Evaluating Transit and Driving Disaggregated Commutes through GTFS in ArcGIS

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DEDICATION

I’d like to dedicate this paper to my beautiful wife Irina who has been patiently waiting for me to finish. Now that I am done, we can finally go out again.

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LIST OF ABBREVIATIONS

ACS	American Community Survey
DOT	Department of Transportation
GIS	Geographic Information Systems
GTFS	General Transit Feed Specifications
MWCOG	Metropolitan Washington Council of Governments
NCRTPB	National Capital Region Transportation Planning Board
OD	Origin - Destination
TAZ	Traffic Analysis Zone
TCRP	Transit Cooperative Research Program
TDM	Transportation Demand Management
WMATA	Washington Metropolitan Area Transit Authority

ABSTRACT

This research implements an additive travel cost model to calculate and compare the perceived cost of commuting by transit and driving at a disaggregated level. The model uses open source General Transit Feed Specification (GTFS) data and “Yay Transit!,” an ArcGIS tool developed by Melinda Morang and Patrick Stevens of Esri, to create a transit network for the Washington DC metropolitan area. Departure sensitive route paths and travel times on transit are solved through the Route Tool of the ArcGIS Network Analyst Extension and compared to travel data calculated using Waze for driving between similar origins and destinations. Additional travel cost components are plugged into additive cost formulas designed to resemble the mode choice modeling formulas created by MWCOG (Metropolitan Washington Council of Governments) in order to compare the perceived cost of one mode over the other.

Results from this model suggest that taking transit is in general less cost effective than driving for even some of the most transit advantageous commutes. Transportation Demand Management opportunities to most effectively “balance” the perceived cost of transit and driving are identified through assessing variable sensitivity of the additive formula. This research provides a methodology that could be reproduced in mass in order to gage the complex interconnectivity of an urban transportation network. The author suggests hosting this information in an online tool which will assist government and the public in understanding the cost effectiveness of transit versus driving for any given commute situation.

CHAPTER 1 - INTRODUCTION

The daily commute is a significant portion of everyday life for a large number of people. It may be hard to believe, but most Americans spend more time commuting to work than on vacation. The 2011 American Community Survey revealed that the nationwide average one-way commute trip is 25.5 minutes, equivalent to roughly 27 8-hour work days a year. Washington DC, the geographic area of the model, contains even longer commutes second only to New York City. The average Washingtonian spends 34.5 minutes commuting, or roughly 36 8-hour work days a year traveling to work (Chester 2013). On average people will spend roughly one fifth of their total yearly income on transportation (NPR 2012).

Individuals may not always have a choice of where they work, or live where it would be most convenient for their jobs, but they do have the power to choose how they travel to work. In the Washington DC metropolitan area, 76 percent of these individuals choose to ride in a personal vehicle whereas only 14 percent choose to take public transportation (U.S. Census Bureau 2012). The high percentage of commuters who drive and the low percentage of commuters who choose to take transit is a problem that is hazardous to society, the environment, personal health, and the American economy.

The choice to drive a personal vehicle as opposed to traveling by other means is environmentally hazardous to society. Automobile transportation generates greenhouse gases that accumulate in earth's atmosphere and contribute to the onset of global warming. These emissions also are primary culprits of air pollution, which is hazardous to the general population provoking the onset of respiratory ailments like asthma and lung disease, and cardiovascular effects such as cardiac arrhythmia and heart attack (Center for Disease Control and Prevention 2013).

The choice to drive can also be burdensome to an individual's health. People who commute by driving as opposed to public transportation are 72 percent less likely to spend 30 minutes walking than if they took public transportation (Grimshaw 2013). Inactivity linked to long commutes increases the rate of obesity, one of the leading causes of death in the United States (Hoehner, Barlow, Allen, and Schootman 2012). Societal health effects associated with driving extend beyond obesity, to collisions as well. Transit passengers have about 0.10 the traffic casualty (death or injury) rates as automobile occupants (Litman 2012). In the United States over 35,900 people died in car accidents alone in 2009 making it one of the leading causes of preventable death (U.S. Census Bureau 2012).

Driving is not economically sustainable for the future. Road maintenance costs continue to increase as road conditions deteriorate. The American Society of Civil Engineers predicts that maintenance costs will increase from 1.66 trillion dollars in 2011 to 2.75 trillion in 2020 (Economic Development Research Group 2013). Energy demands from oil have continued to put pressure on the American economy. In 2012, the United States imported 40 percent more oil than it exported primarily to feed the growing fuel demands of the country's primary transportation needs (U.S. Energy Information Administration 2013). Health care costs related to the treatment of obesity have skyrocketed partly because of inactivity related to commuting with personal automobile. In 2008, healthcare costs related to obesity reached 147 billion dollars (Center for Disease Control and Prevention 2013).

The desire to design cities around the use of private transportation has negatively affected livability in cities. The decentralization of development caused by the onset of driving has obstructed transit's ability to connect workers to opportunity and jobs (Tomer et al. 2011). The most affected are those who may not have access to a private vehicle, including the poor, the elderly, the young, and the sick. Due to the dominance of driving, cities continue to expand outwards, often consuming precious agricultural lands. In California alone, 538,000 acres have been developed since 1990, 28 percent of which is prime agricultural land (Thomson 2009). Urban sprawl has intruded into ecosystems, disturbed sensitive equilibriums, and destroyed local fauna and flora (Nature Conservancy 2008).

It is evident that the effects of driving are harmful for society, human health, the American economy, and the environment. Unfortunately, these factors do not manifest significantly on an individual's decision to travel to work. The human psyche cannot comprehend the process of accumulation, feedback, time delays, nonlinearity, and other concepts necessary to understand the dynamics of complex systems such as the economy, climate change, societal change, or even health care. Generally, individuals are concerned most with what they can perceive now not what will most probably happen later (Sterman 2011, 811-826). Short-term thinking encourages commuters to favor personal benefit above all in their daily commute decisions. Similarly, like many behaviors routinely performed in everyday life, travel mode decisions are made in a "mindless," automatic fashion. In other words, travel behavior is often habitual (Aarts et al. 1997, 1-14). A lack of such deep thought regarding daily travel decisions makes it a challenge to sway individuals to use alternative travel options.

Through planning, strategies, and policy measures, Transportation Demand Management (TDM) attempts to help individuals make different choices in their daily commute routines. TDM approaches increase the knowledge and personal benefit of using alternative transportation options while also reducing the need to travel in single occupancy vehicles (Richmond Regional Planning District Commission 2004). The TDM toolbox includes strategies to raise awareness of transportation options, control monetary cost of commutes, and provide alternative transportation infrastructures. TDM policies can effectively alter potentially harmful commute patterns by encouraging the consideration of alternative transportation options or directly eliminating these trips. When all costs and benefits are considered, an integrated TDM program that includes an appropriate set of complementary strategies is often the most cost effective way to improve transportation (Litman 2010).

Each TDM strategy has its own inherent opportunities and limitations. In general, TDM strategies complement each other (Seattle DOT 2008). For example providing transit subsidies may not encourage as many users to try transit, but when integrated with a strategy to charge for parking, the combination might well convince people to use transit. This research combines GIS with an additive travel cost model to help identify the effectiveness of TDM strategies to better "balance" the perceived cost of using transit versus driving for sample locations.

The unique contribution of this study is the methodology used to simulate schedule-aware transit trips in ArcGIS. Using open source, free, General Transit Feed Specific (GTFS) data and equipped with the "Transit to GIS" tool "Yay Transit!," developed by Melinda Morang and Patrick Stevens of Esri, the author was able to build a transit network in ArcGIS which incorporates transit routes and schedules. Optimal transit routes sensitive to departure times were found through the application of the Route tool in the Network Analyst ArcGIS extension. Commutes on transit were compared to real-life traffic driving conditions for select origins and destinations. Variables related to optimal mode itineraries were plugged into an additive formula based on the mode choice modeling formulas by MWCOG (Metropolitan Washington Council of Governments) to garner the empirical "perceived cost" of a commute by both transit and driving.

A sensitivity analysis of the model elements was conducted to identify where "balancing" TDM policy measures need to be pursued in order to encourage a higher portion of the population to use transit. Results identified the importance of specific TDM strategies to balance the perceived cost of utilizing transit versus driving for specific Origin-Destination trips included in this model. This research also lays a framework for the development of an online tool which could assist government and the public in understanding the effectiveness of transit versus driving for any given commute situation.

Specifically, the model developed in this research is designed to answer the following questions:

- If you are commuting from residential area X to employment area Y, is it more cost effective to take transit or to drive?
- If it is more cost effective to drive, then what needs to be done in order to improve the convenience of transit for one's travel commute between zone X and Y?
- Given these findings, are there TDM strategies or service improvements that make sense to increase the convenience of transit travel between travel nodes?

This report continues in the next chapter with a review of relevant literature and, in particular, describes in detail the structure and contents of the MWCOG model. Chapter 3 discusses the travel forecast formula developed for this model, the development of a time sensitive transit network on ArcGIS, and the overall methodology used to determine the perceived cost of travel by mode for sample trips. Following this discussion, Chapter 4 summarizes model outputs and determines the sensitivity of components within the travel formula to influence travel costs. Results in this chapter reveal favorable TDM strategies to balance the perceived costs of using transit and driving. Finally, Chapter 5 compares model results with Census data to validate model outputs. This chapter discusses the implications of these results on the region as a whole in terms of the ability of transit to compete with driving and deliberates on limitations with current tools that constrain this model from being executed en masse. If limitations can be overcome, the author proposes to visualize this data through an online application in order to inform the public, the private section, and the government of complex accessibility patterns in the urban environment.

CHAPTER 2 - BACKGROUND

An extensive literature exists about the relationship between mode choice and the factors that influence it. Foremost and underlying most mode choice models, including this one, is that individuals will choose their routes based on Utility Theory. Utility Theory assumes that the decision-maker's preference for an alternative is captured by a value, called a utility, and the decision-maker selects the alternative in the choice set with the highest utility (Ben-Akiva and Bierlaire 1999). This chapter discusses how transportation mode choice models are constructed from Utility Theory.

2.1 Utility Theory Models

Utility in transportation is expressed by the equation:

$$B_T + C_T = U_T \quad (1)$$

Where:
B_T = Benefit of transportation
C_T = Cost of transportation
U_T = Utility of transportation

When considering commuting traveling, given that the destination defines the benefit of the trip, and all transportation choices reach the same destination, one can set the benefit to zero. Therefore one defines the cost of commuting as the utility.

Ben-Akiva and Bierlaire state that utility is comprised of perceived costs, such as travel time, and individual characteristics, such as individual income, that determine one's likelihood of choosing a particular transportation mode. In their research, “Discrete Choice Methods,” they propose the idea that mode choices should contain both a utility function and a probabilistic function:“the complexity of human behavior suggests that the decisions rule should include a probabilistic dimension” (Ben-Akiva and Bierlaire 1999, 5). Their acknowledgement of the analyst's inability to account for all variables implies that there needs to be a measurement of uncertainty within the formula.

Ben-Akiva and Bierlaire describe typical assumptions used within transportation models to determine route choice. Value of time, access to information, and trip purpose are foremost in determining route choice. In addition to those, travel models usually include elements of (1) path length, (2) travel cost, (3) transit-specific elements such as transfers, waiting and walking times, and service frequency, and (4) other variables including traffic conditions, and road types.

The deterministic portion of the utility function, often called the systematic portion, is a simple additive formula of all costs. This part of the formula can include elements related to (1) the attributes of the alternatives, (2) exclusive elements related to the decision-makers, and (3) interactions relating decision-makers and their mode preference (Koppelman and Bhat 2006). As stated by Koppelman and Bhat, the utility formula is represented by:

$$V_{i,t} = V(S_t) + V(X_i) + V(S_t, X_i)$$

Where:
$V_{i,t}$ is the systematic portion of utility of alternative i for individual t
$V(S_t)$ is the portion of utility associated with characteristics of individual t
$V(X_i)$ is the portion of utility of alternative i associated with the attributes of alternative i
$V(S_t,X_i)$ is the portion of the utility which results from interactions between the attributes of alternative i and the characteristics of individual t.

The output of the equation provides a value of cost associated with travel for utilizing the particular mode. A larger output value reflects a less convenient commute whereas a smaller cost reflects a more convenient commute. The difference between formula costs reflects the level of additional convenience for utilizing one mode over the other.

There are several commercial software packages that apply Utility Theory in mode choice to predict future transportation patterns at the Metropolitan or State Level. These programs include Transcad, Emme4, Cube, PTV Vissum, and TranSIM. TransCAD and Cube are amongst the most popular Travel Demand Model programs (Ullah and Molakatalla et al.

2011). These programs analyze traffic flows primarily for principal streets and mode choice at multi-block levels. The models combine existing transportation infrastructures and user characteristics extracted from existing data sources such as the census in order to predict travel flows. These programs tend to be used by Metropolitan Planning Organizations to understand future impacts of changing land use patterns and the effects of transportation investments on transportation patterns.

These programs combine transportation analysis and simulation with GIS. They almost universally use the existing road conditions and networks to simulate true travel times. TransCAD even has the capability to understand data structures for handling transit routes in their natural complexity including giving estimations of wait times, using distinct fare structures, determining shortest path trips, and even predicting future ridership of routes (Caliper.com 2013). These programs allow for a degree of customization of standard or default inputs already integrated into the program. Mode Choice desirability can be dynamic for each individual because as trips are assigned onto the network, congestion increases travel time, making driving less attractive. Additional factors such as demographic information can be assigned to individuals randomly, which generates a varied range of probability between one commuter and another (Ullah and Molakatalla et al. 2011). As is true with most transportation modeling, results are heavily dependent upon the chosen utility function. The following section discusses the utility function that serves as a foundation for the model in this thesis.

2.2 Defining Utility Functions

The determination of utility is foremost to predicting mode choice. Many variations of utility functions have been used to predict mode share at a disaggregate level. As mentioned previously, utility functions include (1) elements related to the attributes of the alternatives,

(2) elements related exclusively to the decision-makers, and (3) interactions relating decision-makers and their mode preferences.

The Metropolitan Washington Council of Governments (MWCOG) in partnership with AECOM has developed a travel forecast model that incorporates utility functions of perceived commute costs in order to determine mode share (National Capital Region Transportation Planning Board 2013). The extent of this model includes the capitol region area including the District of Columbia, neighboring parts of Maryland, Virginia, and one county in West Virginia. The most recent update of this model, in 2013, calibrated variables to 2010 conditions. The formulas applied in the MWCOG forecast model use the following variables to determine mode perceived commute costs:

- Travel time for each mode,
- Travel cost for each mode,
- Accessibility of mass transit,
- Automobile ownership, and
- Proximity to carpool lanes.

A significant amount of resources has been spent to develop the MWCOG model; this model is customized specifically to the Washington DC region. Due to the overlap in geographic area, the MWCOG model heavily influenced the design of this study. The remainder of this chapter reviews the structure and components of the MWCOG model in order to lay the foundation for discussion of this study’s model later in the next chapter.

2.2.1 Travel Time Cost

In an article titled a “Theory on the Allocation of Time,” Becker (1965) argues that time in itself is a resource because it allows the consumer to increase their allocation of money. He believes that time should be closely linked to money (Becker 1965). Since it is in the decision-maker’s interest to be able to compare time costs to monetary policy, many studies have evaluated the cost of time (Litman 2013). In the case of the MWCOG Travel Forecast Model, planners believed that the most appropriate value for time would be decided by income and purpose of trip. The following table is from the user manual of the MWCOG Travel Forecast Model.

Table 1: Value of Time by Purpose of Trip and Income (NCRTPB, 2013).

Household Income	Midpoint of Household Income	Hourly Rate per Worker (1)	Time Valuation (Minutes per Dollar)	
			Work Trips (75% Value of Time)	Non-work (50% Value of Time)
$ 0 - $ 50,000	$25,000	$9.23	8.7	13.0
$ 50,001 - $100,000	$75,000	$27.70	2.9	4.3
$100,001 - $150,000	$125,000	$46.17	1.7	2.6
$150,001 +	$175,000	$64.64	1.2	1.9

Notes:
(1) Hourly rate based on 1,920 annual hours/worker * 1.41 workers/HH = 2707.2 hrs/HH

Travel time cost in the MWCOG model varied based on the wealth of the trip maker and whether the trip was work related or non-work related. As income increases and the value of time increases, less minutes are valued to a dollar resulting in a drop for the “time valuation” column. The hourly rate per worker was derived by dividing the total number of hours worked by a household (2707.2) by the Midpoint Household income. The “Valuation of Time” column was derived by taking the hourly rate and multiplying it by the value of time for the trip type. This was then divided by 60 to get the number of minutes valued for each dollar.

MWCOG planners determined that all commute trips should be valued at 75 percent of a workers wage whereas all non-commute trips would be valued at 50 percent of a commuter’s value of time. In the model, the value for one’s commute is greater than the recommended value of 50 percent by the U.S. Department of Transportation (DOT) and the summary of literature identified within this memo (Belenky 2011).

The U.S. DOT memo and Litman advocate increasing the value of time for walking and waiting components on transit trips. This is addressed in the MWCOG model which explicitly states (NCRTPB 2013, 172):

- Drive access time: Equal to 1.5 times the in-vehicle time
- Walk access time: Equal to 2.0 times the in-vehicle time
- Other out-of-vehicle time: Equal to 2.5 times the in-vehicle time
- In-vehicle time for transit has no additional weight therefore it is equal to the value of time itself.

For driving trips, the MWCOG model also adds to their simulated perceived cost a parking penalty which represents the amount of time it takes to park one's vehicle at the destination. This can be between 1 and 8 minutes and is calculated as a direct function of the trip end employment density. The link between density and time is a result of the assumption that denser areas tend to have less parking spaces and more demand for parking. As a result, finding parking becomes more difficult and time consuming. Table 2 is taken directly from the MWCOG model and identifies the parking penalty by employment density.

Table 2: Parking Penalty Time (NCRTPB, 2013).

Employment Density Range (Emp/Sq. Mi.)	Parking Penalty (Minutes)
0 - 4,617	1
4,618 - 6,631	2
6,632 - 11,562	4
11,563 - 32,985	6
32,986 +	8

2.2.2 Out of Pocket Cost by Mode

Out of pocket costs are the direct monetary burdens put on the traveler to get from their origin to their destination. Out of pocket costs for driving include operational and parking costs, whereas transit out of pocket costs include primarily the fare one must pay to ride transit.

2.2.2.1 Out of Pocket Cost for Driving

Within the MWCOG model, vehicle costs include parking, tolls, and operational costs comprised of fuel, oil, maintenance, tires, and wear and tear. Vehicle ownership, vehicle registration fees, and insurance are not considered within the cost of driving.

The MWCOG model sets the total out of pocket vehicle cost at 10 cents per mile. Other research suggests higher rates for the cost of driving. In 2013, the American Automobile Association estimated a total of 21.9 cents cost per mile (AAA 2013). This amount is calculated from a fuel cost of 3.46 dollars per gallon and an average fuel efficiency around 23 miles per gallon. Gary Barnes and Peter Langworthy in their study "Per Mile cost of Operating Automobiles and Trucks" used a cost of 19.1 cents per mile in city. This value was found in 2003 when the price of gas was $1.50 and accounted for only 50 cents of the total operating cost of driving a vehicle (Barnes and Langworthy 2003).

