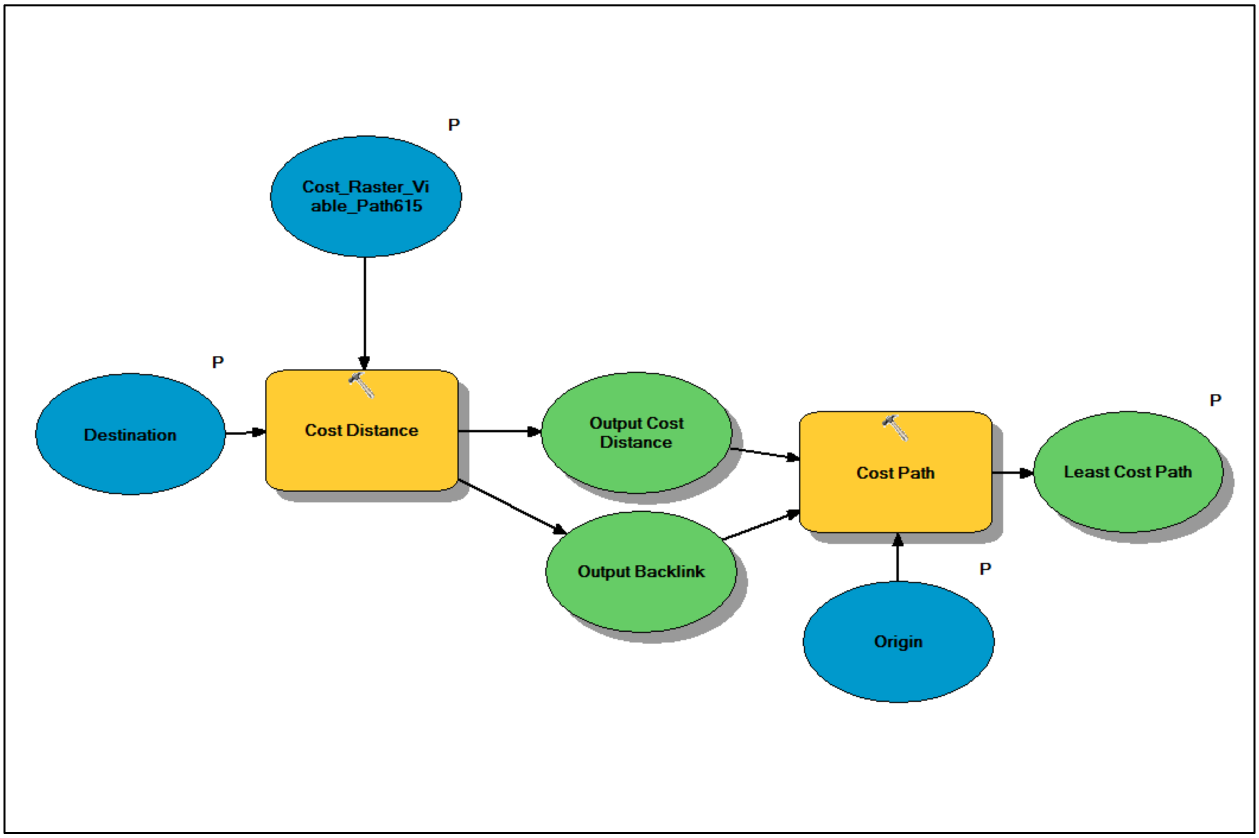

Figure 15 LCP Workflow for ArcGIS 10.3

The Cost Distance tool calculates the least accumulative cost distance for each cell to the nearest source over a cost surface, also known as the weighted overlay raster in this study. This tool is different from Euclidean distance, as it determines the lowest travel cost from one raster to another rather than actual distance. The Cost Distance tool is accessed via ArcGIS Toolbox > Spatial Analyst > Distance > Cost Distance. The Cost Path calculates the least-cost path from a source to a destination using the aforementioned Dijkstra's Shortest Path Algorithm and is accessed by ArcGIS Toolbox > Spatial Analyst > Distance > Cost Path.

Chapter 4 Results

Chapter four presents the results of the determination of least-cost paths based on the VPC for several LCP iterations. It includes descriptions of the resulting paths along with maps, comparisons of the iterations, and lessons learned. The paths found are similar in ROW in most instances, with only slight deviations due to different cost factors included in various iterations. The results include four iterations of the model: The VPC only, Population, Residential Roads, and All Cost Rasters runs.

4.1 Model Iterations of LCPs

As a prologue it is important to note that numerous iterations of routes were run and created based on various factors. Eventually, four specific models were chosen to present results of the modeling based on prior light rail literature and engineering design specifications. The four model iterations were chosen using the VPC raster as a base. The first run is an LCP using the VPC only, meaning that the shortest distance was calculated along the VPC. The second run was created using the population cost raster only. The third run was created using the residential roads cost raster only. The final run was created using all cost factors weighted equally. Further details of the path name, source data, reclassification method, and path characteristics are shown in Table 2.

Table 2 Source Data and Characteristics for Model Iterations

Path	Source data	Path characteristics
VPC only	Viable Path Corridors (Secondary/Tertiary Streets; Light Rail Corridors; Freight rail corridors; Houston Metro parcels).	The VPC only run is the shortest path from start to end, but does not account for any other factors.
Population	United States Census Blocks.	The Population only run uses the VPC and takes into account the highest possible population density within 0.5-miles of the line, but also does not account for any of the other cost raters including flood zones and slope.
Avoid Residential Roads	Open Street Map Roads.	The Residential Roads run uses the VPC and overlays residential road corridors as a cost raster that intersect.
All Cost Rasters	Major Highways, Residential Roads, Flood Zones, Safety and Security Parcels, Slope, Congressional Districts, and City of Houston Parcels.	The All Cost Raster run uses the VPC and overlays all cost rasters weighted equally.