Parking cost is a major component of driving costs. The MWCOG model correlates parking cost directly to the employment density of the end destination. This relationship was determined based on 2007/2008 Housing Travel surveys that linked the price of parking to the one mile floating employment density of the location (half mile radius from site). The regression formula below was created for the MWCOG model. This model was last calibrated in 2010.

$$\text{Parking Cost} = 2.1724 * \text{Ln}(\text{Floating Employment Density}) - 15.533 \qquad (2)$$

2.2.2.2 Out of Pocket Costs for Transit

Transit costs for users consist of the complete fare paid by a patron to use transit. This value contains the combined value of travel on all transit links and is dependent on the transit operator fare rules. For example, in the Washington DC region, trips connecting to or from Metrorail will receive a $.50 reduction on the fare paid for the second link. Bus to bus transfers on the WMATA system automatically acquire free transfers as long as the transfer is within 2 hours. Also, the MWCOG model automatically adds an additional parking fee if transit trips are accessed by driving to park and ride facilities.

2.3 Building the Network

MWCOG uses two networks to simulate multimodal traffic flows in the region, the highway network dataset and the transit network dataset. Full documentation of these network datasets are publically available online (National Capital Region Transportation Planning Board 2010). The highway network dataset consists of highways, arterials, collector streets, and some local roads. That model uses TAZ's (Traffic Analysis Zones) for trip origins and destinations and therefore does not include many local roads. Traffic flows are modeled between TAZ along primary roads. The model uses historical traffic data in two time periods, peak and non-peak, to calculate travel times.

The transit network data model is made up of Transit-only links, Transfer links, Transit service times, and Transit fares. It contains operation and spatial data for approximately 1,000 routes during the peak period and 700 routes during the off-peak period. Spatial data came from operators directly, or through manual entry of paper transit schedules. Transit operations for peak hour consists of operational conditions between 7:00 – 7:59 AM whereas non-peak hour transit operations reflected operation conditions between 10:00 AM – 3:00 PM.

Operational conditions associated with the network include the headway and speed of transit vehicles. The average headway consists of the time in-between trips used to understand wait time conditions. The average speed of a link is derived by taking the entire route time and dividing it by the distance of the route. This speed allows the model to understand the in-vehicle time between two points within a transit line.

It is worth highlighting that the MWCOG model does not utilize the complexities of true travel conditions for transit and lacks the capability to analyze mode attractiveness at a disaggregate, single address location. The MWCOG model generalizes transit operations by assuming a constant speed throughout the entire route irrelevant to individual road link speeds. Furthermore, because the MWCOG transit network is connected to an incomplete road network, MWCOG cannot model disaggregate trip behavior, only aggregated travel patterns from one TAZ to another. These key deficiencies are addressed in the model created within this research.

The 2010 transportation network development guide for MWCOG model notes the potential for use of General Transit Feed Specification (GTFS) data in the future. Directly taken from the document they state:

> WMATA has posted information about WMATA transit routes in the open [General] Transit Feed Specification (GTFS). Staff imagines that future programs written to summarize bus run times and headways by time-of-day period would be written to take advantage of these files. If other transit providers also provide their schedule data in GTFS format, we would have a common format across providers and could develop one program which could handle all of the transit providers (instead of a separate program for each provider). (NCRTPB 2010, 49).

This data, which is incorporated into the model developed in this research, is discussed in greater detail below.

2.3.1 General Transit Feed Specification (GTFS)

General Transit Feed Specification (GTFS) defines an open, common format for public transportation schedules and associated geographic information. GTFS "feeds" allow public transit agencies to publish their transit data and developers to write applications that consume that data in an interoperable way (Google Developers 2012). WMATA and Ride-On Transit who provide the majority of transit service within the National Capital Region offer this type of information. Walk Score (Walkscore.com) and Google Transit are two applications that take advantage of GTFS data to specify transit operations.

Although GTFS data is relatively new, tools by Esri have already been created to translate GTFS data into a network which reflects transit operational conditions. “Yay Transit!,” developed by Melinda Morang and Patrick Stevens of Esri, facilitate the importation of GTFS data into ArcGIS Network Analyst. Specifically, the “Add GTFS to a Network Dataset” toolbox, contains the programing and documentation necessary to replicate operational transit conditions in ArcGIS (Yay Transit! 2013). Use of this toolbox is discussed in greater detail in the next chapter.

Having outlined the components of the MWCOG model that provides an essential foundation for transportation modeling in the Washington area, I now turn to a detailed description of the structure of my model developed in this research.

CHAPTER 3 - MODEL DESIGN

The objective of this model is to compare, at a disaggregated level, the convenience of driving a car versus taking transit. The model determines the effective connectivity of the highest density employment and residential nodes in the region during the peak hour and identifies where transit does not serve as a convenient commute option compared to driving. Although sophisticated tools for modeling transit behavior exist such as Cube by Citilab or Transcad by Caliper, this model demonstrates that similarly useful results can be obtained by using general-purpose tools and open access data. This model uses the Network Analyst ArcGIS extension and open source transit data to simulate transit operations on ArcGIS and uses excel to disaggregate travel costs.

As stated in the introduction, this model attempts to answer the following questions:

- If you are commuting from residential area X to employment area Y, is it more cost effective to take transit or to drive?
- If it is more cost effective to drive, then what needs to be done in order to improve the convenience of transit for one’s travel commute between zone X and Y?
- Given these findings, are there TDM strategies or service improvements that make sense to increase the convenience of transit travel between travel nodes?

The design of the model is discussed within this chapter. Chronologically, this chapter explains:

- The development of the travel model formula,
- The procedure used to determine the sample employment and residential locations,
- The methodology used to set up the transit network in ArcGIS,
- The manner in which transit paths within the transit network were solved in order to obtain variable inputs, and
- The method for obtaining car model variables.

3.1 Developing the Travel Model Formula

The core component of this model is the formula used to estimate the disaggregated cost incurred by a commuter traveling from location X to location Y. Selected variables and their associated parameters are strongly based on the MWCOG Travel Forecast Model. The following travel formulas were used to estimate mode choice perceived cost for one's commute:

For Transit:

$$\text{Total Dollar Cost} = pVT \times [\, pW \times (WT + W2T^*) + pWa \times (WaT + W2T^*) + pIV \times (IVT + IVT2^*)] + Fare + Fare2^* \qquad (3)$$

Where:

pVT = Value of Time Parameter
pW = Walk Parameter
pWa = Wait Parameter
pIV = In Vehicle Parameter
WT = Walking Time
WaT = Waiting Time
IVT = In Vehicle Time
W2T* = Walking Time for transfer
Wa2T* = Waiting Time for transfer
IVT2* = In Vehicle Time for transfer
Fare = Fare Cost
Fare2* = Fare Cost of Transfer
*If necessary

For Car:

$$\text{Total Dollar Cost} = pVT \times [\, DT + KT \,] + pCM \times DD + KC \qquad (4)$$

Where:

pVT = Value of Time Parameter
pCM = Cost per Mile Parameter
KC = Parking Cost
DT = Drive Time
KT = Parking Penalty Time
DD = Drive Distance

The cost functions for Transit and Car are comprised of sums of incurred financial and perceived costs (related to trip time duration). All elements beginning with a p are parameters which are constant throughout the model whereas all remaining elements are variables which change value for each commuting trip.

Parameter values are, in general, based on those used in the MWCOG model, however, in some cases they have been modified based on research discussed in the previous chapter. As is suggested within the U.S. DOT memo and implemented within the MWCOG travel model, different weights were used for each component of the transit trip in order to account for the perceived cost of each travel activity. In the model, the walking component of the transit trip was weighted at twice the actual time (thus pW = 2), the waiting time of the transit trip was weighted at 2.5 times the actual time (pWa = 2.5), and the in-vehicle time consisted of the actual time on the bus or train (pIV = 1). These parameters are identical to those used within the MWCOG model. These values are multiplied by the time of travel for each component of the transit trip in order to obtain the weighted travel time of the trip.

The fare cost (Fare) consists of the out of pocket cost of travel between the starting and ending point. Walking times (WT), waiting times (WaT), in-vehicle times (IVT), and fares for each additional connection (termed transfers) within the travel route are added as needed. All access to transit is assumed by walking in order to ignore any cost incurred by parking or driving to the transit station. This was done to simplify the execution of the model.

As noted in the previous chapter, Litman (2013) and Belenky (2011) argue that travel time cost (pVT) is a direct function of income. Travel time cost for this model was derived by using the Washington DC area median household income for 2013 from the U.S. census at 84,523. Similar to the procedure of the MWCOG model (see Table 1 above), individual median income was derived from the median household income and divided by the average hours worked by household (2707.2 = 1920 hours per worker * 1.41 workers per household). This value was then multiplied by 50 percent instead of 75 percent as used in the MWCOG model. This modification was chosen due to the overwhelming amount of research found by the U.S.

DOT (2011) and Litman (2013) which argues that travel time cost for commute trips reflect more closely 50 percent of one's income. This rendered a pVT value of $.26 cents per minute.

It is worth noting that travel time for this model was kept as a constant parameter even though different origins contain distinct median incomes. This was done on purpose to measure the effectiveness of current transit service regardless of origin or TAZ income. For example, two adjacent neighborhoods with distinct incomes, but identical travel paths could render different results even though they share the same travel path. One could conclude that one neighborhood has stronger access to transit than the other, but by no means would this result hold true. By turning time into a parameter, it allows for a more effective comparison of transit services.

Similar to transit, car utility consists of values for time and out-of-pocket costs. The values for time include the time it takes to drive from the origin point to the destination (DT) and the parking penalty time (KT). The time it takes to travel from the origin to the destination reflect real travel times based on traffic congestion conditions. To model here, this data was manually obtained by running origin-destination queries on Waze.com, a crowdsourced traffic navigation application owned by Google. The parking penalty time was extracted directly from the MWCOG travel model table for parking penalty, included above as Table 2.

The variables for the out-of-pocket cost of driving a vehicle include the operations cost for using the vehicle (pCM) and parking costs (KC). As noted in the previous chapter, according to AAA, in 2013 the operating cost of driving a vehicle per mile is 21.9 cents. This value was much higher than the 10 cents per mile cost used by the 2010 MWCOG Model. Thus in this model, pCM is set at 21.9 cents per mile is used.

Parking cost was calculated for each destination using the equation used in the MWCOG model introduced in the previous chapter. These calculated prices were checked against current daily parking cost values published online through parking applications such as bestparking.com and the local bureau of commerce website. While parking fees found online were higher than those used in the MWCOG model, these are not representative of what commuters are paying for parking due to the fact that employers may be subsidizing their parking costs. Therefore, it was decided to keep the MWCOG parking cost calculation.

In addition to travel time and travel cost, the MWCOG model also includes functions that influence travel demand including transit accessibility, automobile ownership, and proximity to carpool lanes. These functions from the MWCOG model were not added to this model. This model assumes transit accessibility throughout the study area, which will be discussed later in this chapter. Furthermore, this model presumes that a vehicle is available to compete with a transit trip. Carpool access is ignored because this model does not attempt to calculate or model carpool behavior.

Ben-Akiva and Bierlaire stated in their research, “Discrete Choice Methods,” that mode choices should contain both a utility function and a probabilistic function. This model does not contain a probabilistic function, because this model does not attempt to predict travel flows, but instead, measure the overall cost of travel for different travel modes. The model does not attempt to suggest human behavior, it measures the effectiveness of current transportation infrastructure. By adding a probabilistic function, compiled results would obscure prominent cost trends within the model and make individual trips difficult to compare to each other.

In summary, Table 3 below identifies the data sources for variables and parameters used to solve the disaggregated cost of travel by mode:

Table 3: Summary of Variables Used Within Travel Model.

For Transit:

Given by Equ (3): Total Dollar Cost = pVT x [pW x (WT + W2T*) + pWa x (WaT + W2T*) + pIV x (IVT + IVT2*)] + Fare + Fare2*

Symbol	Variable/Parameter	Source
pW	Walking Parameter = 2	MWCOG Model
pWa	Waiting Parameter = 2.5	MWCOG Model
pIV	In-Vehicle Parameter = 1	MWCOG Model
WT	Walking Time	ArcGIS Network Analyst; Google Transit
WaT	Waiting Time	ArcGIS Network Analyst; Google Transit
IVT	In Vehicle Time	ArcGIS Network Analyst; Google Transit
W2T*	Walking Time for transfer	ArcGIS Network Analyst; Google Transit
Wa2T*	Waiting Time for transfer	ArcGIS Network Analyst; Google Transit
IVT2*	In Vehicle Time for transfer	ArcGIS Network Analyst; Google Transit
Fare	Fare Cost	Manually Obtained from Transit Website
Fare2*	Fare Cost of Transfer	Manual Obtained from Transit Website

For Car:

Given by Equ (4): Total Dollar Cost = pVT x [DT + KT] + pCM x DD + KC

Symbol	Variable/Parameter	Source or value
pCM	Drive Cost Per Mile Parameter	.219 cents/mile (AAA Recommended)
DT	Drive Time	WAZE.com
DD	Drive Distance	WAZE.com
KT	Parking Penalty Time	See Table 2
KC	Parking Cost	Parking Cost = 2.1724* Ln (Floating Employment Density) – 15.5333

For Both:

Symbol	Variable/Parameter	Source or value
pVT	Value of Time Parameter	.26 cents/minute (50 percent of individual income for Washington DC median HH income)

3.2 Determining Origin and Destination Samples

Once the travel formula was developed, the next step is to identify the origin and destination locations to be studied. The Washington DC metropolitan area is an expansive region that incorporates 4 states and 22 counties. Within this region, a sample of origin and destination points were chosen from within the inner beltway region, all of which are generally urban in development characteristics. Tysons Corner was added to the sample area even though it lies outside of the beltway because of its high concentration of jobs, over 100,000 as of 2014. The sample area was chosen in this manner to simplify the number of transit operators that need to be simulated in ArcGIS. Furthermore, selecting the inner beltway region (and Tysons) fortifies the assumption that respondents have access to transit for both their origin and destination. Figure 1 shows the study area within the context of the greater Washington Metropolitan Region.

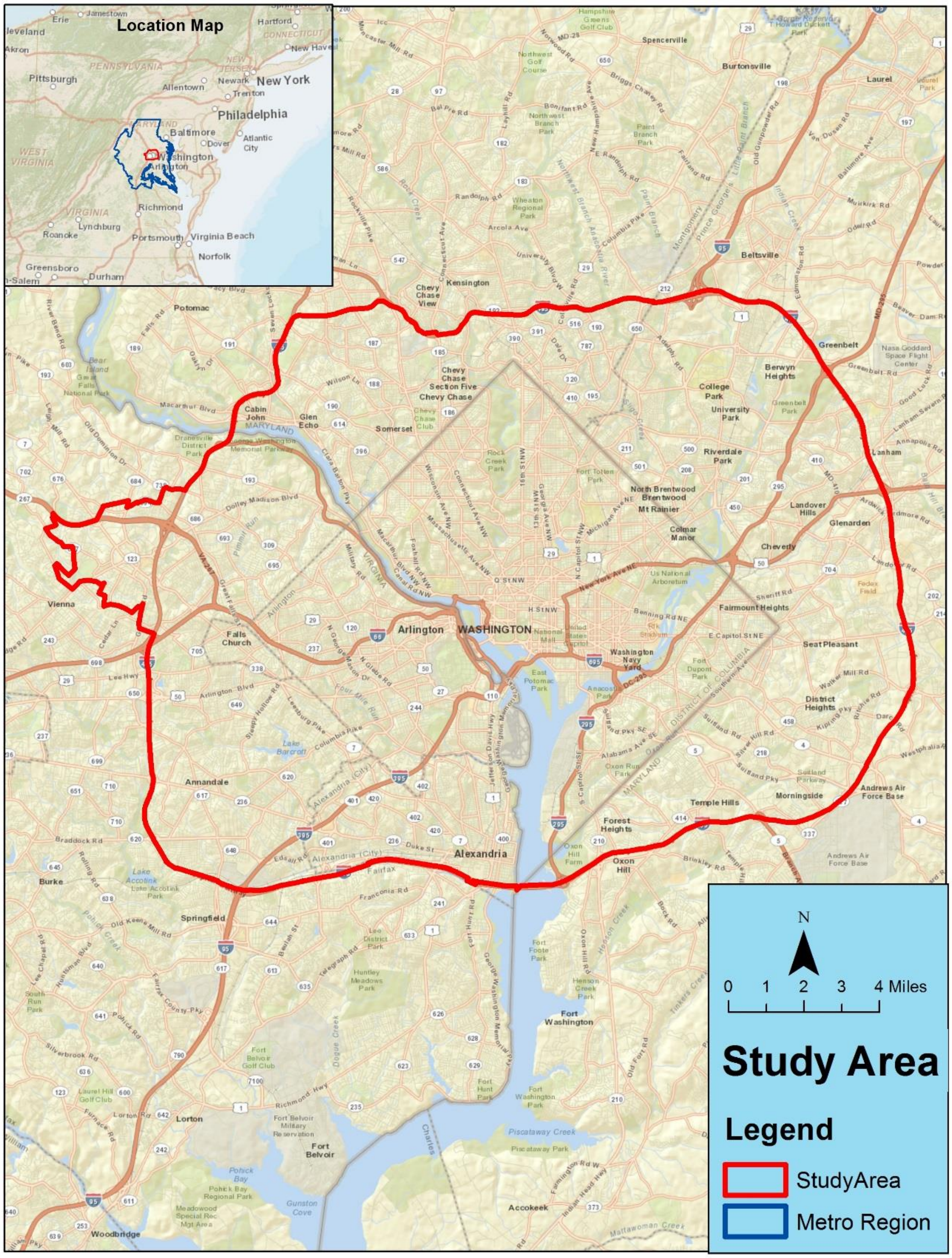

Figure 1: Study Area. Inner Beltway Area of the Washington DC Region.

Traffic Analysis Zones (TAZ) were used to choose origins and destinations in the region. On request, the most recent TAZ shapefile (last updated in 2013) was provided by MWCOG. These are the same files that are used for input by the MWCOG Travel Forecasting Model. This shapefile contains current and projected employment and population values in five-year increments out to 2040. TAZ's were used in this model because they are the smallest geographic units which contain population and employment data. In return, this allows for more detailed analysis of demographic information.

High Density locations for 2015 population and employment were used to determine the sample origin and destination locations used in this model. Density was found for each TAZ by dividing the overall population or employment number by its area in square miles. A hotspot analysis followed to identify areas of significantly high residential or employment densities indicating residential hubs or employment centers. A distance band of 1,878 meters identified through the Average Nearest Neighbor tool was inserted into the distance band of the hot-spot analysis. Both the Hot-Spot analysis and the Average Nearest Neighbor analysis used Euclidean distances. Figures 2 and 3 display the hotspot analysis conducted for 2015 population and employment data using a distance band of 1,878 meters.