4.2 Comparisons of the LCPs

Each run shares many of the same links in the VPC, particularly near the origin and destination. However, the resulting routes also diverge in ways that could represent different priorities for planners and engineers to consider, as shown in Figure 16.

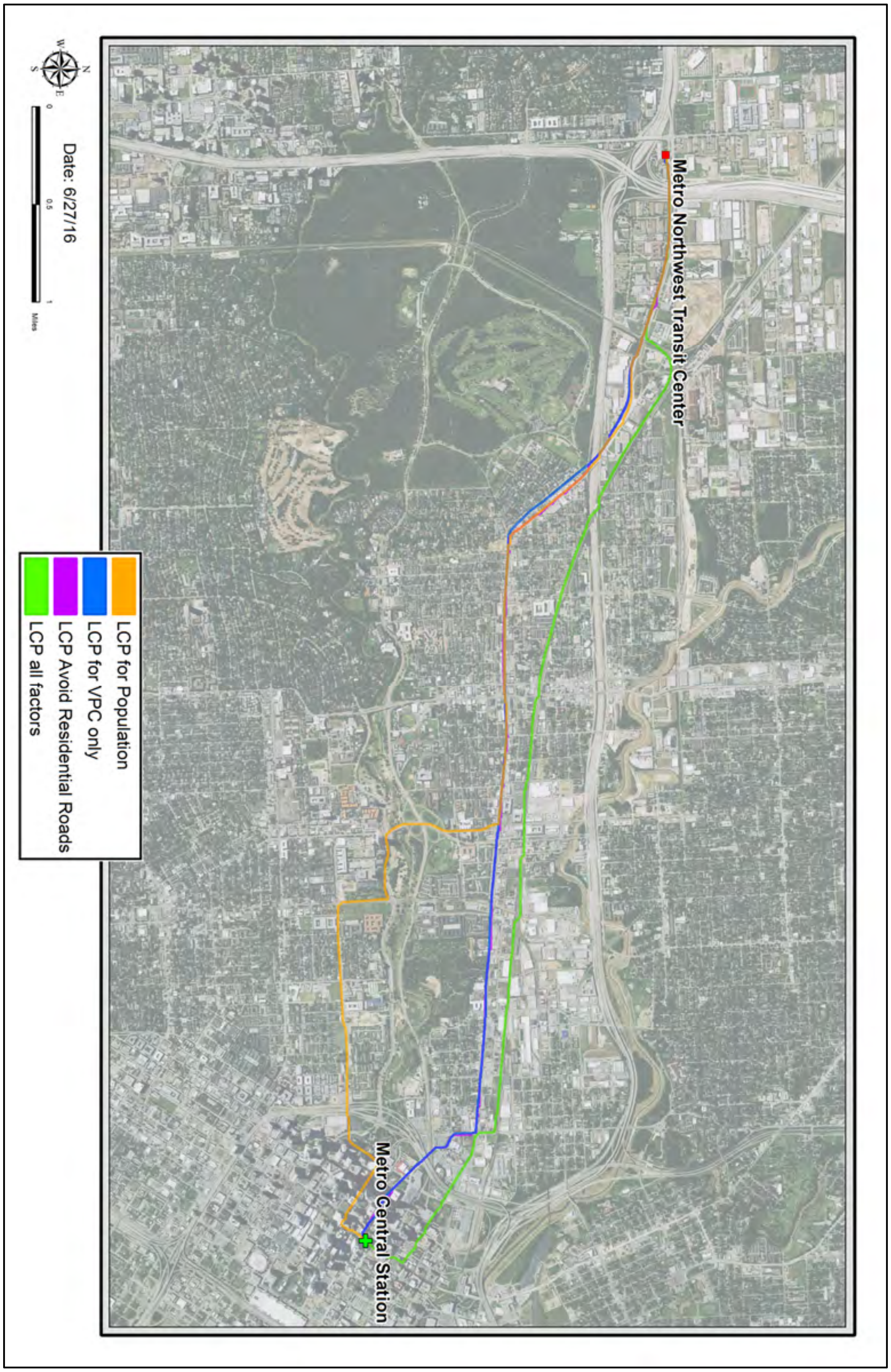

Figure 16 Least Cost Path Iterations

The VPC only run is the shortest path from start to end, but does not account for any other factors. It selects segments of the viable paths corridors that neighbor residential roads such as the Washington Ave to Westcott Street section. The path first follows the existing Purple light rail line to its endpoint at Interstate 45. Next, the path follows the tertiary road of Lubbock Street. The path then stays on the secondary roads of Houston Avenue, Washington Avenue (3 miles), Westcott Street (1.1 miles), and Katy Road (1.06 miles), ending at the Northwest Transit Center. This path runs down a four lane road near gentrifying residential and commercial neighborhoods. Use of a four-lane road is consistent with the original failed route.

The Population run models the shortest line that also runs near the highest possible ridership, route length and population density are included. But, the run does not account for other cost rasters including flood zones, slope, and residential roads. As in the VPC only iteration, the path follows the existing light rail corridor to McKinney Street. Then follows the secondary streets of McKinney, Bagby, West Dallas Street, Montrose Avenue, Waugh, Washington Avenue, and Katy Road, ending at the Northwest Transit center. This path runs down four lane roads and passes through neighborhoods with public housing, high income-high density housing, as well as gentrifying residential and commercial neighborhoods.

The residential road run avoids the most likely objections due to NIMBYism but also does not account for the other cost rasters. The path mirrors the VPC route deviating from Westcott Street, which has a closer proximity to residential roads, and instead staying on Washington Avenue which does not. This path runs near gentrifying residential and commercial neighborhoods avoiding residential roads below Interstate 10.

The All Cost Raster run incorporates physical constraints such as slope and flood zones, but unlike the other paths also follows the existing freight rail ROW. The All Cost Raster path follows the existing light rail line north instead of south to Preston Street. It then follows the secondary streets of Preston and Houston Ave to the existing Amtrak/BNSF freight line. Next, the path follows the freight line 4.3 miles to Katy Road. The path then follows Katy Road 1 mile to the Northwest Transit Center. This path runs near high income residential and industrial neighborhoods. The run bypasses the major flood zones and steepest slopes of Buffalo Bayou that accounts for the deviation from the other routes. The identification of slight deviations and shared corridors of the runs is also important to indicate. The LCP with VPC only run follows the residential road adjacent side of the split road after the round-a-bout on Westcott Street on the right side as seen in Figure 18.

Figure 17 Residential Route along Westcott Street

This deviation is due to the fact that only distance is taken into consideration, and the run ignores the fact that it intersects residential roads. On the other hand, the Avoid Residential Roads and Population runs follow the side road on the Washington Avenue side of the round-a-bout, the side with less intersecting residential roads. Visual verification in the form of site analysis illustrates that the side road along Washington Avenue as seen in Figure 19 has less impact on residential roads and homes.

Figure 18 Non-Residential Route along Washington Avenue

As shown in the site analysis photographs, this path follows the Washington side of the split after the round-a-bout. This corridor has a lack of residential roads and homes near the ROW. All runs coverage on Katy Road and share the same ROW for approximately 1 mile into the terminus of Metro Northwest Transit Center. Also, equally interesting to note is the fact that three of the four runs depart from the Metro Central Station at different ordinal directions: southwest for the Population run, northwest for the VPC only run, and northeast for the LCP all factors run. This is due to the fact that each run is following existing light rail lines as part of the VPC, but later heading toward slightly different parts of the study area.

4.2.1 Ridership and Uses of an Additional Rail Line

Additionally, it is important to recognize the possible ridership of the new line. One use of the light rail line would be for transporting daily commuters from Metro Northwest Transit Center via the park and ride suburban bus system and the Dallas to Houston high-speed rail line. Another ridership use for the line would be for moving workers between the two largest business districts in the city of Houston which include residential towers and neighborhoods. Having a short, efficient rail path matters for these uses. A further use would be for riders to explore and visit places of interest between the central station and terminus. As mentioned in Chapter 3, researchers have determined that individuals are generally willing to walk up to 0.5-mile for light rail public transportation (Schlossberg and Brown 2004). Extrapolating on those findings, this study has built a half-mile corridor from the four final routes and identified places of interest that potential passengers would be interested in visiting as illustrated in Figure 20.