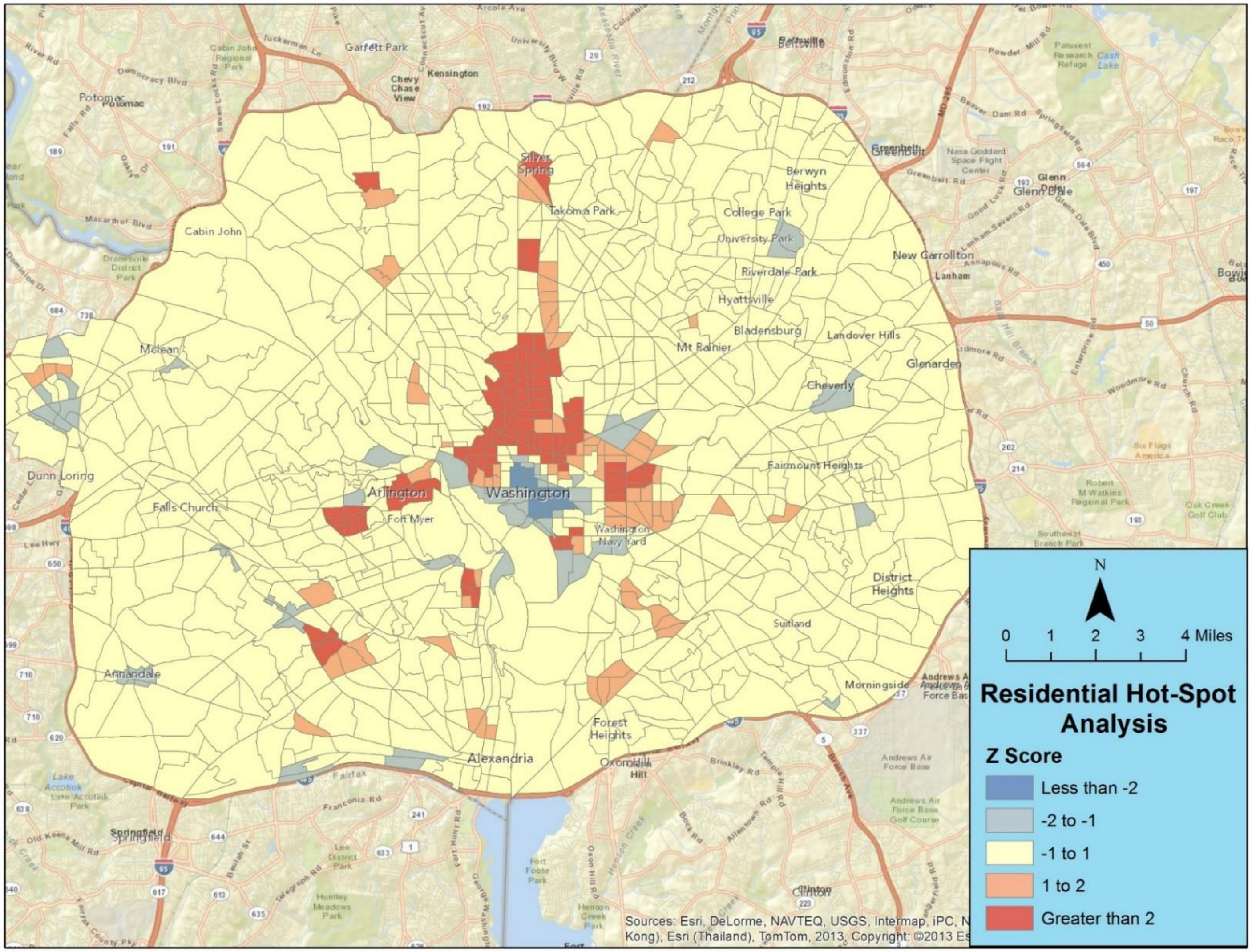

Figure 2: Residential Hot-Spot Analysis. The Z Score indicates the significance of local density. The red areas have high residential density whereas the blue areas have low residential density.

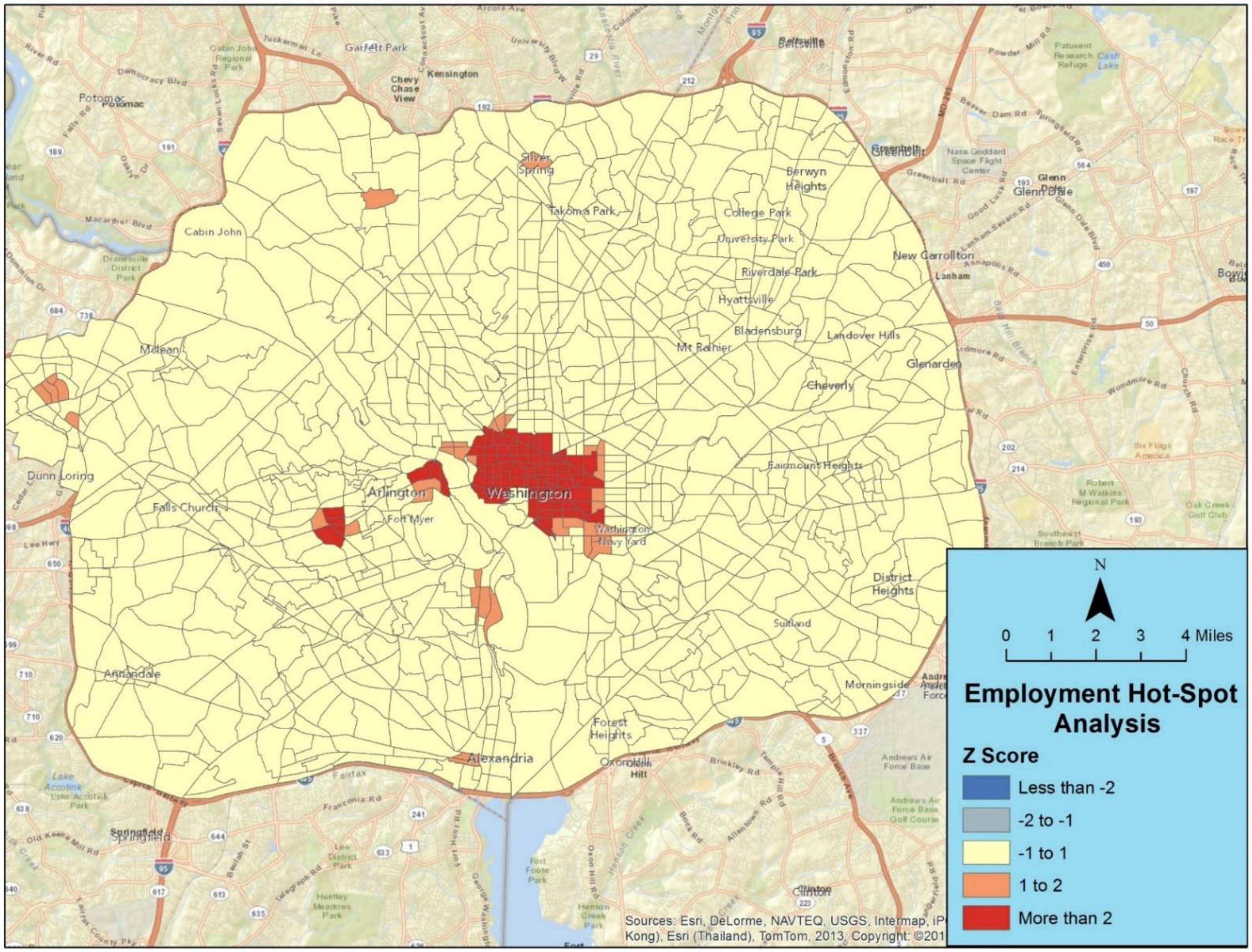

Figure 3: Employment Hot-Spot Analysis. The Z Score indicates the significance of local density. The red areas have high job density whereas the blue areas have low job density.

The residential hot-spot analysis revealed several significant residential hubs in Downtown DC, Ballston, Arlington, Crystal City, Silver Spring, and Capitol Hill. Less significant residential cores also appeared in Bethesda, Southwest DC, Alexandria, and Brightwood. Employment cores appear in Downtown DC, Rosslyn, Ballston, Crystal City, Tysons Corner, Alexandria, Bethesda, and Silver Spring.

Continuously significant TAZ's were manually grouped together into neighborhoods. The first six residential neighborhoods and the first five employment neighborhoods were selected based on TAZ's with the highest Z scores in the region. The centroid of each neighborhood was chosen for the start (high density residential areas) or end point (high density employment areas) of study trips. Figures 4 and 5 display the chosen origin and destination neighborhoods and their associated centroids which also serve as the sample origins and destinations. These centroids were reverse geocoded on Google Maps to find the exact address corresponding to the location on the map. Table 4 provides the exact address for each origin and destination point. This thesis selected locations based on TAZ density, but ultimately, the methodology designed for this model can be applied to compare the attractiveness of transit and driving for any two points within the study area.

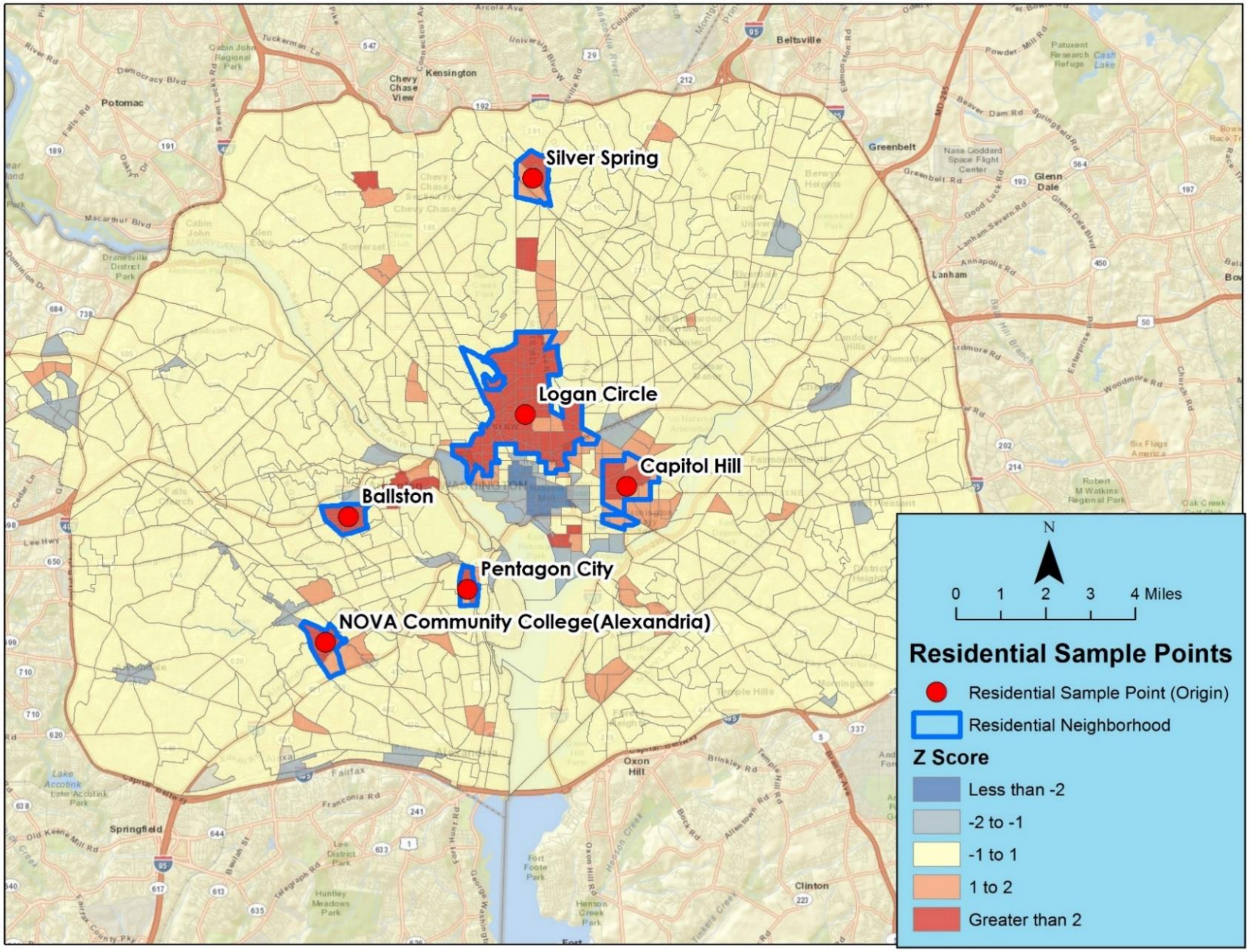

Figure 4: Selected Residential Sample Points. The centroid of each neighborhood determined the sample point. Sample origins selected include: Washington DC (Logan Circle), Capitol Hill, Pentagon City, Ballston, and NOVA Community College (Alexandria).

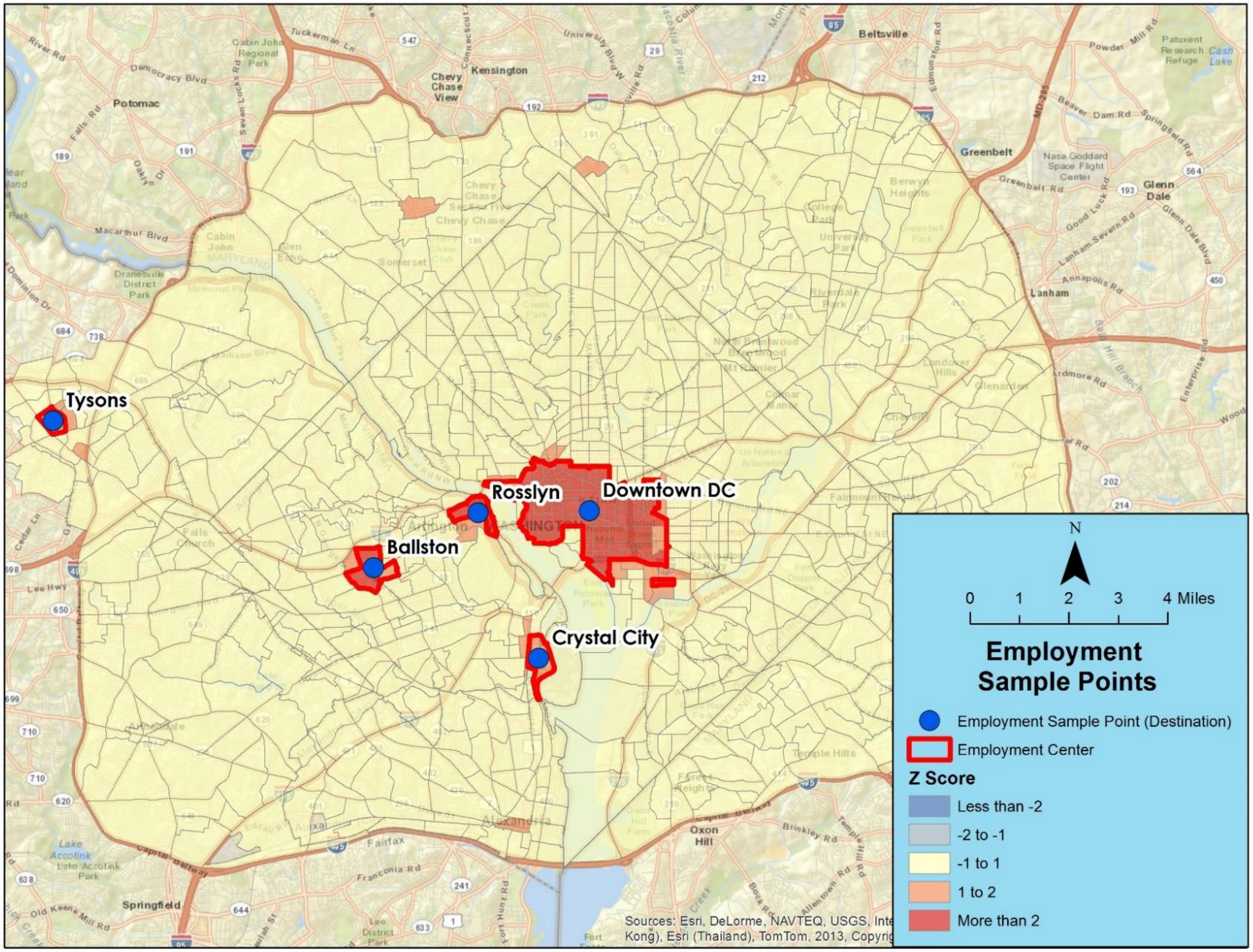

Figure 5: Selected Employment Sample Points. The centroid of each neighborhood determined the sample point. Sample destinations selected include: Washington DC (Near White House), Crystal City, Rosslyn, Tysons, and Ballston.

Table 4: Exact Addresses for Sample Locations.

Residential (Origin)	
Downtown DC (Near Logan Circle)	1820 14th Sr. NW Washington DC 20009
Ballston	3835 9th St N, Arlington, VA 22203
Pentagon City	1698 S Fern St, Arlington, VA 22202
NOVA Community College (Alexandria)	Dawes Ave & Campus Ln E, Alexandria, VA
Capitol Hill	150 12th St NE, Washington, DC 20002
Silver Spring	1305 East-West Hwy, Silver Spring, MD 20910

Employment (Destination)	
Downtown DC (Near White House)	555 13th St. NW, Washington, DC 20004
Rosslyn	1817 N Moore St. Arlington VA 22209
Ballston	4200 Wilson Blvd. Arlington VA 22101
Crystal City	2345 Crystal Dr, Arlington, VA 22202
Tysons	8214 Greensboro Dr, McLean, VA 22102

The origin and destination points in Table 4 are the points studied for mode convenience. Values for each of the variables discussed in the travel formulas of the section prior were determined for all trips between each of these origins and destinations in order to find the perceived cost of each trip. In order to do this, the next step in this model consisted of creating a transit network to model the trips between selected points.

3.3 Designing the Transit Network

Until recently, it has been difficult to represent the complexities of transit operations in GIS. Transit operations function beyond points, lines, and polygons; as Martin Catala noted during his address to the audience at the Transit and GIS 2013 conference; transit has a geographic component as well as temporal and network components which are complex in nature (Catala 2013). Fortunately, as of 2012, a standard transit format has been designed to translate and communicate complex transit operations into GIS applications. This new type of data is called General Transit Feed Specification Data (GTFS). With the assistance of the toolset, "Yay Transit!," designed by Melinda Morang and Patrick Stevens, the author was able to translate this GTFS data into a transit network in ArcGIS which captures the functionality of transit operations in the region.

GTFS data summarizes transit run times and headways by time-of-day through easily translatable data types. The typical GTFS dataset is required to contain text files which store operational information by date, route trip departure times, route stop sequences, geographic information related to transit stops and routes, and the exact time at which each stop is served by each scheduled transit vehicle. GTFS data was obtained for WMATA, the predominant transit operator in the study area, directly from the WMATA website. The data used was released on January 21st 2014 and included operational data on Metrobus, Metrorail, and the DC Circulator. Due to abundant service in Tysons Corner, the Fairfax Connector was also built into the transit network. This data was obtained directly from the Fairfax County website, but had no specific production date indicated on the website. Even though multiple transit providers were included in the data, it is worth noting that all providers were integrated into one network.

"Yay Transit!" GIS tool translates the data contained within multiple GTFS text files into simulated operational transit data within ArcGIS. The package contains tools to build the spatial component of the transit network and to interpolate temporally conscious transit operations. The download package to build the network dataset comes with two toolboxes each with tools that perform specific tasks necessary to build the transit network dataset. Figure 6 depicts the content within each toolbox obtained from the Yay Transit! free download package used to develop the network dataset. Detailed step-by-step instructions on how to build the transit network are included in the Yay Transit! website.

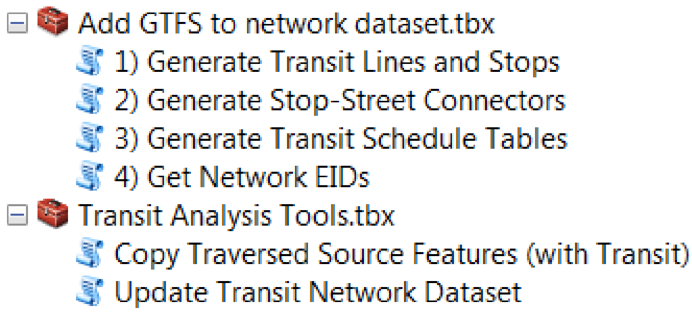

Figure 6: Yay Transit! ArcGIS Tool Contents.

The resulting transit network dataset contains three distinct layers and two node layers to capture the process of travel on transit. The first level of the transit network dataset is the road network which theoretically includes all walkable segments in the network. All origin and destinations were snapped to this road network through a setting in the Network Analyst extension. This was done because all origins and destination points can only be accessed from the street and not, for example, while riding a bus. The road network dataset used to build the transit network came from the 2013 Esri roads shapefile which is available for download directly from Esri. It should be noted that not all segments in this shapefile are walkable and not all walkable segments are included in the shapefile, but for simplification purposes, it is assumed that all links on the road network can be walked and links within the shapefile are the only feasible walking links.

The second level in the network are the transit links. These are the links one would theoretically travel while riding the bus or Metrorail. It is essential that the transit lines and road shapefile reside on different levels because pedestrians can only enter or exit the transit system by way of a transit stop. This dataset was produced by the "Create Transit Lines and Stops" tool located within the "Add GTFS to Network Dataset" toolbox. As the name implies, this tool georeferences all stops, and creates connector lines between stops in sequence served by a transit trip. Transit stop locations are produced by latitude-longitude coordinates stored in the GTFS data which originate directly from the transit operator who creates the data. Lines that connect transit stops are in the form of straight lines and do not reflect the actual geographic path the transit vehicle would traverse. The final product is a transit dataset network containing 13,795 transit stops and 16412 transit links. Figure 8 illustrates the transit network in its entirety.

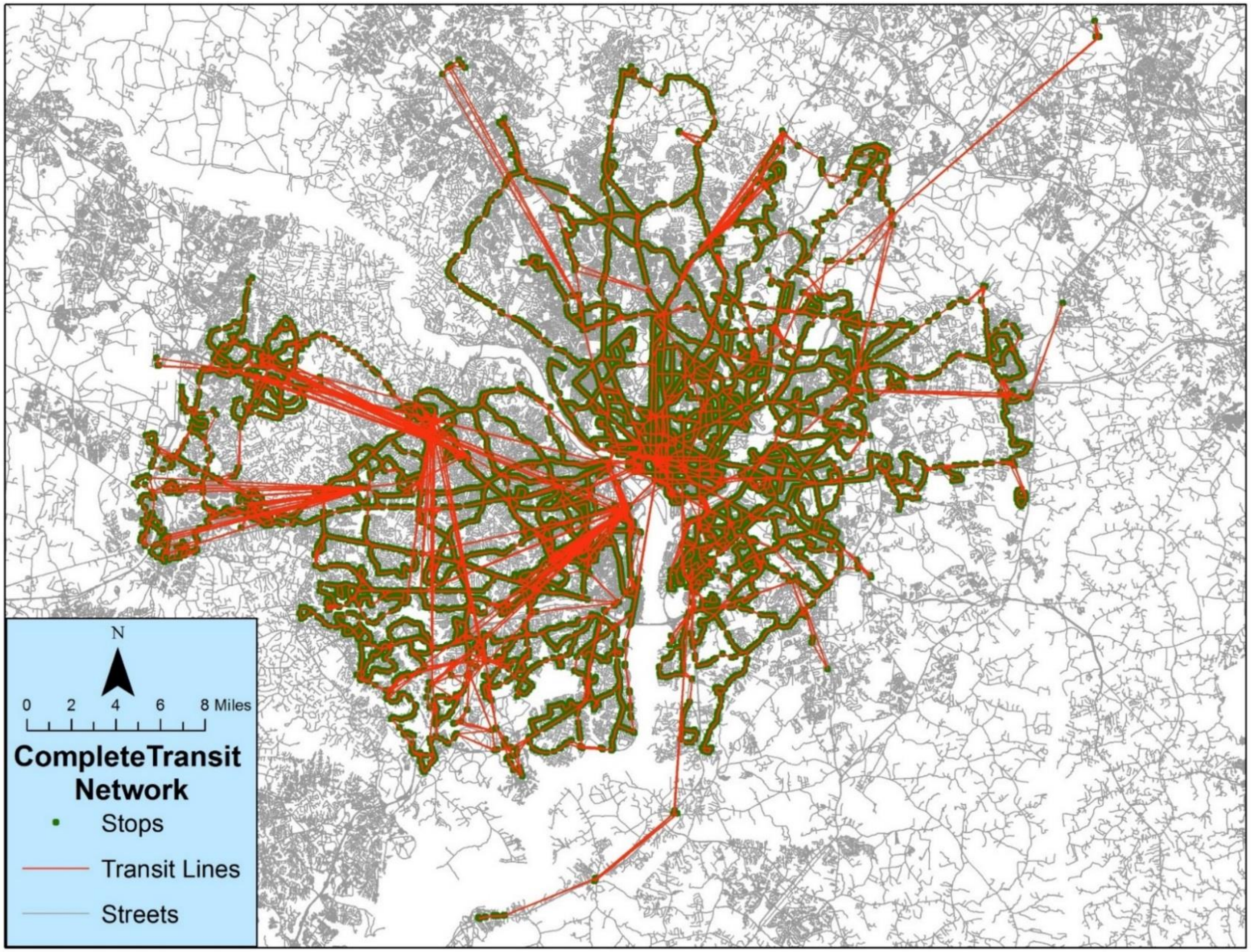

Figure 7: Complete Transit Network. The long straight lines are express or limited service transit routes. The "Create Transit Lines and Stops" tool connects sequential transit stops with a straight line. The long lines occur because the subsequent transit stop served by the route is in a different part of the region.

Connector lines, the third level in the transit network allows for the transfer between the road layer and the transit layer. In terms of real-life transit travel steps, the transfer between the road layer and the transit layer represented in this dataset is comparable to boarding or exiting the transit vehicle. Connector lines are a figurative step in transit travel and do not represent actual geographic travel. Connector lines link with the transit system at transit stops and link with the road network at the nearest street segment from that stop. Stops are rarely on the road network because the road network represents the centerline of the road and stops are usually located on the sidewalks away from the street centerline. This layer is produced through the "Generate Stop-Street Connectors" tool found within the "Add GTFS to Network Dataset" toolbox. A detailed sample of the transit network is shown in Figure 8.

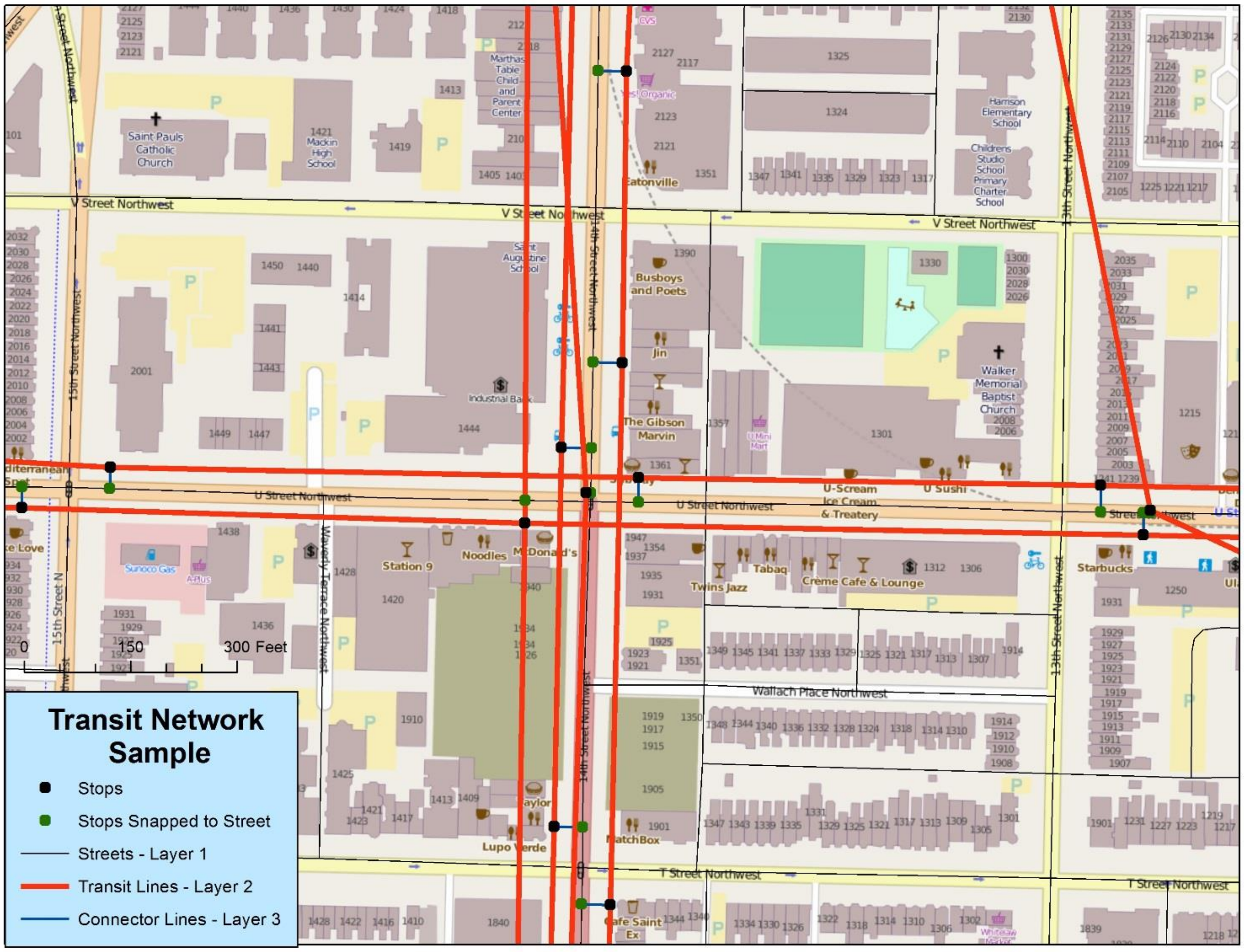

Figure 8: Transit Network Sample. The transit network dataset contains three layers (Street Layer, Transit Layer, and Connector Layer) and 2 nodes (Stops and Stops Snapped to streets).

Temporally conscious route queries are possible through the “Transit Evaluator,” a separate program which understands the transit schedules stored within the GTFS data and applies them to segments on the transit network. This program tells ArcGIS how to calculate the travel time across elements in the transit network dataset when solving a Network Analyst problem. Without this tool, solving for travel time within the travel network is not possible.

To confirm that this network as constructed was valid and that Network Analyst solutions were accurate, trips were tested versus trips on Google Transit. Routes between sample points generated using both systems produced results similar in itinerary and travel time. Unfortunately, Fairfax Connector and DC Circulator routes could not be verified against Google Transit results because Google Transit currently does not host transit operations data for the Fairfax Connector or DC Circulator. Given the good correspondence in the other sample tests, it was concluded that the transit network as constructed is a valid model.

Due to this methodology, limitations in the MWCOG model's ability to simulate transit operations at the disaggregate level has been eliminated. The MWCOG model generalizes transit operations by assuming a constant speed throughout the entire route irrelevant to individual road link speeds. Furthermore, these speeds relate to travel conditions during one hour of the day. Because the MWCOG transit network is connected to an incomplete road network, MWCOG cannot model disaggregate trip behavior, only aggregated travel patterns from one TAZ to another. In contrast, this model uses the exact time at which a transit vehicle arrives or departs a stop and does not generalize operational conditions for one snapshot in time. This model utilizes an up-to-date detailed road network and therefore has the capabilities to model the intricacies of a disaggregated trip departing at a specific time and date. The model has the sensitivity to address different travel times based on small changes in departure times.

3.4 Creating Travel Paths to Solve Transit Variables

Once the transit network was built, trips were solved through the ArcGIS's Route Analysis tool, part of the Network Analyst package. This tool allows the GIS to identify the quickest traveled transit route in the network one can immediately take between the selected origin and destination. The route analysis tool has the flexibility to change the specific date and time of route departures to control for travel time variation based on varying departure times. The departure time for this model was conducted specifically at 8:00 AM. This time was selected because it falls within the peak time of transit operations and the morning commute. This study conducts the analysis from the departure time as opposed to the arrival time to weight the exact cost of travel one would experience if they had to choose between transit and driving at exactly 8:00 AM.The tool “Copy Traversed Source Features (with Transit)” within the “Transit Analysis Toolbox” also developed by Melinda Morang and Patrick Stevens, which accompanies the download of the “Add GTFS to Network Dataset” toolbox takes the selected route solutions from the Route Analysis tool and extracts it into a new shapefile containing the composite pieces of the travel path. This file contains specific details on the departure and arrival time of the trip, the walk time, the wait time, and the in-vehicle travel time. Figure 9 illustrates what a transit route output looks like between an origin and destination point. Figure 10 displays the attribute data of the extracted route.

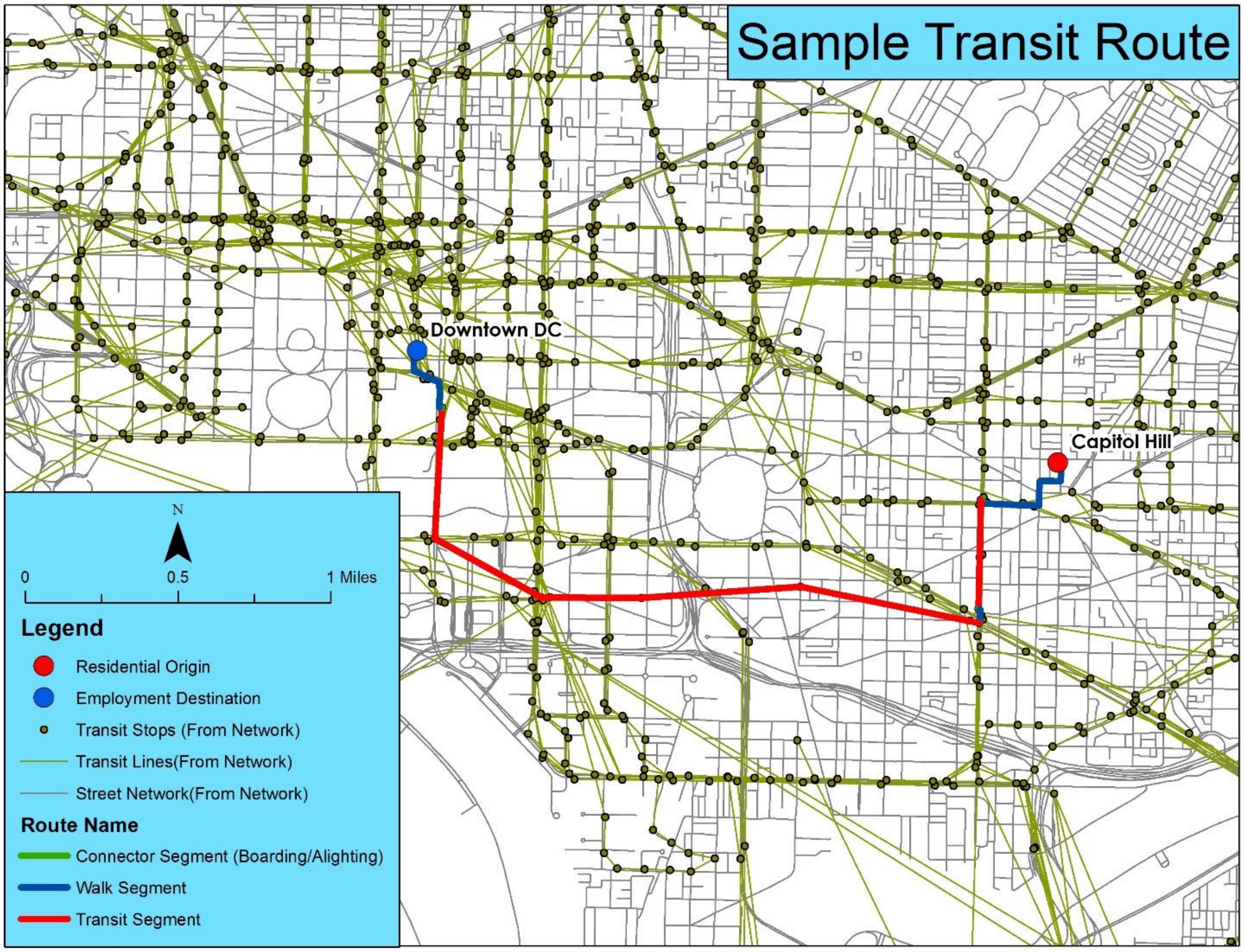

Figure 9: Sample Transit Route. Part of every transit route solution are links from each of the three layers: Connector Links, Walk Links, and Transit Links.

Table

CapHill_DC_Edges

SourceName	RouteID	Attr_TravelTi	Cumul_Tr	route_id	route_type	route_type_t	route_s	wait_time	transit_time	depart_ti	arrive_timeofday	from_stop_name	to_stop_name
Streets_UseThisOne	38	1.15633	1.15633	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.692857	1.849188	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.616667	2.465854	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.740476	3.20633	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.807143	4.013473	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.309166	4.32264	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.833691	5.15633	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	1.171429	6.327759	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.970987	7.298746	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.259966	7.558711	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.227501	7.786212	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Connectors_Stops2Streets	38	0	7.786212	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Connectors_Stops2Streets	38	0	10.899996	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.264307	11.164303	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.114898	11.279201	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.316054	11.595255	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.165247	11.760503	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Connectors_Stops2Streets	38	0	11.760503	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
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Streets_UseThisOne	38	1.370332	23.370335	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
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Streets_UseThisOne	38	0.121429	23.623906	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
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Streets_UseThisOne	38	0.398932	24.764382	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.580952	25.345335	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.785714	26.131049	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
Streets_UseThisOne	38	0.505437	26.636486	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>	<Null>
TransitLines	38	1.713783	9.499996	Folder2:120	3	Bus	92	0.51	1.2	08:08:18	08:09:30	8TH ST & EAST CAPI	SE 8TH ST & SE INDE
TransitLines	38	1.4	10.899996	Folder2:120	3	Bus	92	0	1.4	08:09:30	08:10:54	SE 8TH ST & SE IND	8TH ST & D ST (N)
TransitLines	38	2.2395	14.000003	Folder2:ORAN	1	Subway, Metr	Orange	0.24	2	08:12:00	08:14:00	EASTERN MARKET	CAPITOL SOUTH MET
TransitLines	38	2	16.000003	Folder2:ORAN	1	Subway, Metr	Orange	0	2	08:14:00	08:16:00	CAPITOL SOUTH ME	FEDERAL CENTER ME
TransitLines	38	2	18.000003	Folder2:ORAN	1	Subway, Metr	Orange	0	2	08:16:00	08:18:00	FEDERAL CENTER M	L'ENFANT PLAZA MET
TransitLines	38	2	20.000003	Folder2:ORAN	1	Subway, Metr	Orange	0	2	08:18:00	08:20:00	L'ENFANT PLAZA ME	SMITHSONIAN METRO
TransitLines	38	2	22.000003	Folder2:ORAN	1	Subway, Metr	Orange	0	2	08:20:00	08:22:00	SMITHSONIAN METR	FEDERAL TRIANGLE

Figure 10: Attribute Table of Extracted Transit Route. Here "Source Name" names the layer source. "Streets_UseThisOne" represents the pedestrian street layer, Connectors_Stops2Str" is the connector layer, and "TransitLines" is the transit layer. "Route Type" indicates whether the route is bus or rail, "Route Short" provides the name of the line, "Wait Time" provides the amount of time one needs to wait for the bus/train, and "Transit Time" is the amount of time one travels on the bus/train.

Utilizing the Route Analysis tool and the Yay Transit! toolset, A total of 30 routes, which originate from six origins and terminate at five destinations were compiled. It is difficult to show all 30 trips because many of these trips overlap along the same routes, primarily the Metrorail system. Figure 11, displays all the transit trips extracted. In green, are all trips that terminate at Rosslyn.