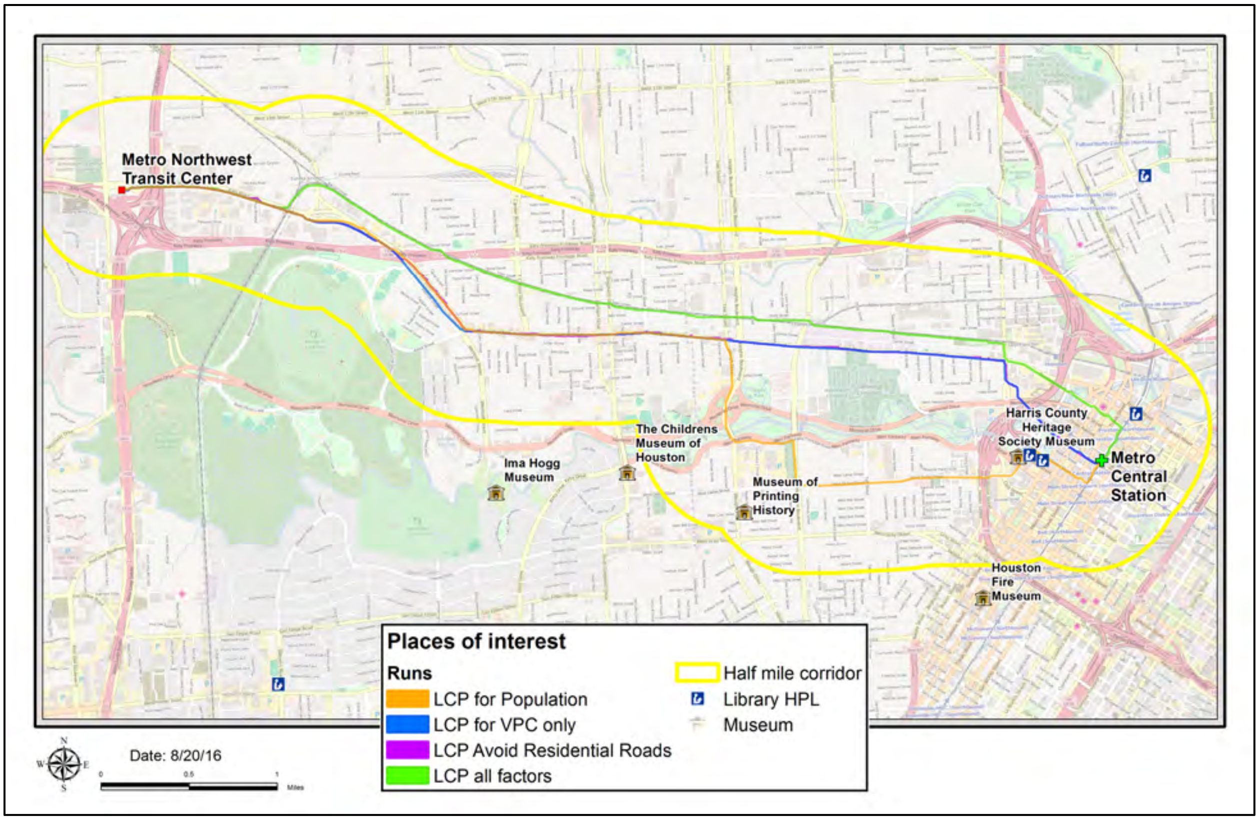

Figure 19 Places of Interest 0.5 Miles from Routes

Although proximity of alternative lines to places of interest was not calculated as part of any of the cost rasters, it is worth noting descriptively how places of interest relate to these alternative paths. Notable places of interest along the half-mile corridor of all runs include the Children's Museum of Houston, Museum of Printing History, Harris County Heritage Society Museum, Bayou Bend Collection and Gardens, Spotts Park, Buffalo Bayou Park, Memorial Park, Eleanor Tinsley Park, Sam Houston Park, Cleveland Park, White Oak Park, Memorial Public Golf Club, Carnegie Vanguard High School, High School for Law Enforcement and Criminal Justice, St. Thomas High School, Revention Music Center, Alley Theatre (musical theater), Houston Grand Opera, and Jones Hall for the Performing Arts (Houston Symphony). The source of the data is from the Houston Galveston Area Council. There are also numerous bars, gyms, and eateries. All of the aforementioned places of interest are within a 0.5-mile walking distance from the four final routes, with the exception of the Children's Museum of Houston and Museum of Printing History which are only present in the LCP for Population run.

4.2.2 Model Routes and U.S. Congressional Districts

As seen in Figure 21, it is important to recognize that all four of the runs completely miss the district of U.S. representative John Culberson, whose opposition was the primary factor along with the secondary factor of building adjacent to residential roads NIMBYism in the failure of the previous route failure (Culberson 2014, DOT AND METRO 2010, 3:107, 4:83). Even the simple, shortest route between the two destination points never needed to traverse Culberson's district.

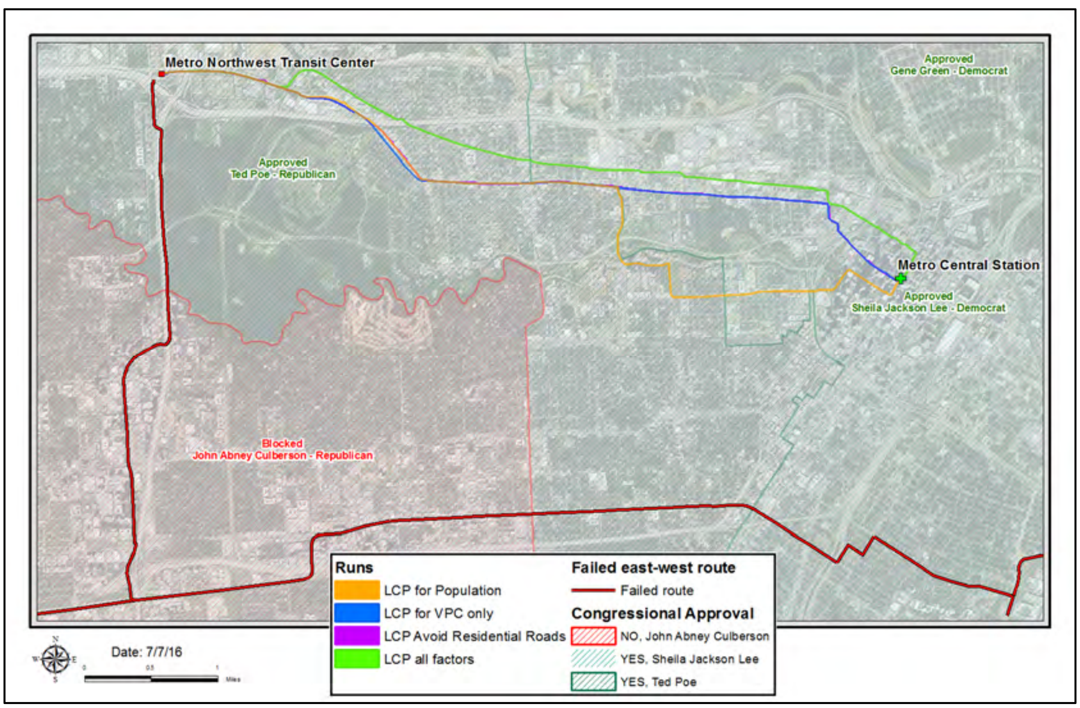

Figure 20 Four Potential Routes with Failed Prior Route

The original failed line's route was chosen based on studies that indicated a connection along Richmond Street and Westpark Road would provide enhanced service to the existing light rail infrastructure. This route sought to connect the CBD, with the Medical Center, Greenway Plaza, and the Galleria. Although the model for this study was not built around reaching these particular points of interest, it still demonstrates potential for planners. Use of this methodology as part of their planning for future light rail projects would avoid prohibitive cost factors.

4.2.3 Adjusting Terminus Location

Bagli et al.'s (2010) study noted that small changes in the start and end locations can result in significantly different route paths. Thus, a test LCP iteration was performed using a copied terminus end point moved to the southeast of the parcel by 500-feet. Adjusting the location of the Terminus was feasible because the potential station has not been constructed yet and so could reside at most positions inside the parcel. This change in the end point parameter showed no changes in the routes path to the Metro Northwest Transit Center seen in Figure 22.

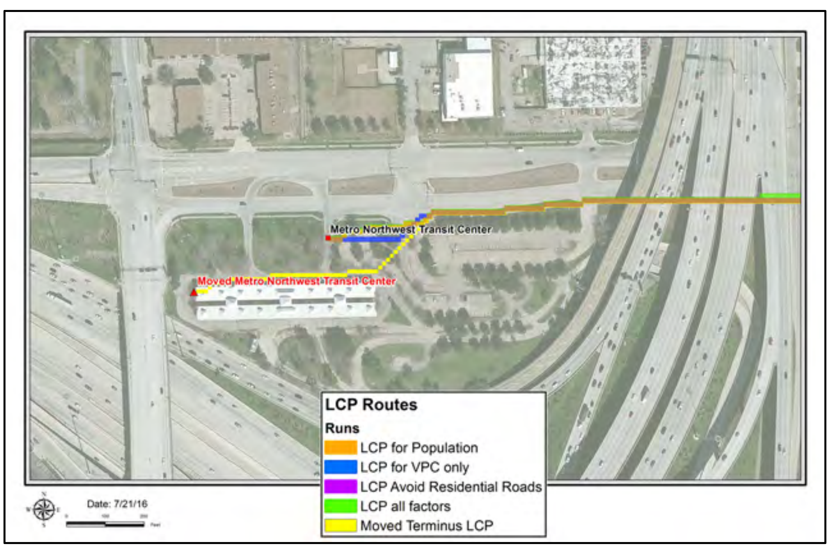

Figure 21 Adjusting Terminus Location to Test Route Change

This lack of change in route is primarily due to the constraint on the size of the end points movement within the Metro parcel. The total area of the Metro Northwest Transit Center parcel is only 0.02 square miles. An additional influence was the minimal number of viable paths corridors into the Transit Center. The study did not explore adjusting the Metro Central Station starting point as it is already built and could not be moved without incurring substantial financial costs.

4.3 Lessons Learned

The following lessons were learned from this four-way comparison. First, each path has positives and negatives associated with it. The Population run would maximize potential ridership by population, but would conversely potentially cause the highest potential negative NIMBYism impact on the residential neighborhoods. Second, routes that predominantly traverse freight rail corridors would cause less traffic and noise disruption to the surrounding residents during construction, although they would likely incur expensive ROW acquisition costs (DOT and METRO 2010, 4:24, 6:59). Conversely, routes that mostly bypass freight rail ROW would cause more distribution noise and traffic disruption to the surrounding neighborhoods (DOT and METRO 2010, 4:24, 6:59). Third, all paths followed the existing light rail lines leaving the start location of Metro Central though in different directions. These runs would need to share track and schedule coordination with existing light rail lines as the downtown districts ROW is extremely limited. Fourth, all runs followed Old Katy Road into Metro Northwest Transit Center. Fifth, locational changes in the end point generate no discernable path changes. Sixth, it is important to note that acquisition costs could be restrictive on some of these paths. Finally, there is an abundance of places of interest within walking distance to all four paths.

Chapter 5 Conclusion

This chapter summarizes lessons learned from the study's method, limitations, strengths, and opportunities for future work. The process of VPC and LCP adopted for this study provides several practical alternatives to for decision makers (DMs) to consider for reviving the planning process for a new light rail line in Houston.

The study found several feasible route options other than the previously failed route based on lessons learned from the prior DOT and METRO light rail line study and the application of the combined VPC and LPC method. These alternatives are suggested as preliminary routes that will later be refined by planners, engineers, and surveyors. The primary reason for this was understanding the reasons why the previously lines failed and incorporating those lessons into the GIS analysis. Applying lessons learned from background history and research provided a strong foundation to build the VPC. Secondly, this study used related GIS, LCP, Engineering, and light rail research to build upon existing proven methodologies, apply them to the study area, and extend the research to the light rail domain.

The unforeseen roadblocks of the prior failed lines negated countless man hours and hundreds of thousands of dollars in research, outreach, and planning (DOT and METRO 2010, 8-1). The first unforeseen roadblock was the congressional opposition of John Culberson who blocked Federal funding. The route options for the failed lines had a federal funding to cost ratio component that was the secondary deciding factor after using existing transportation corridors. METRO defines this ratio as preliminary capital cost divided by preliminary ridership forecast. Because of Culberson blocking federal funding, the financing of the project was abruptly halted, and without prior knowledge or research into this possibility, no contingency was in place to mitigate this obstruction. Relatedly, the public NIMBYism of building rail along and near their residential streets and homes acted as a catalyst for the political obstruction of federal funds. It is important to note that this study intentionally does not include monetary cost or funding criteria in any cost rasters.

Studies reviewed by METRO for failed the University and Uptown lines had shown the key need for connectivity was a transit spine that would serve the CBD, Greenway Plaza, The Galleria (financial district), and the Texas Medical Center. It was determined that the construction of the METRO Red Line made this failed connection more practical and urgent in the overall Houston light rail network. The widening of adjacent highways and increased development in the corridor limited the option for future roadway expansion. METRO found that this line was an option to preserve mobility and maintain the vitality of the CBD to Galleria corridor (DOT and METRO 2010, 1:67).

Based on those prior studies, alternative routes that led to the University and Uptown lines were proposed and considered that fell within that corridor. The proposed routes were developed to primarily avoid and minimize impacts by using existing transportation corridors. These existing corridors included roadways and freight rail lines. Secondary concerns after using existing transportation corridors focused on routes that had the best ridership potential and Federal funding opportunities.