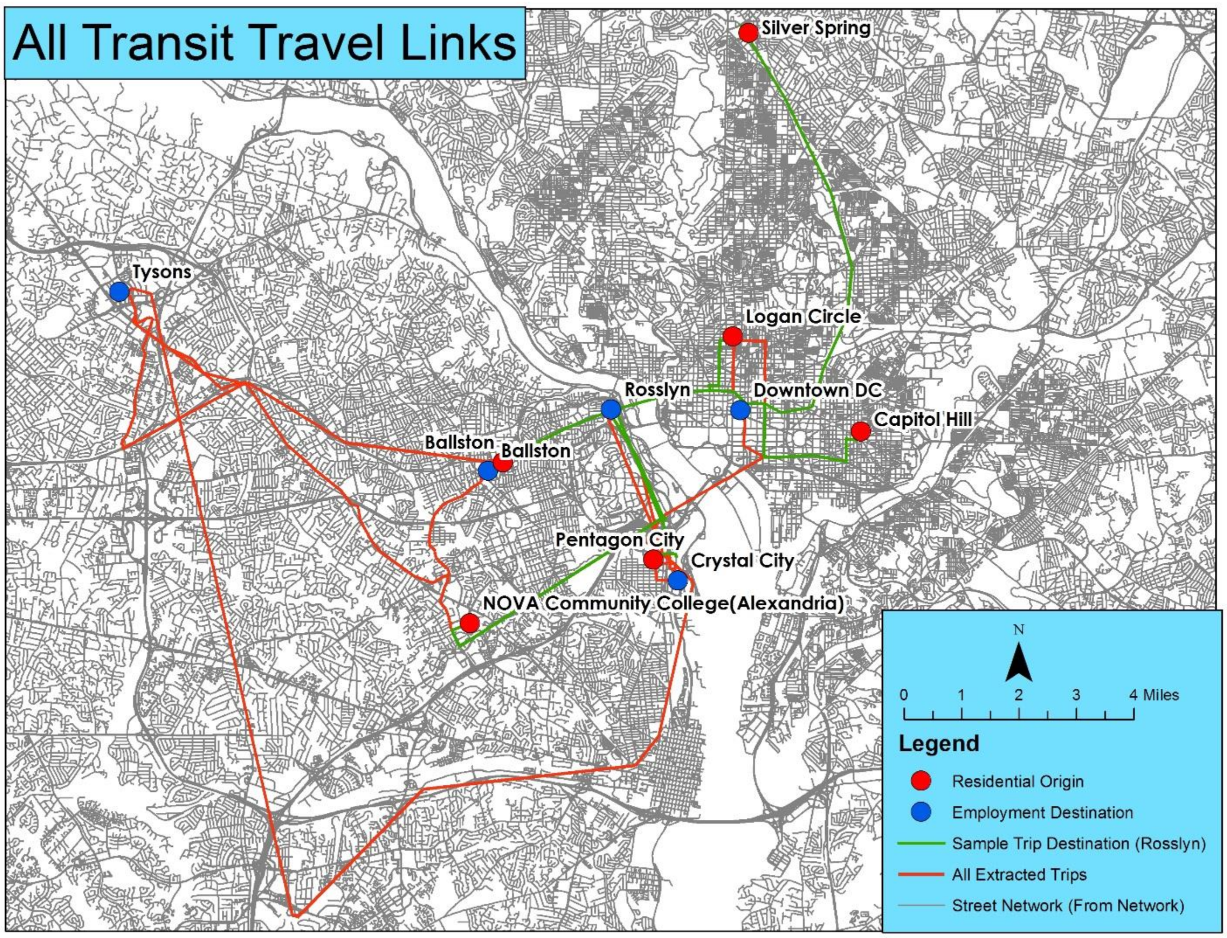


Figure 11: All Origin-Destination Transit Travel Trips. The red routes show all 30 transit routes solved and the green trips show only routes that end at Rosslyn.

To confirm Yay Transit! results, each of the 30 origin-destinations pairs were queried a second time using Google Transit. In either case the travel time was not calculated from 8:00 AM, but instead by the time one needs to leave their origin after 8:00 am to catch their first transit connection. In effect, the cost calculated in this model minimizes the waiting time for the initial transit link. For example, if the initial bus does not serve a stop until 8:10 AM and it takes 1 minute to walk to the stop, the trip will not start until 8:08 to allow for that minute walk to the bus stop. Those extra 8 minutes waiting at the origin are not included in the perceived cost of using transit.

The two solutions calculate optimal transit itineraries differently from origin to destination. The ArcGIS transit network will automatically select the first transit trip leaving the site, not necessarily the optimal trip. In effect, this is a limitation because the immediate trip may not always be the best trip for the calculation. Trips leaving later may have shorter walking times, less connections or even shorter travel times. Google Transit on the other hand, displays a spectrum of transit trips connecting the origin and destination based on departure time. The user can choose the itinerary most convenient to the individual based on the shortest travel time, least walking distance, or fewest transit connections. Considering that the user will optimize their commute, the shortest travel time within 15 minutes of 8:00 AM was selected as the optimal trip on Google Transit.

The flexibility provided by Google Transit produces results that are not consistent with Yay Transit! solutions. Importantly, even though Google Transit allows the selection of optimal times, the lack of transit operations for some transit services such as the DC Circulator and the Fairfax Connector, which are included in the GTFS data, provided for an even split of shortest itineraries generated by Yay Transit! and Google Transit. As a result, transit costs were calculated for all origin-destination pairs using both solutions and the lowest cost solution for each pair was chosen. Figures 12 and 13 compare transit results obtained from Google Transit and Yay Transit!. Figure 12 identifies the number of trips that were found cheaper for Yay

Transit! Vs. Google Transit. As one can see, Yay Transit! found more optimal trips than Google Transit. Figure 13 identifies the distribution of the difference in perceived cost between the Google Transit and Yay Transit!. Differences between the two tools can range up to $12.

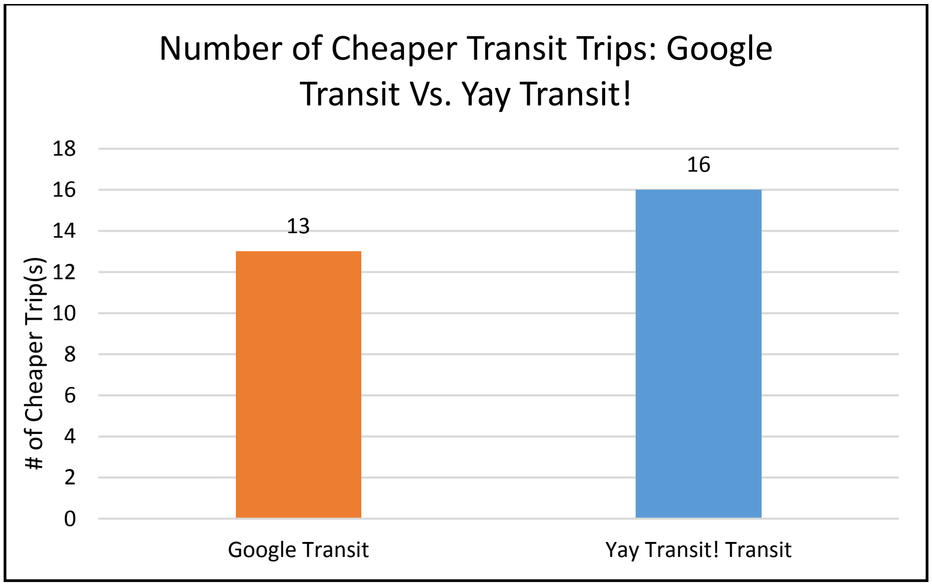


Figure 12: Google Transit vs. Yay Transit! Optimal Trips Comparisons. Yay Transit! found three routes cheaper than on Google Transit.

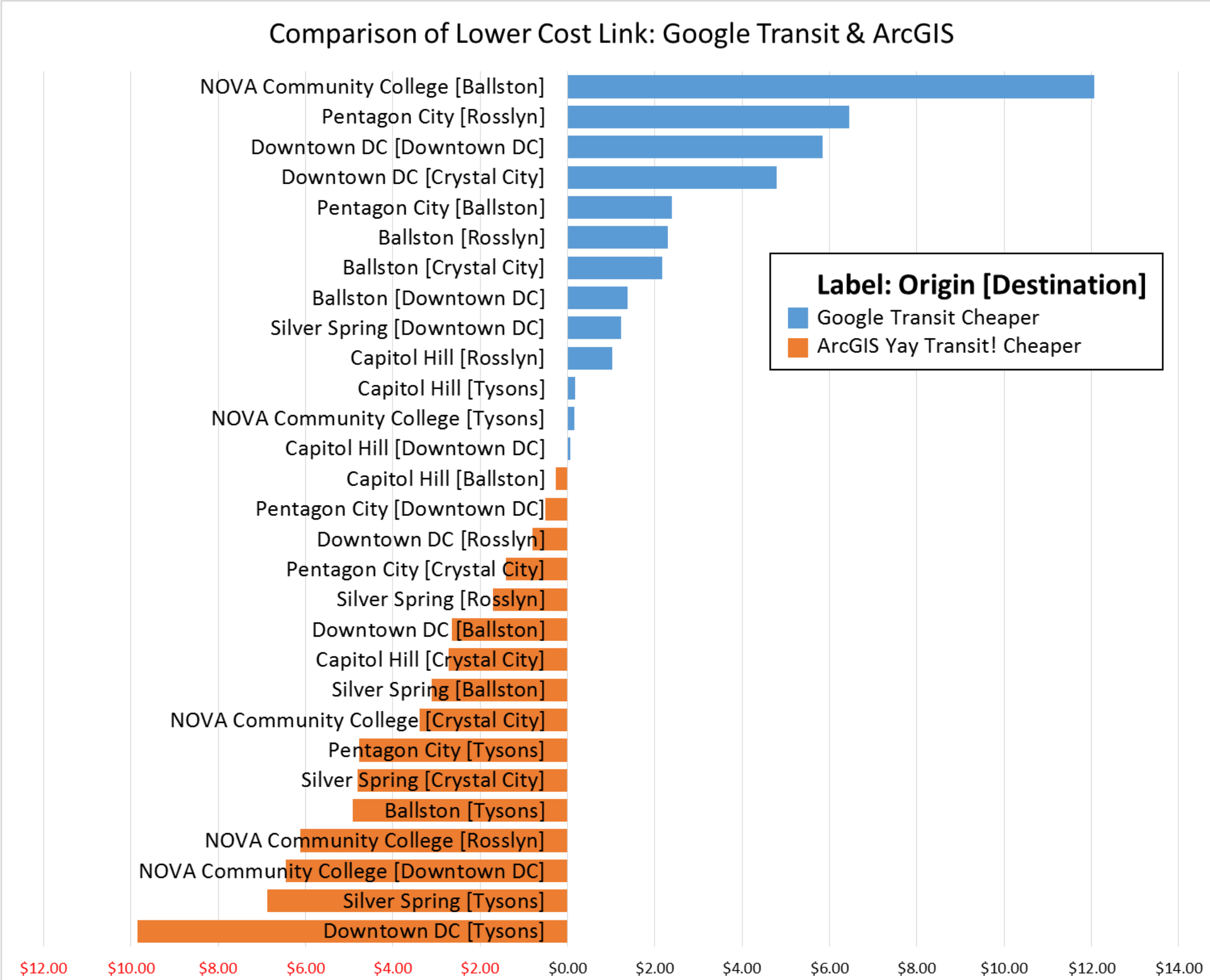


Figure 13: Difference of Yay Transit! and Google Transit Perceived Cost. The orange bars represent cheaper trips calculated using Yay Transit! whereas the blue bars represent cheaper trips calculated by Google Transit. Differences between the two tools can be as great as $12.

Once the transit trips have been derived, all variables have been found with the exception of fare cost. Unfortunately, fare cost must be calculated manually based on the transportation system rules. Although, GTFS data has the capability to store fare values and incorporate them into the transit network, no GTFS data exists for WMATA fares as of January 2014. Developing this data would be complex considering that over 44,000 fare combinations exist for the WMATA Metrorail system alone. Besides, Yay Transit! and Google currently lack the capability to account for complex fare systems or solve route costs based on trip origin and destination.

3.5 Solving Car Variables

Attaining values to be used for the automobile perceived cost formula was more straightforward than transit. Driving conditions and driving distances were obtained directly from Waze.com. Waze is a crowd sourced traffic map that stores actual traffic data for up to 12 hours. This allows queries to be run for periods within the previous 12 hours. Google Maps was not used for this step because the Google Maps interface does not store recent actual traffic conditions. In order to find the true travel time using Google Maps, one would have to be on Google Maps exactly at 8:00 AM running all 30 queries. Waze offers up to three travel options, the route with the shortest travel time was selected for input into the car travel formula. Figure 14 provides a sample of the Waze interface showing the recommended travel route and the exact travel time based on traffic conditions.

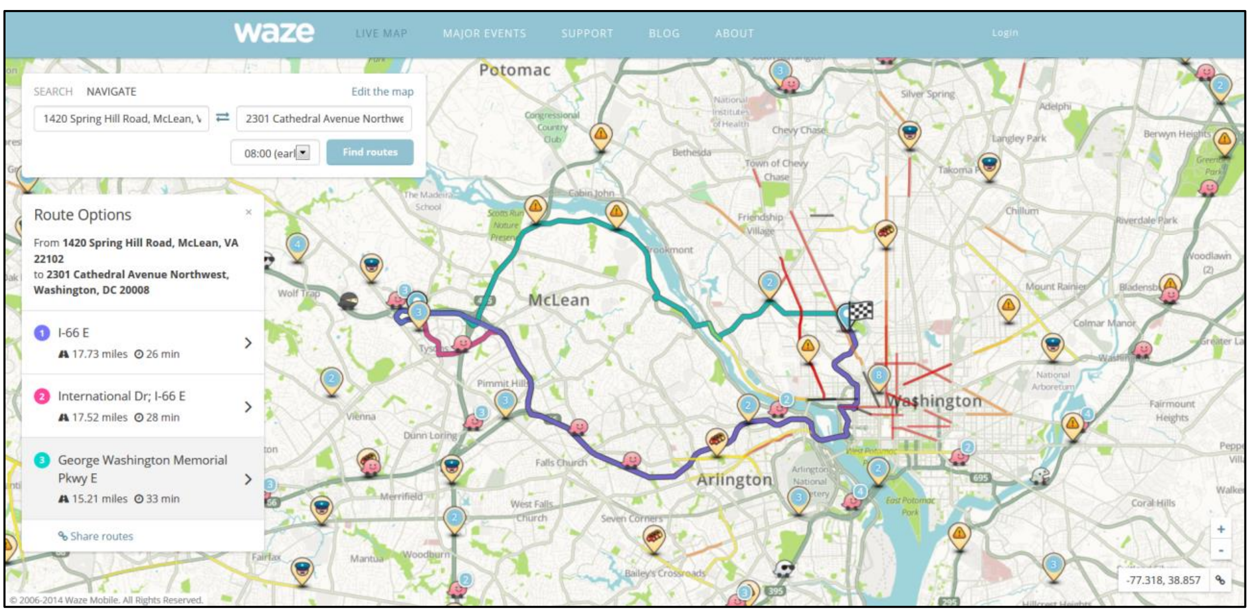


Figure 14: Waze Route Options for Determining Drive Time Values.

As described in the background chapter, parking time and parking cost was determined by using the employment densities within one mile of each destination point. To calculate the employment densities, one-mile diameter circular buffers were laid over each destination point and employment numbers were extracted from each intersected TAZ polygon using areal interpolation. Thus for each TAZ polygon, the employment count was multiplied by the proportion of the total area that fell inside the buffer. The total employment count within the one mile buffer is the sum of all of the partial TAZ polygon counts. Dividing by $(0.5^2\ \pi)$ (produced the floating employment density per square mile. Table 5 displays the values determined for Terminal Time and Parking Costs for each of the five destinations based on the calculations described in section 2.2.1 and 2.2.2.

Table 5: Employment Terminal Time and Parking Cost.

Employment Area	Employment within Buffer	Floating Density Per Mile	Terminal Time (1)	Parking Cost (2)
Downtown DC	374,581	119,233	8	$9.88
Rosslyn	74,582	23,740	6	$6.37
Ballston	55,459	17,653	6	$5.73
Crystal City	66,338	21,116	6	$6.12
Tysons	81,566	25,963	6	$6.56

Notes:
(1) Calculated from Table 2.
(2) Calculated from parking cost formula.

With values determined for all variables in the model, results can be calculate and interpreted. The next chapter examines these results.

CHAPTER 4 - RESULTS AND DISCUSSION

Having completed the calculation of the utility function for the 30 sample origin – destination pairs, we can now return to an analysis directed towards the fundamental goal of this research which is to evaluate mode travel convenience through perceived costs. From these results the employment and residential areas that are most conveniently linked by transit can be determined. Also, these results identify TDM strategies or service improvements that will most benefit transit connections between locations.

4.1 Results

A compilation of results reveal on average that transit provides six percent higher perceived costs than driving. Thus, overall, for the selected study trips, driving is more convenient than transit. Note that the model could only be calculated for 29 of the 30 links. The Ballston to Ballston trip was a distance of .33 miles, too short to warrant a commute on transit and was therefore not analyzed using this methodology.

Figures 15, 16, and 17 summarize all model results. Figure 15 lists the values obtained for transit from Yay Transit! and Google Transit tools. Included in these results are the itineraries solved by each application. It is worth noting, that these itineraries are not always identical because of the issues discussed in Section 3.4 related to missing transit operator data and the flexibility of route solutions. Figure 16 lists the values obtained for driving from the Waze application.