In contrast, the alternative routes proposed in this project focus on connecting the downtown CBD to the financial district based on using geospatial data for many criteria and that avoids presumptively non-supportive congressional districts completely. This is easy to do via background research, related work, and geospatial data from Esri Congressional districts. Additionally, a route iteration is included that avoids residential roads. These route iterations apply direct lessons learned from the previously failed route and offer viable alternatives as part of a larger methodology that utilizes VPC and LCP.

This study's review and use of related work on GIS, LCP, Engineering, and METRO studies allowed for routes that built upon prior accepted methodologies. This included the incorporation of The Track Design Handbook for Light Rail Transit from the Federal Transit Administration, Siemens vehicle data sheet for physical constraints of route planning, and the DOT and METRO's design study for the failed lines as the basis of preferred corridors and the factors to avoid and embrace. Also included were lessons learned from related works of the Transportation Research Board (2012), Bagli (2010), Pingel (2010), and improved upon DOT and METRO's design study (DOT and METRO 2010). Attention was paid to determining alternative route paths based on moving the terminus position, which in this study found no discernable difference. Lessons learned from Pingel included incorporating engineering specifics such as maximum acceptable slope grade for Siemens light rail vehicles which the original DOT and METRO' study does not explore. FTA guidelines on Flood Zones is also directly applied to the route path selection rather than analysis after the final route was chosen (DOT and METRO 2010, 11-108). These methodological improvements to previous related work and studies seek to stand on the shoulders of giants and thusly strengthens the final route iterations.

5.1 Strengths and Limitations

Some limitations should be identified for this study. First is the lack of survey level precision or accuracy of the GIS data. This was important because the final GIS analyses accuracy and precision are only as good as the raw data. Additional resources are required such as surveyors to ground truth the results to verify the final routes. Second, access to subject matter experts and DMs was not able to be obtained. This was important because while engineering design specifications determine the reclassification of GIS data, Houston transit officials and stakeholders in light rail are better suited to determine which datasets should be ranked over the others. Numerous attempts were made at contacting members at Houston METRO and related engineering firms with no success. Also, it is important to reiterate the general limitation of the VPC and LPC approach will never result in an absolute route selection, but that this step is important as an input to stakeholders, project managers, engineers, and many others. Studies such as these can save countless wasted man-hours and hundreds of thousands of dollars.

5.2 Future Work

Opportunities for future work include expanded research in data, analysis, and methods for delineating VPC. The next step for this particular study would be to secure input from transit decision-makers (DMs) in Houston and clearly delineate business processes for weighing data for LCP for light rail.

Data sources such as residences without vehicle ownership could be included and applied to cost rasters. The prior failed DOT and METRO route study included a visualization of the data; it would ideal to take the representation and preform analysis on the data similar to using the Focal Statics tool on population density data. Economic data incorporation and analysis could be useful to add to the Federal funding to cost ratio formula present in the prior failed study. Adding possible future economic growth and property tax revenue increases could offset monetary costs. Similarly, looking into ethnicity by following the Denver's Regional

Transportation District approach that utilized GIS for Title VI Compliance would provide additional insights. The analysis could be done to insure compliance with the Title VI of the Civil Rights Act of 1964, which prohibits discrimination on the grounds race, color, and national origin. This would also avoid possible funding shortfalls as well as directly address equitable access to public transportation options.

Including the possibility for mono-directional lines between stations, with their correspondingly narrower width requirements could also yield additional route options. By including these smaller ROW, the options for VPC increase as well as the possible routes along them. Additionally, exploring the option of allowing bi-directional routes to diverge and mono-directional lines converge adds even more possible routes to be made available for stakeholders, project managers, engineers, and others to evaluate.

Securing subject matter experts to weigh data with a business process in the form of an analytic hierarchy process (AHP) would further add to the study. Weighing rasters in LCP for GIS is the means in which one classified data set is prioritized over another. Utilizing this would yield a more thorough and defendable accumulative cost raster layer. Decision-makers (DMs) could use business processes and rankings towards GIS data in the form of an AHP.

Jankowski (1995) describes how using multi-criteria-evaluation methods like AHP work best when handling different types of GIS data. This is because they are capable of handling different, usually incomparable criteria. The AHP would allow DMs the ability to pairwise compare different factors by ranking them against each other which could provide a final total rank in number or percentage of importance. Moreover, Banai's (2006) journal article on light rail corridors found that AHP was introduced to the Federal Transportation Administration

(FTA) in 2000. It was an executive decision-making tool for resource allocation for United States Department of Transportation (DOT) and FTA decision-making processes. Yakar et al. (2014) discusses the use of iterative AHP results. The authors' state that different DMs such as government entities prefer weighting economics highest and others such as NGO's may prefer to weight environmental factors higher.

Future work would address this issue by interviewing DMs in accounting, environmental, and construction who might pairwise compare the criteria. The group's iterative rankings would then generate a summary weight and rank. AHP is accomplished with pairwise comparisons of values by assigning priority rankings. The comparisons show how much more one element dominates another with respect to a given attribute, often by rankings or weighted percentages. This iteration option allows for multiple DMs to adjust the weights based on their needs. For example, an engineering firm's accounting, environmental, and construction groups could each pairwise compare the criteria separately. An example would be an environmental group would pairwise rank environmental factors such as flood zones over all other criteria. Furthermore, the accounting group may rank existing METRO ROW parcels higher than all other criteria based on their lack of added acquisition costs. The sum iterative weights of the DMs could then be applied to the reclassified factors using the weighted overlay spatial analyst tool. One could quickly model different iterations in near real-time live settings such as meetings with DMs and other stakeholders. The emergent field of Geodesign could allow for such iterative evaluation at reduced times as an alternative to traditional evaluation processes (Esri 2016).

REFERENCES

Bagli, S., Geneletti, D., and Orsi, F. 2011. "Routing of Power Lines through Least-cost Path Analysis and Multicriteria Evaluation to Minimise Envronmetnal Impacts." *Environmental Impact Assessment Review* 3, no. 31: 234-239.

Banai, R. 2006. "Public Transportation Decision-Making: A Case Analysis of the Memphis Light Rail Corridor and Route Selection with Analytic Hierarchy Process." *Journal of Public Transportation* 9, no. 2: 1-24.

Carlyle, E. 2014. “America’s Fastest Growing Cities” *Forbes*, February 14. Accessed March 2, 2016. http://www.forbes.com/sites/erincarlyle/2014/02/14/americas-20-fastest-growing-cities.

Chang, K. 2012. *Introduction to Geographic Information Systems.* Boston: McGraw-Hill.

Congalton, R. 1997. "Exploring and Evaluating the Consequences of Vector-to-Raster and Raster-to-Vector Conversion." *American Society for Photogrammetry and Remote Sensing.* 63, no. 4: 426-434.

Cormen, T., Leiserson, E., and Rivest, R. 2001. *Introduction to Algorithms.* Cambridge: MIT Press.

Cowen, D., Jensen, J., Hendrix, C., Hodgson, M., and Schill, S. 2000. "A GIS-Assisted Rail Construction Econometric Model that Incorporates LIDAR Data." *Photogrammetric Engineering & Remote Sensing* 66, no. 11: 1323-1328.

Culberson, J. 2014. “Transportation.”Accessed March 2, 2014. http://culberson.house.gov/issues/issue/?IssueID=109037.

DOT and METRO. 2010. *University Corridor Fixed Guideway in Houston, Harris County Texas: Environmental Impact Statement and Section 4(f) Evaluation*. Houston, TX: DOT and METRO.

Effat, H., and Ossman, H. 2013. "Designing and Evaluation of Three Alternatives Highway Routes Using the Analytical Hierarchy Process and the Least-cost Path Analysis, Application in Sinai Peninsula, Egypt." *The Egyptian Journal of Remote Sensing and Space Science* 16, no. 2: 141-151.

Emerson, M., Howell, J., Jeanty, W., and Cline, M. 2014. *Houston Region Grows More Racially/Ethnically Diverse, With Small Declines in Segregation.* Urban Research, Houston: Kinder Institute for Urban Research & the Hobby Center for the Study of Texas.

Esri. 2016. "Cell size of raster data." Accessed June 6, 2016. http://webhelp.esri.com/arcgisdesktop/9.2/index.cfm?TopicName=Cell_size_of_raster_data.

Esri. 2016. "Interative Evaluation." Accessed August 9, 2016. http://www.esri.com/products/arcgis-capabilities/geodesign/overview#iterative_panel

Esri. 2016. "Understanding Euclidean distance analysis." Accessed March 27, 2016. http://help.arcgis.com/EN/ARCGISDESKTOP/10.0/HELP/index.html#//009z0000001t000000.htm

Esri. 2016. "USA 113th Congressional Districts." Accessed March 2, 2016. http://blogs.esri.com/esri/arcgis/2013/01/09/usa-113th-congressional-districts-now-available

Federal Transit Administration. 2012. *Track Design Handbook for Light Rail Transit.* Handbook, Washington, D.C.: National Research Council. Transportation Research Board.

GHP. 2016. “Corporate Headquarters.” Accessed August 17, 2016. http://www.houston.org/newgen/14_Company_Information/14A%20W001%20Fortune%20500%20Companies.pdf

Harris County Appraisal District. 2016. “HCAD GIS DATA”. Accessed March 2, 2016. http://pdatahcad.org/GIS/index.html

Harris County Public Infrastructure Department Engineering Division. 2007. "Regulations of Harris County Texas for Floodplain Management." Regulatory, Houston.

HGAC. 2011. *The 2035 Houston-Galveston Regional Transportation Plan.* Transportation Plan, Houston-Galeveston: Houston-Galveston Area Council.

Hochmair, H. 2004. "Towards a Classification of Route Selection." Cognitive Systems Group, University of Bremen.

Howard, C. 2016. Forbes. Accessed August 17, 2016. http://www.forbes.com/sites/carolinehoward/2016/02/22/the-best-college-in-every-state/5/#48ae62bf19ef

Jankowski, P. 1995. "Integrating geographical information systems and multiplecriteria decision-making methods." *International Journal of Geographical Informationsystems* 9, no. 3: 251-273.

Jenks, G. 1967. "The Data Model Concept in Statistical Mapping." *International Yearbook of Cartography* 7: 186–190.

John, D., Goodchild, M., and Longley, G. 2007. *A comprehensive guide to principles, techniques and software tools.* Leicester: Matador.

KHOU. 2014.“Metro Announces $49M Budget Shortfall." Accessed March 2, 2016. http://www.khou.com/story/local/2014/08/13/11354188/

Knaap, W. 1995. "The vector to raster conversion: (mis)use in geographical information systems." *International Journal of Geographical Information Systems* 6, no. 2: 159-170.

Kotkin, J., and Gattis, T. 2014. “Success and the City.” *Wall Street Journal*, July 14. Accessed August 2, 2016. http://online.wsj.com/articles/joel-kotkin-and-tory-gattis-success-and-the-city-1405379881.

Lawrence, F., Andresen, M., and Schmid, T. 2004. "Obesity Relationships with Community Design, Physical Activity, and Time Spent in Cars." *American Journal of Preventive Medicine* 27, no. 2: 87-96.