Link	Origin	Destination	Yay Transit!						Google Transit						Yay Transit!	Google Transit
			Walk Time (Min)	Wait Time (Min)	In Vehicle Time (Min)	Total Travel Time (Min)	Fare ($)	Route Itenerary	Walk Time (Min)	Wait Time (Min)	In Vehicle Time (Min)	Total Travel Time (Min)	Fare ($)	Route Itenerary		
1	Downtown DC	Downtown DC	12.69	1.61	6.9	21.2	$3.20	53 to Orange(McPherson to Metro Center)	4	0	12	16	$1.60	52	$ 9.81	$ 5.24
2	Ballston	Downtown DC	6.42	1.78	13	21.2	$2.55	Orange (Virginia Square to Metro Center)	6	0	13	19	$2.55	Orange (Virginia Square to Metro Center)	$ 8.06	$ 7.10
3	Pentagon City	Downtown DC	12.85	1.78	10	24.63	$2.10	Yellow line to Orange Line(Pentagon City to Smithsonian)	11	0	22	33	$1.60	7Y	$ 9.41	$ 9.61
4	NOVA CC	Downtown DC	13.1	2.04	21.5	36.64	$3.20	16L to Yellow to Orange (Pentagon to Federal Triangle)	18	8	21	47	$3.35	16L to Yellow Line(Pentagon City to Gallary Place)	$ 12.81	$17.36
5	Capitol Hill	Downtown DC	13.28	0.75	12.6	26.63	$3.20	92 to Orange Line(Eastern Market to Federal Triangle)	17	0	11	28	$2.10	Orange Line(Eastern Market to Metro Center)	$ 10.67	$10.29
6	Silver Spring	Downtown DC	8.18	1.02	21	30.2	$3.45	Red Line(Sivler Spring to Gallery Place)	7	0	21	28	$3.50	Red Line(Sivler Spring to Metro Center)	$ 10.71	$ 9.87
7	Downtown DC	Rosslyn	13.64	1.51	9.8	24.95	$2.70	S2 to Orange Line(Farragut West to Rosselyn)	2	8	18	28	$3.20	53 to Orange Line(McPherson to Rosselyn)	$ 10.14	$10.84
8	Ballston	Rosslyn	5.19	1.78	6	12.97	$2.10	Orange Line(Virginia Square to Rosselyn)	3		6	9	$2.10	Orange(Rosselyn to Ballston)	$ 5.89	$ 4.28
9	Pentagon City	Rosslyn	12.47	7.35	7.5	27.32	$1.60	10E	8	0	10	18	$1.60	10E	$ 10.85	$ 6.33
10	NOVA CC	Rosslyn	11.43	6.04	17.5	34.97	$3.20	16L to Blue Line (Pentago to Rossrlyn)	8	18	18	46	$3.20	16L to Blue(Pentafon Station to Rosselyn)	$ 13.29	$17.58
11	Capitol Hill	Rosslyn	11.61	0.75	20.6	32.96	$3.75	92 to Orange Line(Eastern Market to Rosslyn)	14	0	18	32	$2.65	Orange Line(Eastern Market to Rosslyn)	$ 12.07	$11.02
12	Silver Spring	Rosslyn	6.94	2.02	28	36.96	$3.95	Red to Orange Line(Silver Spring to Rosselyn)	4	7	28	39	$3.95	Red to Orange Line(Silver Spring to Rosselyn)	$ 12.49	$13.69
13	Downtown DC	Ballston	15.15	1.51	16.8	33.47	$3.60	S2 to Orange Line(Farragut West to Ballston)	11	7	21	39	$3.75	S2 to Orange Line(McPherson to Ballston)	$ 12.86	$14.76
14	Ballston	Ballston	8.04			8.04	$ -	Walks	8				$ -	Walk		
15	Pentagon City	Ballston	9.94	12.73	16.8	39.47	$3.25	7Y to Blue line to Orange(Arlington Cemetary to Ballston)	10	9	17	36	$3.20	10E to OrangeLine(Rosselyn to Ballston)	$ 15.72	$14.03
16	NOVA CC	Ballston	28.4	3.85	13	45.25	$1.60	28A to 25A	6		21	27	$1.60	25A	$ 16.06	$ 7.61
17	Capitol Hill	Ballston	13.12	0.75	27.6	41.47	$4.45	92 to Orange Line (Eastern Market to Ballston	18		25	47	$3.35	Orange Line (Eastern Market to Ballston	$ 14.59	$14.45
18	Silver Spring	Ballston	8.45	2.02	35	45.47	$4.45	Red to Orange Line(Silver Spring to Virginia Square)	8	7	35	50	$4.55	Red to Orange Line(Silver Spring to Ballston)	$ 14.81	$17.02
19	Downtown DC	Crystal City	19.18	2.58	14	35.76	$2.70	Green line to yellow line (Shaw to Crystal City)	12	0	16	28	$2.80	Green to Yellow(Ust to Crystal City)	$ 13.40	$10.08
20	Ballston	Crystal City	13.67	3.98	14.6	32.25	$4.80	Orange Line (Virginia Square to Rosslyn) to 9E to 16H	9	8	14	31	$2.60	Orange to Blue(Virginia Square to Crystal City	$ 14.24	$12.06
21	Pentagon City	Crystal City	12.87			12.87	$ -	Walks	11	0	3	14	$1.60	9S	$ 4.68	$ 6.15
22	NOVA CC	Crystal City	15.2	2.04	15.5	32.76	$3.20	16L to Blue Line (Pentagon to Crystal City)	14	8	16	38	$3.20	16L to Blue Line(Pentagon Metro to Crystal City)	$ 12.48	$14.85
23	Capitol Hill	Crystal City	15.41	3.75	16.6	35.76	$3.60	92 to Orange to Yellow line(Eastern Market to Crystal City)	20	7	14	41	$2.50	Orange to Yellow line(Eastern Market to Crystal City)	$ 13.94	$15.51
24	Silver Spring	Crystal City	10.74	1.02	30	41.76	$4.50	Red to Yellow(Silver Spring to Crystal City)	10	9	30	49	$4.50	Red to Yellow(Silver Spring to Crystal City)	$ 14.33	$17.70
25	Downtown DC	Tysons	17.4	2.32	45.56	65.28	$7.20	53 to Orange(McPherson to Dunn Loring) to FFX 401	16	15	57	88	$6.55	53 to Orange(McPherson to West Falls Church) to 28T	$ 22.88	$29.57
26	Ballston	Tysons	8.98	5.59	30.76	45.33	$4.45	Orange(Virginia Square to Dunn Loring) to 401	6	15	29	50	$5.25	Orange(Ballston to West Falls Church) to 28X to T	$ 15.86	$19.54
27	Pentagon City	Tysons	9.06	16.88	45.68	71.62	$5.95	Blue Line(Crystal City to Springfield) to 494(to Galeria at Tysons) to 495(Greensboro at Goodridge)	27	17	34	78	$4.35	10E to Orange(Rosselyn to West Falls Church) to28X	$ 25.24	$28.10
28	NOVA CC	Tysons	14.7	7.1	58.49	80.29	$1.60	28X to 494	28		49	77	$1.60	28X	$ 20.83	$20.71
29	Capitol Hill	Tysons	28.67	6.43	45.19	80.29	$7.30	92 to Orange Line(Eastern Market to West Falls Church) to 28T to 494	35	8	42	85	$3.65	Orange(Ballston to West Falls Church) to 28X	$ 28.89	$27.67
30	Silver Spring	Tysons	20.73	5.85	54.71	81.29	$8.35	Red to Orange(Silver Spring to West Falls Church) to 28A to 493	12	18	74	104	$6.85	Red to Orange(Silver Spring to Dunn Loring) to 2T	$ 28.51	$32.88

Figure 15: Transit Perceived Cost for Yay Transit! and Google Transit. Green squares on the right side identify the cheaper trip. The Ballston to Ballston trip was not calculated due to the short travel distance.

Link	Origin	Destination	Waze Distance (mi)	Waze Time (min)	Parking Penalty (min)	Parking Cost ($)	Total Automobile cost ($)
1	Downtown DC	Downtown DC	1.46	9	8	$ 9.88	$ 14.62
2	Ballston	Downtown DC	6.15	23	8	$ 9.88	$ 17.21
3	Pentagon City	Downtown DC	3.84	16	8	$ 9.88	$ 14.88
4	NOVA CC	Downtown DC	7.94	23	8	$ 9.88	$ 18.14
5	Capitol Hill	Downtown DC	2.54	13	8	$ 9.88	$ 13.81
6	Silver Spring	Downtown DC	7.51	24	8	$ 9.88	$ 17.76
7	Downtown DC	Rosslyn	4.17	17	6	$ 6.37	$ 13.26
8	Ballston	Rosslyn	3.03	8	6	$ 6.37	$ 10.67
9	Pentagon City	Rosslyn	3.61	7	6	$ 6.37	$ 10.54
10	NOVA CC	Rosslyn	7.25	14	6	$ 6.37	$ 13.16
11	Capitol Hill	Rosslyn	7.26	14	6	$ 6.37	$ 13.16
12	Silver Spring	Rosslyn	10.86	30	6	$ 6.37	$ 18.11
13	Downtown DC	Ballston	8	20	6	$ 5.73	$ 14.24
14	Ballston	Ballston	0.33	2	6	$ 5.73	$ 7.88
15	Pentagon City	Ballston	4.73	10	6	$ 5.73	$ 10.92
16	NOVA CC	Ballston	4.18	11	6	$ 5.73	$ 11.06
17	Capitol Hill	Ballston	8.92	17	6	$ 5.73	$ 13.66
18	Silver Spring	Ballston	14.55	33	6	$ 5.73	$ 19.05
19	Downtown DC	Crystal City	5.21	16	6	$ 6.12	$ 12.98
20	Ballston	Crystal City	5.19	14	6	$ 6.12	$ 12.45
21	Pentagon City	Crystal City	0.8	4	6	$ 6.12	$ 8.89
22	NOVA CC	Crystal City	4.97	13	6	$ 6.12	$ 12.14
23	Capitol Hill	Crystal City	5.93	13	6	$ 6.12	$ 12.35
24	Silver Spring	Crystal City	13.3	33	6	$ 6.12	$ 19.17
25	Downtown DC	Tysons	15.75	29	6	$ 6.56	$ 19.11
26	Ballston	Tysons	9.29	14	6	$ 6.56	$ 13.80
27	Pentagon City	Tysons	15.24	20	6	$ 6.56	$ 16.66
28	NOVA CC	Tysons	17.25	23	6	$ 6.56	$ 17.88
29	Capitol Hill	Tysons	19.54	28	6	$ 6.56	$ 19.68
30	Silver Spring	Tysons	17.41	26	6	$ 6.56	$ 18.70

Figure 16: Automobile Perceived Cost from Waze.com. The last column to the right shows the total perceived cost for driving.

In order to compare the relative perceived costs (i.e. “convenience”) for each OD pair, the magnitude of the difference between the two perceived costs was found. This difference between the two modes was found by using the following formulas:

If Transit > Car
Perceived Cost Difference = (Transit – Car)/Transit * 100

If Transit < Car
Perceived Cost Difference = (Transit – Car)/Car * 100

If Transit = Car
Perceived Cost Difference = 0 (6)

Figure 17 compares the most convenient transit result with the Waze result and shows the difference in perceived cost between the two modes.

Trip	Origin	Destination	Lowest Transit	Waze Automobile cost	Convenient Mode	Transit Cost Difference Vs. Driving
1	Downtown DC	Downtown DC	$ 6.80	$ 14.62	T	-53%
2	Ballston	Downtown DC	$ 9.05	$ 17.21	T	-47%
3	Pentagon City	Downtown DC	$ 12.54	$ 14.88	T	-16%
4	NOVA CC	Downtown DC	$ 16.93	$ 18.14	T	-7%
5	Capitol Hill	Downtown DC	$ 13.80	$ 13.81	T	0%
6	Silver Spring	Downtown DC	$ 12.60	$ 17.76	T	-29%
7	Downtown DC	Rosslyn	$ 13.32	$ 13.26	C	0%
8	Ballston	Rosslyn	$ 5.22	$ 10.67	T	-51%
9	Pentagon City	Rosslyn	$ 8.36	$ 10.54	T	-21%
10	NOVA CC	Rosslyn	$ 17.62	$ 13.16	C	25%
11	Capitol Hill	Rosslyn	$ 14.61	$ 13.16	C	10%
12	Silver Spring	Rosslyn	$ 16.15	$ 18.11	T	-11%
13	Downtown DC	Ballston	$ 16.83	$ 14.24	C	15%
14	Ballston	Ballston	$ -		W	
15	Pentagon City	Ballston	$ 18.67	$ 10.92	C	42%
16	NOVA CC	Ballston	$ 10.18	$ 11.06	T	-8%
17	Capitol Hill	Ballston	$ 18.94	$ 13.66	C	28%
18	Silver Spring	Ballston	$ 19.26	$ 19.05	C	1%
19	Downtown DC	Crystal City	$ 13.20	$ 12.98	C	2%
20	Ballston	Crystal City	$ 16.12	$ 12.45	C	23%
21	Pentagon City	Crystal City	$ 6.69	$ 8.89	T	-25%
22	NOVA CC	Crystal City	$ 16.46	$ 12.14	C	26%
23	Capitol Hill	Crystal City	$ 18.37	$ 12.35	C	33%
24	Silver Spring	Crystal City	$ 18.55	$ 19.17	T	-3%
25	Downtown DC	Tysons	$ 29.60	$ 19.11	C	35%
26	Ballston	Tysons	$ 20.75	$ 13.80	C	34%
27	Pentagon City	Tysons	$ 33.51	$ 16.66	C	50%
28	NOVA CC	Tysons	$ 28.90	$ 17.88	C	38%
29	Capitol Hill	Tysons	$ 37.97	$ 19.68	C	48%
30	Silver Spring	Tysons	$ 37.16	$ 18.70	C	50%
		Average:	**$ 17.52**	**$ 14.76**	**12 Transit to 17 Car**	**6%**

Figure 17: Transit vs. Car Perceived Cost Comparison. On average perceived costs for transit were six percent more than driving.

The average of perceived cost differences was found to be six percent higher for transit when compared across the 29 trips. This means that on average, when considering the set of sample commutes, trips have a six percent higher perceived cost when taking transit rather than driving. For simplicity in discussing and analyzing trips difference, results have been categorized into five separate categories introduced in Table 6.

Table 6: Categories - Differences in Cost of Transit Versus Driving.

Category Name	Percent Cost Difference
Transit Much Cheaper	Less than -30.0%
Transit Moderately Cheaper	-30% to -10.1%
Neutral	-10% to +10 %
Car Moderately Cheaper	+10.1% to +30.0%
Car Much Cheaper	Greater than 30%

As the name implies, a trip classified as “Transit Much Cheaper” is a trip in which the user pays less than 30 percent what the individual would pay for the same travel trip by car. Vice versa a trip classified as “Car Much Cheaper” is a trip in which it cost the user 30 percent or more to take transit for that trip than driving. Figure 18 aggregates trips into these categories and orders them from least expensive travel on transit to most expensive travel on transit. Thirteen trips had a perceived cost of more than 10 percent higher for transit travel whereas only eight trips had a perceived cost of 10 percent or less cheaper travel on transit than car. Eight trips were found to have similar costs for transit and driving travel. The downtown-to-downtown trip was least expensive on transit whereas the Pentagon City to Tysons trip was found to be most expensive.

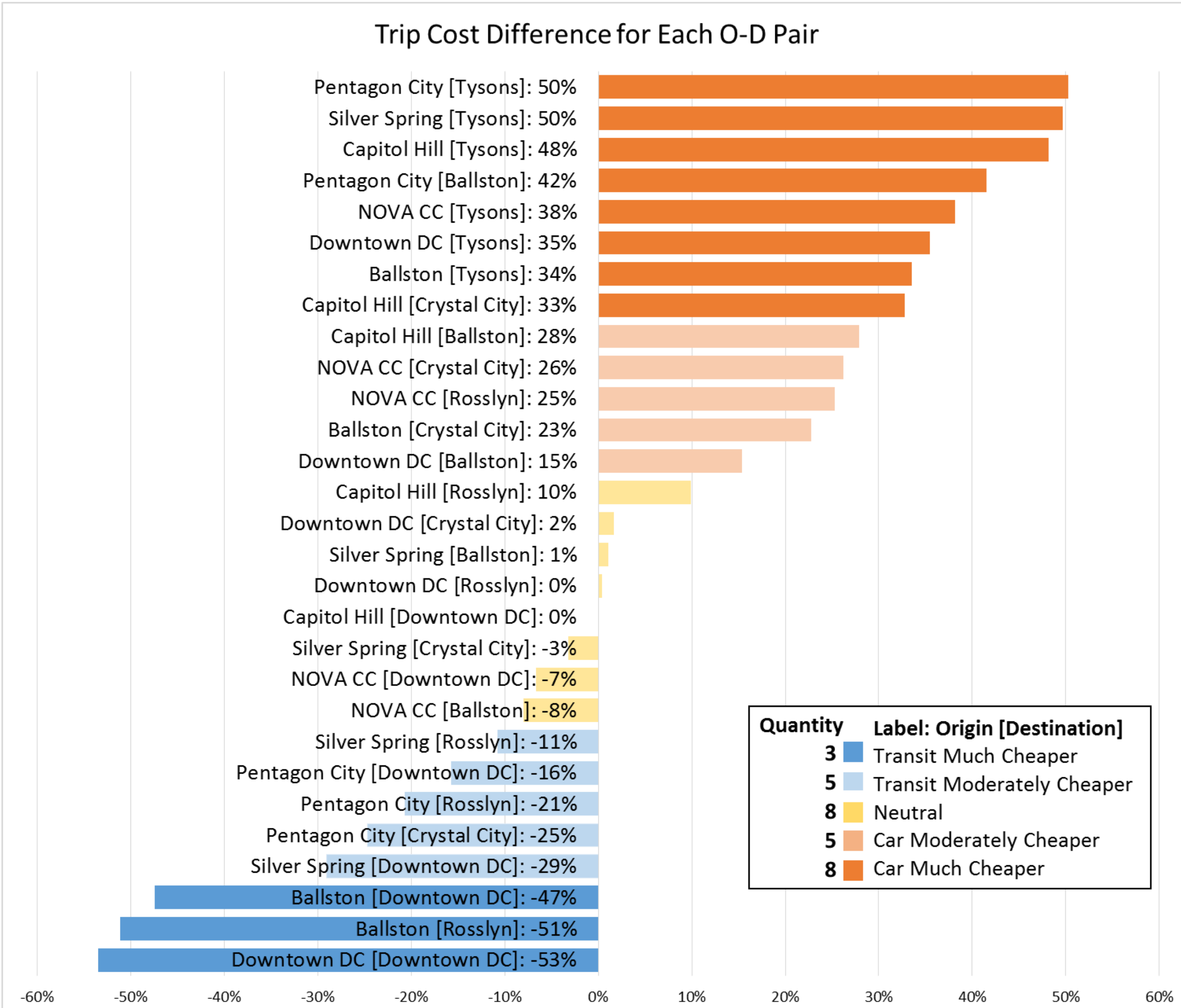


Figure 18: Trip Cost Difference for Each OD Pair.

The 29 trips were grouped by their Origin and then their Destination to reveal any common trends based on the trip starting or ending points. All trip values starting or ending at a specific point were averaged by their trip cost difference.

Trips grouped by origin revealed that most residential neighborhoods had on average cheaper perceived costs for driving than taking transit leaving the neighborhood. Ballston and downtown were the only neighborhoods with trips cheaper on transit. Capitol Hill had the most expensive trip on transit compared to driving. Average perceived costs grouped by origins can be seen on Figure 19.

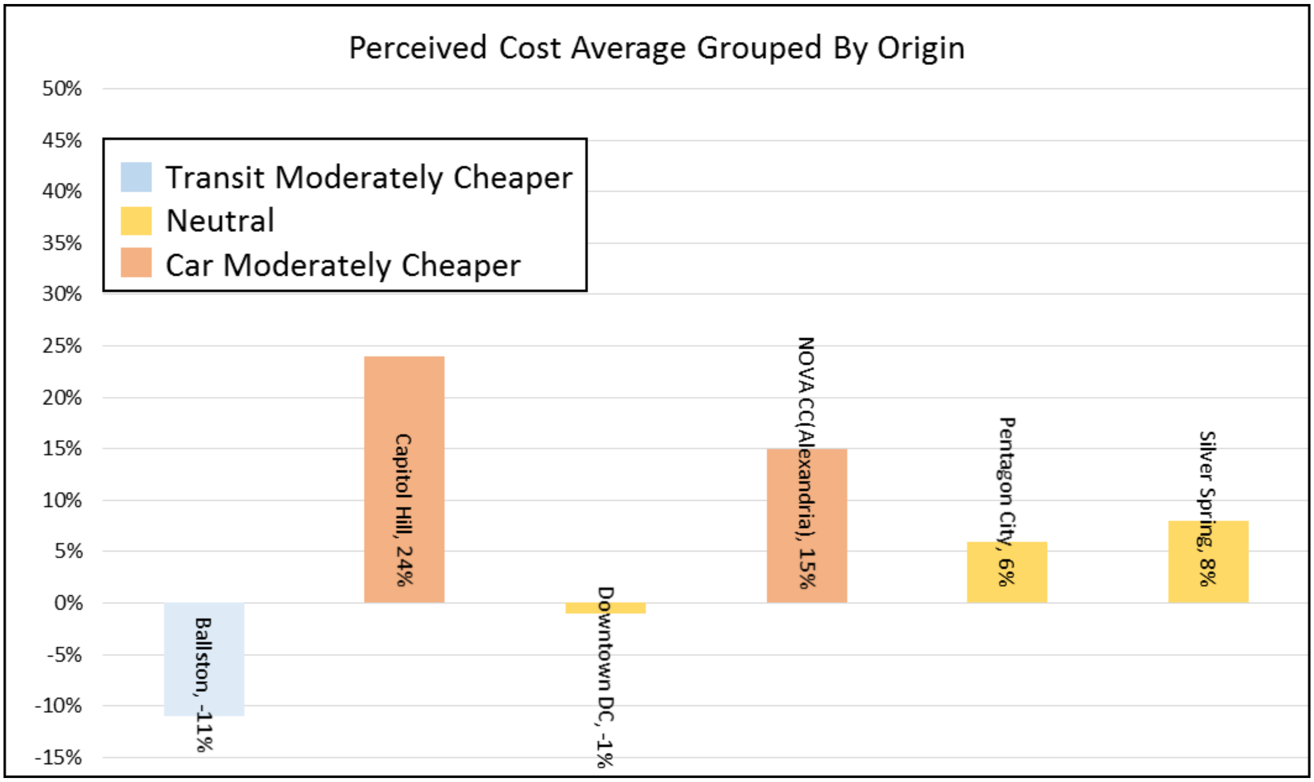


Figure 19: Average Perceived Cost of Trip Origins. On average the most expensive perceived cost transit trips relative to driving left from Capitol Hill whereas on average the cheapest perceived cost trips on transit left from Ballston

Grouped by destinations results revealed a broader difference in average perceived costs by mode. Downtown DC for example, had on average 25 percent cheaper perceived costs trips for transit whereas Tysons Corner had 43 percent more expensive perceived costs trips on transit. Average perceived costs grouped by destinations can be seen on Figure 20.