Mccoy, G., Growdon, K., and Lagerberg, B. 1994. "Applying Electrical Utility Least-cost Approach to Transportation Planning." Transportation Report, Portland.

Mehlhorn, K., and Sanders, P. 2008. *Algorithms and Data Structures: The Basic Toolbox.* Berlin: Springer.

METRO. 2003. “Prior Houston Metrorail Construction, and Maintenance Costs.” Accessed June 2, 2014. www.ridemetro.org/currentprojects/default.aspx

Millado, N., and Vigneri, S. 2014. “The Fittest and Fattest Cities in America.” Accessed August 2, 2014. http://www.mensfitness.com/life/travel/fittest-fattest-cities-america-2014

Pan, Q. 2013. "The Impacts of an Urban Light Rail System on Residential Property Values:Case Study of the Houston METRORail Transit Line." *Transportation Planning and Technology* 36, no. 2: 146-169.

Pingel, T. 2010. "Modeling Slope as a Contributor to Route Selection in Mountainous Areas." Cartography and Geographic Information Science., University of California Santa Barbara., Santa Barbara.

Piwowar, J. 1988. *Conversion between vector and raster format data for geographic information systems applications.* Ottawa: National Library of Canada.

Rao, K. 2011. “Seoul Tears down an Urban Highway and the City Can Breathe Again.” Accessed January 29, 2016. http://grist.org/infrastructure/2011-04-04-seoul-korea-tears-down-an-urban-highway-life-goes-on/

Reed, M. 2011. “Metro violated law; $900 million grant stalls.” Accessed March 2, 2016. http://www.yourhoustonnews.com/memorial/news/fta-metro-violated-law-million-grantstalls/article_a6b111d6-69af-5ec8-b801-0945bbf45f2f.html

Reeves, R. 2015. "Deriving Traverse Paths for Scientific Fieldwork with Multicriteria Evaluation and Path Modeling in a Geographic Information System." Master's thesis, GIS&T, University of Southern California.

Reid, E., Tian, G., Spain, A., and Goates, J. 2014. "Effects of Light-Rail Transit on Traffic in a Travel Corridor." *Journal of Public Transportation JPT* 17, no. 4: 93-113.

Rivera, J. 2015. "A Threat-based Least-cost Path Decision Support Model for National Security Resource Allocation along the US-Mexico Border." Master's thesis, GIS&T, University of Southern California.

Rufolo, A., Bronfman, L., Strathman, J. 1996. *Least-Cost Transportation Planning in ODOT.* Transportation, Salem,: ODOT.

Saaty, T. 2000. *Fundamentals of Decision Making and Priority Theory with the Analytic Hierarchy Process.* Pittsburgh: RWS Publications.

Sanchez, T., Stolz, R., and Ma, J. 2004. "Inequitable Effects of Transportation Policies on Minorities." *Transportation Research Record: Journal of the Transportation Research Board* 1885: 104-110.

Schadewald, B. 2014. "Metro's Wild Ride: As Light Rail Moves Full Steam Ahead in Houston, Not Everyone Is on Board." *Houston Business Journal*.

Shrestha, R., Anandarajah, G., Adhikari, S., Jiang, K., and Songli, Z. 2005. "Energy and Environmental Implications of NOx Emission Reduction from the Transport Sector of Beijing: A Least-cost Planning Analysis." *Transportation Research Part D; Transport and Enironment* 10, no. 1: 1-11.

Siemens. 2015. "S70 Low-Floor Light Rail Vehicle: Houston, Texas." Accessed May 5, 2016. http://www.usa.siemens.com/railsystems

Stahl, C. 2015. "Accumulated Surfaces & Least-Cost Paths: GIS Modeling for Autonomous Ground Vehicle (AGV) Navigation." Master's Thesis, Virginia Polytechnic Institute and State University.

Stiles, M. 2014. "Proposed Rail Routes Bypass Afton Oaks Neighborhood." Accessed March 2, 2016. http://www.chron.com/news/houston-texas/article/Proposed-rail-routes-bypass-Afton-Oaks-1548433.php

Texas A&M Transportation Institute. 2014. "Technical Memorandum SUMMARY OF GULF COAST RAIL DISTRICT." Technical.

Texas Department of Transportation. 2014. “Houston District Structures with Low Vertical Clearance.” Accessed May 5, 2016. http://www.txdmv.gov/motorcarriers/low-clearance/item/1779-houston-district-structures-with-low-vertical-clearance

Turner, M., and Duranton, G. 2009. *The Fundamental Law of Road Congestion: Evidence from US cities.* Working Paper, Cambridge: NATIONAL BUREAU OF ECONOMIC RESEARCH.

United States Census Bureau. 2016. “Maps Data” Accessed March 2, 2016. http://www.census.gov/geo/maps-data/data/tiger-line.html

Wang, I., Savage, W., and Shaffer, H. 2009. "Landscape Genetics and Least-cost Path Analysis Reveal Unexpected Dispersal Routes in the California Tiger Salamander (Ambystoma Californiense)." *Molecular Ecology* 18, no. 7: 1-7.

Washington, P. 2015. *RTD Best Practices Report.* Transportation, Denver: Denver Regional Transportation District.

Yakar, F., and Celik, F. 2014. "A Highway Alignment Determination Model Incorporation GIS and Multi-Criteria Decision Making." *KSCE Journal of Civil Engineering* 18, no. 6:1847-1857.

Yu, C., Lee, J., and Munro-Stasiuk, M. 2003. "Research Article: Extensions to Least-cost Path Algorithms for Roadway Planning." *International Journal of Geographical Information Science* 17, no. 4: 361-376.

Zucker, S. 2013. "Midtown and Development: A Love Story." *Houston Business Journal*.