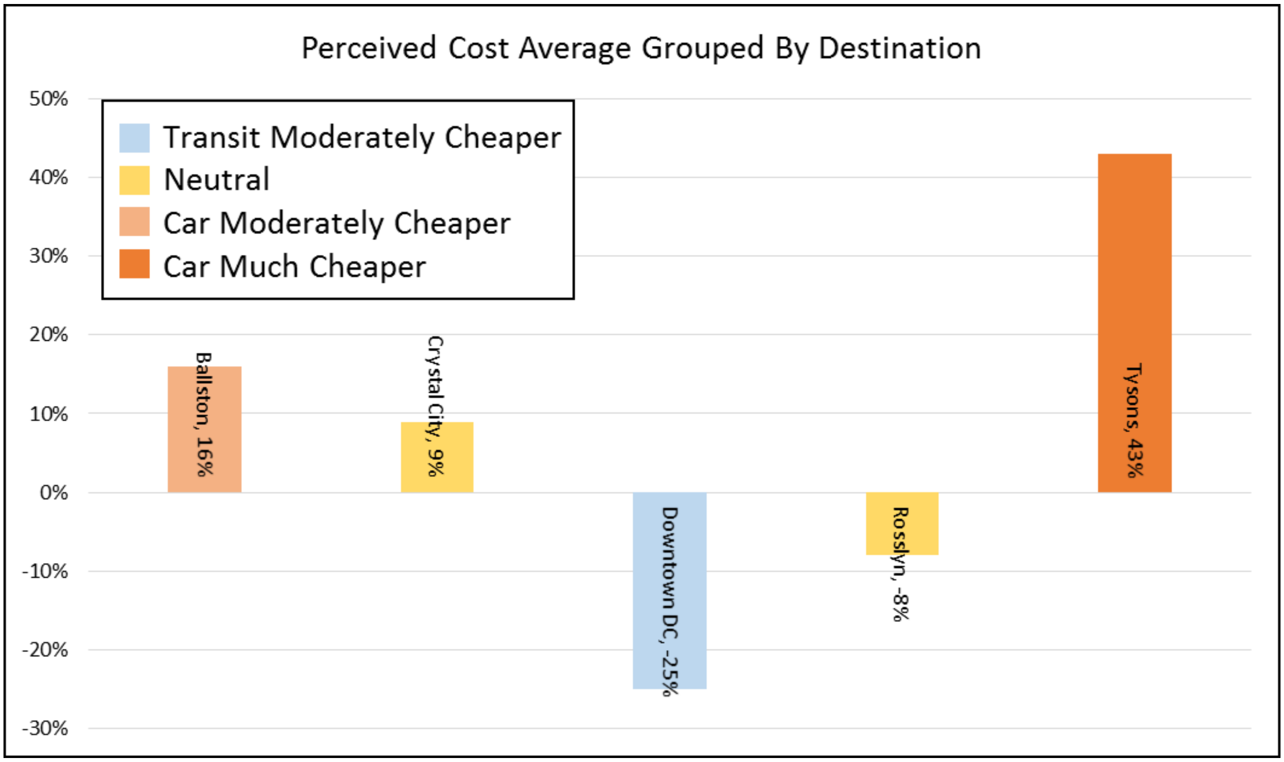
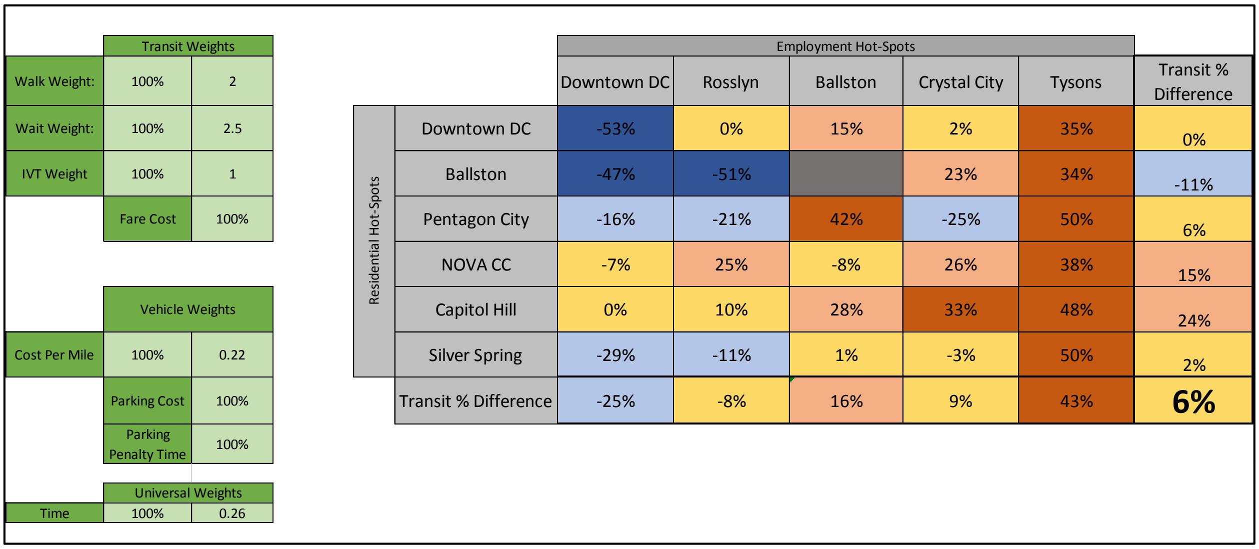


Figure 20: Average Perceived Cost of Trip Destinations. Tysons Corner trips were 43 percent more expensive on transit than driving. Downtown DC trips were on average 25 percent less expensive on transit than driving.

4.2 Sensitivity Analysis

When the differences amongst all trips are averaged, the result is six percent higher cost for using transit, meaning that, on average given these sample locations, commute conditions and model variables, the perceived cost of commuting by car is less than that of transit. But what does this truly tell us about the relationship between perceived costs and the impact of that difference on travel choices? Although this is a small sample from which it is difficult to generalize, the results of this analysis can effectively be used to assess how changes in one or more components in the travel model may change the balance between transit and driving.

All model components were subjected to sensitivity analyses. A dashboard was developed in Excel to analyze changes in the overall perceived cost difference average based on adjustments to formula variables and parameters. The dashboard automatically recalculates individual trip perceived costs, origin/destination average costs, and the overall average cost of all study links when you change a parameter or variable value. Figure 21, shows the dashboard used to test the model formula values.



	Transit Weights	
Walk Weight:	100%	2
Wait Weight:	100%	2.5
IVT Weight	100%	1
	Fare Cost	100%

	Vehicle Weights	
Cost Per Mile	100%	0.22
	Parking Cost	100%
	Parking Penalty Time	100%

	Universal Weights	
Time	100%	0.26

Residential Hot-Spots	Employment Hot-Spots: Downtown DC	Rosslyn	Ballston	Crystal City	Tysons	Transit % Difference
Downtown DC	-53%	0%	15%	2%	35%	0%
Ballston	-47%	-51%		23%	34%	-11%
Pentagon City	-16%	-21%	42%	-25%	50%	6%
NOVA CC	-7%	25%	-8%	26%	38%	15%
Capitol Hill	0%	10%	28%	33%	48%	24%
Silver Spring	-29%	-11%	1%	-3%	50%	2%
Transit % Difference	-25%	-8%	16%	9%	43%	6%

Figure 21: Excel Dashboard for Variable/Parameter Testing. Parameters and variables can be changed in the light green boxes on the left side. Changes to these values will automatically recalculate for the table on the right trip perceived costs, origin/destination average costs, and the overall average cost of all study links.

All model components were tested at increments of 25 percent from 0 percent to 400 percent of the original value of the variable or parameter. Average values for each 25 percent increment were plotted to determine variable and parameter trends. An increment less than 100 percent translates to a reduction in the variable value. Although some variables could go beyond 0 to negative values (such as pleasure from walking, or being on the bus to do work), for comparison purposes this analysis stops at 0 percent because some model values such as time do not make sense as negative values.

In Figure 22, one can see how increasing the value of the individual components of the driving travel formula increases the cost of driving. Driving cost is most impacted by parking increases. In fact, with all other variables held constant, an increase of 25 percent in parking, to a value 125 percent more than the current value, would make transit on average less expensive than driving. At an increase of 50 percent, to a value at 150 percent more than the current value, transit goes from being neutral to being moderately cheaper, and by an increased parking cost of 125 percent, 225 percent the current value, transit becomes much cheaper than driving. In order for other driving variables to rival the impacts of parking at a 25 percent increase, drive costs per mile must be increased from .219 cents per mile to .38 cents per mile, an increase of 75 percent, 175 percent of current value. The parking penalty values must be increased by 200 percent, 300 percent that of current value, to match the effects of parking costs increases at 25 percent. The significance of parking costs stems from the high out-of-pocket cost. For example, the parking cost of Downtown DC at $9.88 is equivalent to roughly an additional 50 miles driven at 0.219 cents per mile, or 40 minutes ridden in the car at 0.26 cents per minute.

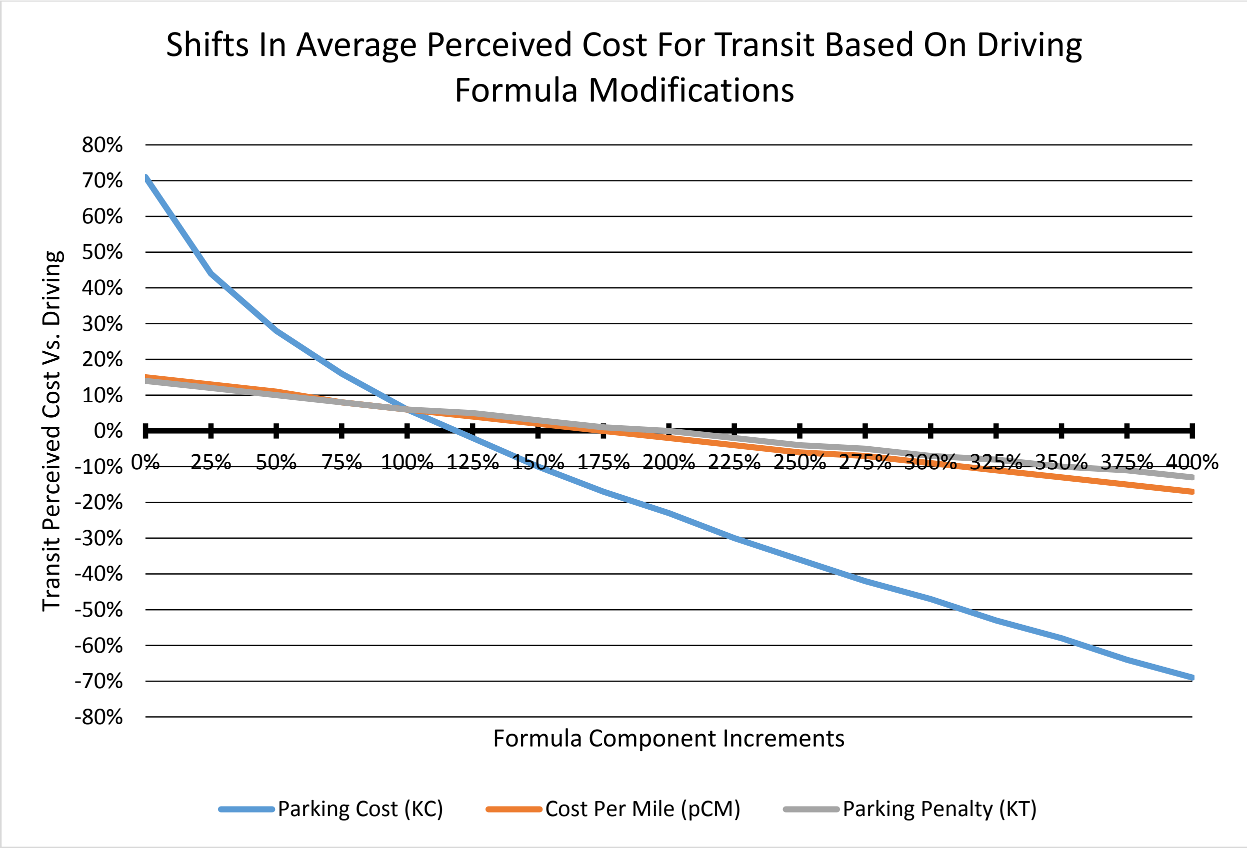


Figure 22: Average Perceived Cost For Transit Based on Driving Formula Modifications. The chart shows the impact of driving formula variables on the difference between driving and transit perceived cost. Parking cost has the most direct impact on this difference.

As would be expected, Figure 23 shows that increasing the price of components of the transit travel formula have the opposite effect on the perceived cost of transit. Although time is a factor which affects both driving and transit, it was only included in the transit formula comparison because it shares a similar negative slope to other transit formula components. Amongst the variables analyzed, dollar value assigned to time has the most direct impact on the average trip cost for transit. The walking parameter, followed by in-vehicle time parameter are front runners to travel time in their effect on the average price of transit. Changes in fare and wait time have the least influence of the variables studied on the cost of transit travel. It is worth noting that a decrease of 25 percent in the in vehicle travel parameter, a 25 percent reduction in the walking parameter, or a 20 percent reduction in time cost to 20.8 cents per minute would level the average cost of taking transit and driving.

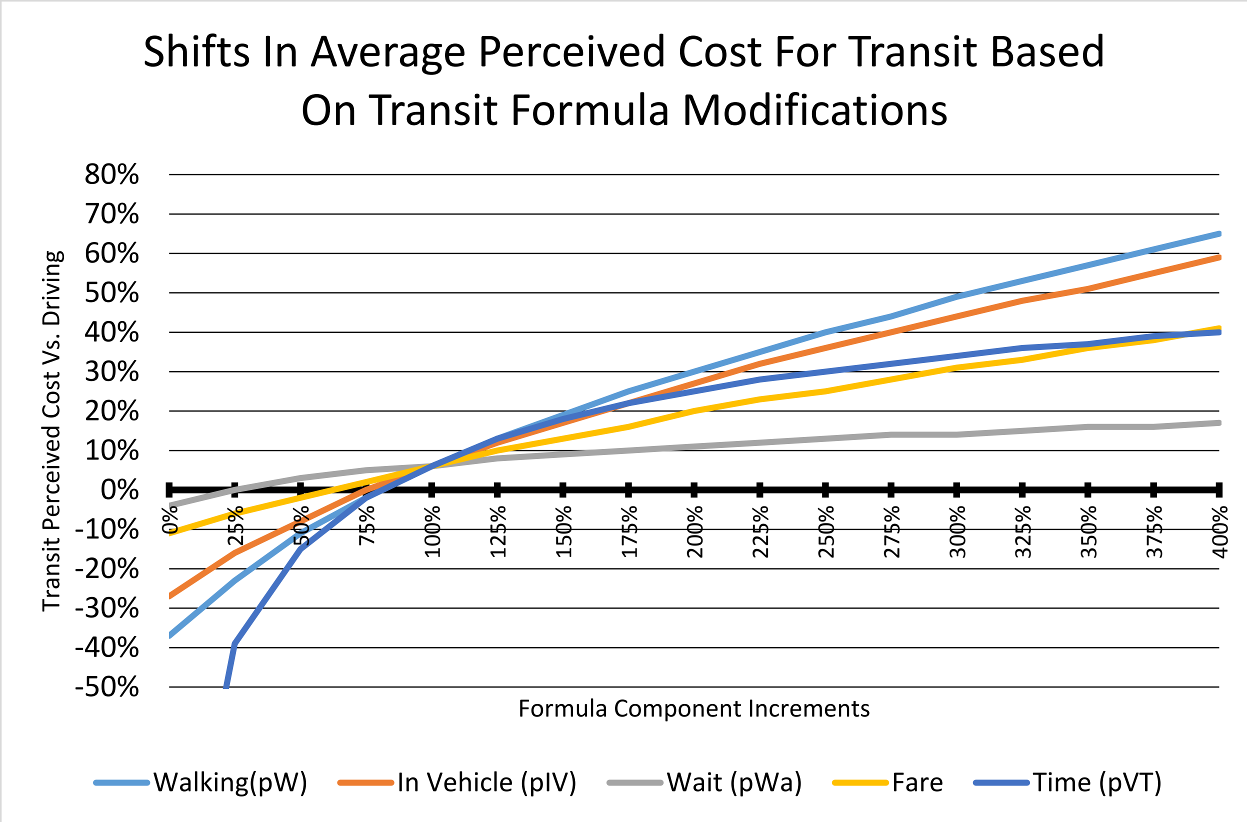


Figure 23: Average Perceived Cost for Transit Based on Transit Formula Modifications. The chart shows the impact of transit formula variables on transit perceived cost. The value of time followed by the walking parameter have the most direct impact on transit perceived cost.

The cost of time is significant in this analysis because of the additional time it takes to utilize transit. If transit were a faster mode option than driving, the curve would increase as the value of time increased. Figure 23 shows that as the value of time is reduced, transit perceived cost quickly falls in comparison to driving. Considering that the value of time is directly related to income, one can assume that as income drops, one is more likely to perceive the cost to take transit as less. For an individual making roughly 50 percent the region's annual income, this person would perceive transit costs to be roughly 20 percent less than that of driving.

4.3 Implications for Transportation Demand Management Strategies

The sensitivity analysis above reveals a handful of Transportation Demand Management Strategies that can help balance the price of transit travel versus driving.

4.3.1 Managing Parking Cost

As shown in Figure 22, the price of parking plays a significant impact on the cost of driving. An increase of just 25 percent would escalate the attraction of transit beyond driving. Transportation Demand Management strategies should continue to focus on increasing the price of parking in employment areas in order to balance the travel commute costs of driving versus transit.

4.3.2 Catering to Those Who Enjoy Walking

After time costs, the second most influential model input found on transit cost was walking. At a weight of 2, it appears that walking severely impacts the commute cost of transit. By promoting the pleasures of walking to the transit stop and subsequently to one's office, the perception of the intensity of the walk may be reduced. Campaigns could promote the fresh air one gets on their walk to transit, or the physical activity one has no time for. These campaigns would effectively lower the walk coefficient and the total cost of taking transit.

4.3.3 Adjusting the Perception of Time on Transit

The in-vehicle time or the time riding transit, was the third most significant model input to affect the total cost of a trip. Strategies can be put into place to reduce the value of the perceived time riding transit by focusing on productive activities that can be achieved while one is commuting. For example, campaigns could highlight the value of reading a book while on the bus, or answering emails, or just relaxing. If one values the time spent traveling to and from work, the time perceived by the individual is weighted less heavily.

4.4 Summary of Results

A comparison of travel costs for driving and transit between a sample of major residential and employment centers in the Washington DC metropolitan area reveals an average six percent higher perceived travel cost for transit than driving. Sensitivity analysis revealed the importance of parking costs, the cost of time, the amount of walking time, and the amount of in-vehicle travel time in determining the perceived benefit of using transit. Based on this analysis, it is suggested that Transportation Management Strategies intend to level the cost of or effectively encourage greater use of transit should include increasing parking costs, promoting the advantages of walking to transit, or promoting the productivity one can achieve during ones commute.

CHAPTER 5 - DISCUSSION OF RESULTS

Outcomes from this study suggest perceived cost advantages for commuting by automobile between sample residential and employment locations. In this chapter these results are verified against "journey to work data." Also, individual elements of the mode travel cost formulas are validated against findings in published research. Finally, this chapter discusses potential improvements to the data model and conceptualizes an online application to visualize these outputs.

5.1 Verifying Trip Results

In this model, the relationship between the perceived costs of commuting choices varied considerably between different residential origins and employment destinations. In order to validate outputs of the model, results for origins were compared to 2012 American Community Survey "Journey to Work" data collected by the U.S. Census. The "Journey to Work" data contains approximations for the number of commuters who use each mode. The percentage of travelers using a particular type of transportation is commonly referred to as the "mode split." Residential origins were compared to the mode split of transit and driving. Only origin locations were chosen because it is more difficult to obtain mode split results for employment areas.

Data for each origin point were compared to data for the census tracts they lie within. Census Tracts were chosen for these comparisons because they are the smallest geographic census unit that contains mode split data. Figure 24 below identifies the location of the census tracts associated with each origin point location.

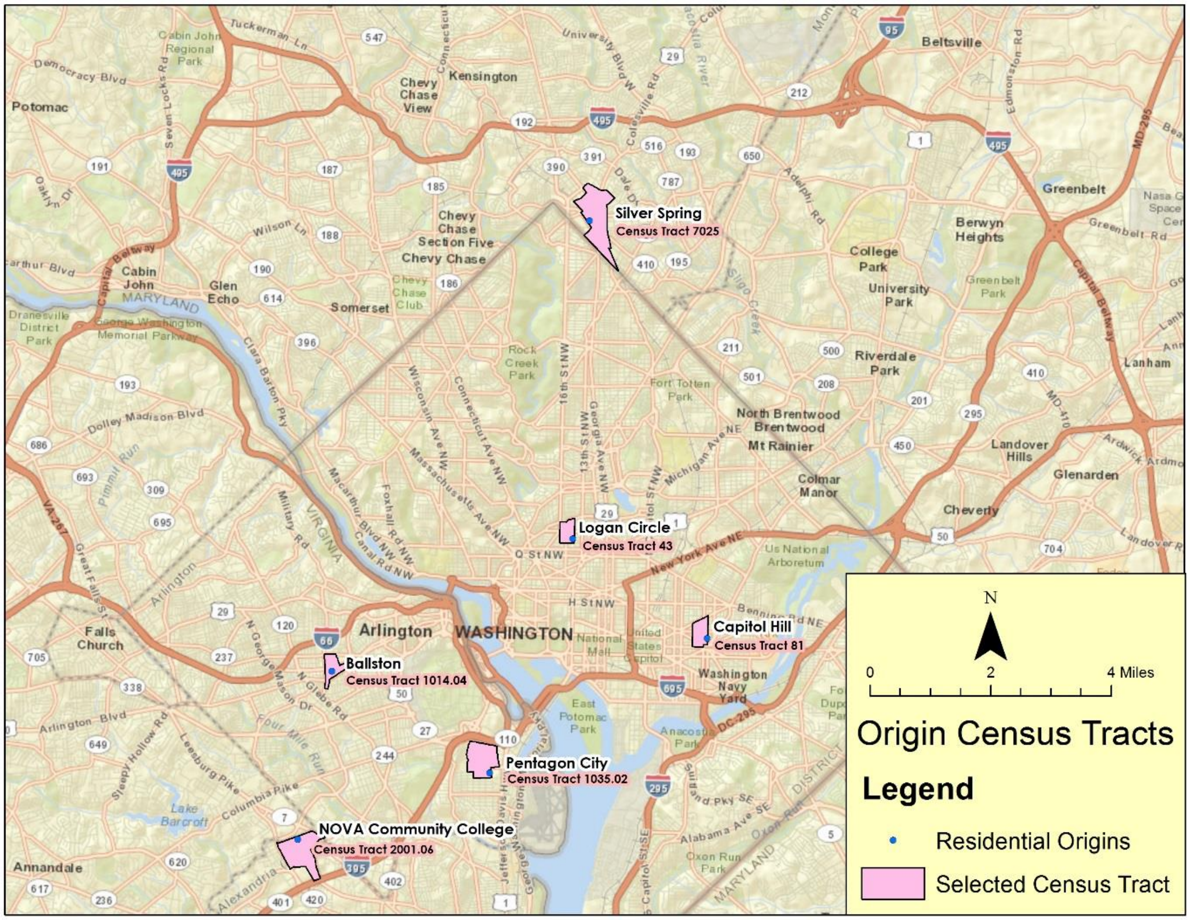
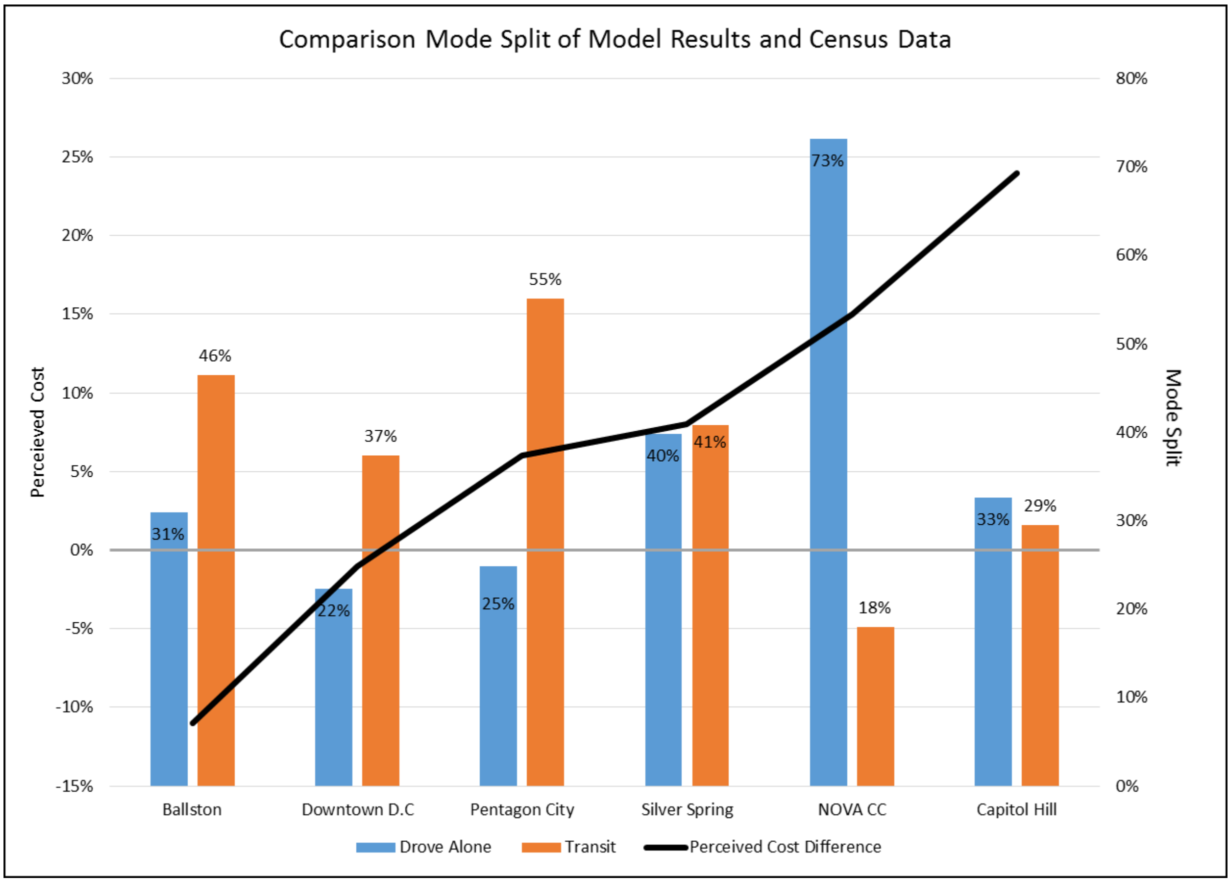


Figure 24: Origin Census Tracts for Model Mode Share Verification.

Census data for 2012 was the used because it is the most recent data available for mode split. Even though this model used 2014 transportation conditions, 2012 values are assumed to be directly comparable because no recent transportation improvements would have significantly shifted transportation perceived cost for origin locations.

From the six residential neighborhoods studied, two neighborhoods, Ballston and Downtown, revealed lower perceived costs for commuting by transit than driving. Capitol Hill and NOVA Community College had the highest perceived cost of transit. Figure 25 compares the mode split for driving alone and transit for all origin locations from the census data with the perceived cost difference between the two modes rendered from this model. While the scales for these two different datasets are not comparable, the trends in differences between modes can be examined. The origins are ordered left to right by increasing perceived cost difference so the increasing trend is shown as a black line. As one can see for the first four locations, Ballston, Downtown DC, Pentagon City, and Silver Spring, had transit perceived costs either lower than automobile or neutral and transit was also the dominant transportation mode. The last two study locations NOVA Community College and Capitol Hill, had higher modes for drive alone and higher perceived cost in favor of driving.



Source: U.S. Census Bureau, 2008-2012 American Community Survey

Figure 25: Transit and Drive Alone Mode Split Comparison with Perceived Cost Difference. The left axis represents the perceived cost between transit and car and the right axis the mode split percentage.

In Figure 25, there appears to be a positive relationship between a lower transit perceived cost and transit mode split. The opposite relationship between perceived cost and drive alone is true as well. As transit has lower perceived costs, more people use transit, and as transit has higher perceived costs, fewer people use transit. Of course, the use of only six sample origins is not sufficient to fully confirm this model's validity.

It is also important to acknowledge that there are some key differences between these two sets of data. The data from the American Commuter Survey (ACS) Census is an estimate of the mode split between all trips leaving the site at all times. This model only takes into account the perceived cost of five destinations at one particular time of day and, as was seen in the previous chapter, destinations of commute trips can play a significant role in determining the average perceived cost. Furthermore, this analysis only takes into account two mode of transportation when in reality there may be many more dominant modes in a census tract. Capitol Hill, for example only displayed a four percent difference between driving and transit, but in reality, it also hosts significant modes splits for biking and walking which obscures the true competition between transit and driving.

5.2 Verifying Formula Trends

In a further attempt to validate this model, conclusions drawn from the sensitivity analysis were compared to results of other studies reported in the academic literature. Model results discussed in Section 4.2 indicate that time costs and parking cost were most influential to the additive travel cost formula; confirmation of this was sought in the literature and discussed here.

5.2.1 Time Cost

This model is constructed such that as the value of time falls, the perceived cost of transit decreases. In this model and in the MWCOG model, cost of time is tied to median income; a drop in income results in a reduction in perceived cost – a situation that can make the additional time required taking transit to be less of an inconvenience. In 2007, American Public Transportation Association (APTA) conducted a demographic study of national transit ridership and found that the median income for transit riders was $39,000, roughly $5,000 less than the average median income of $44,389 (Neff and Pham. 2007). Furthermore Murakami and Young in their research noted that lower income individuals are more likely to take transit to work. While not directly correlated, these studies do suggest that people with lower incomes are more willing to take transit. This appears to support the model's assumption of the relationship between income and perceived cost of transit travel time.

5.2.2 Parking Cost

Due to the additive nature of the driving cost model, as parking cost goes up, the perceived cost difference between transit and driving decreases significantly. This is consistent with general parking management practices and transportation theory. For example, the City of Seattle's Urban Management Plan states "The supply of free or inexpensive parking at the final destination is a key decision factor cited for choosing to drive a personal auto rather than taking a bus, bike, walk or carpool" (Seattle Department of Transportation 2008, 7B -1). Or, from the other perspective, as parking costs go up, so does the desire to commute by transit.

The TCRP (Transit Cooperative Research Program) report by the Transportation Research Board of the National Academies confirms this trend as well. They note under parking pricing objectives: "The price of parking may be used to influence travel choice by altering the cost of private vehicle travel, and hence its attractiveness, relative to travel alternatives including transit" (Vaca and Kuzmyak 2005, 13-2). They directly confirm the perceived cost trends related to parking pricing demonstrated by the model.

5.3 Interpretation of Results in the Greater Regional Context

This model showed six percent higher on average perceived cost for using transit versus driving for the 29 sample commuting trips, but by no means is this average expected to hold for the entire region. This model was heavily dependent on the sample locations chosen and the time at which travel began, conditions which heavily favor transit commute success. As is discussed in this section, the region's typical commute trip does not have characteristics such as close proximity to Metrorail, high density, or costly employee parking. Despite the selection of sample location with transit-favorable conditions, the model results still indicated generally lower perceived costs for driving.

5.3.1 High Density

It is broadly accepted that fairly dense urban development is an essential feature of a successful public transit system (Cervero and Guerra 2011). Origins and destinations in this model were chosen based on highest density. Because of this, walking distances are most likely shorter than average commute trips in the region, and transit presence is almost always guaranteed. Furthermore, in the model, the high density of employment locations produced high parking costs, and high parking penalties. On a regional scale where density is not always guaranteed, trips may have extended walking distances to transit, low parking costs, and almost no additional parking time penalties.

5.3.2 Proximity to Heavy Rail System

Most sample locations chosen in this model were near the WMATA Metrorail system, which provides travel speeds comparable to driving. It is no coincidence that the higher density employment and residential cores are near Metrorail Stations. The presence of heavy rail stations highly encourages development and intensity of use (Diaz n.d.). Likewise, WMATA also promotes smart growth principles throughout this system by fostering a vibrant Transit Oriented Development (TOD) program which includes higher densities near current and future Metrorail stations (WMATA n.d.).

Figure 26 displays a half-mile walkshed from all Metrorail stations within the study area. This distance in this figure reflects the true walking distance along the road network. As one can see, 8 out of the 11 employment and residential sample areas are within a half mile on the network, the standard threshold for walking distance (O'Sullivan and Morrall 1996), of a Metrorail Station. Only Tysons, NOVA, and Capitol Hill are not near Metrorail Stations. All three of these locations had average commutes with perceived costs heavily in favor of driving. Tysons had a perceived commute costs 43 percent higher for transit versus driving, Capitol Hill 24 percent higher, and NOVA Community College 15 percent. By using areal interpolation of the overlap between the half mile walksheds and TAZ polygons, it is possible to determine that only 19.1 percent (360,989 out of 1,887,053) of the population in the entire study area lives within a half mile of a Metrorail Station. This means that the majority of commute trips, at least in the study area, would most likely resemble those of Tysons, Capitol Hill, and NOVA.

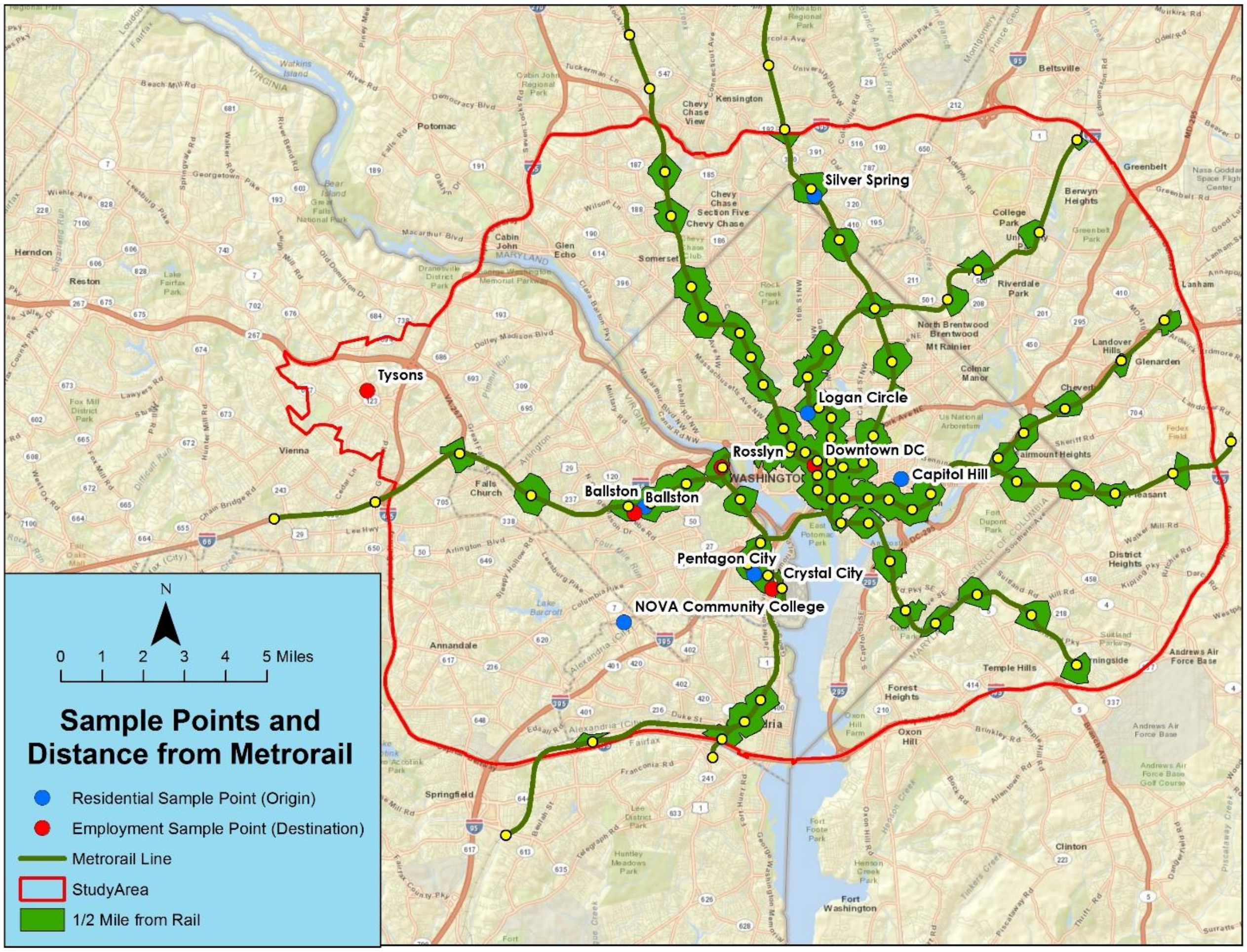


Figure 26: Sample Locations and Half Mile Distance from WMATA Metrorail Station. Only 19.1 percent (360,989 out of 1,887,053) of the population in the entire study area lives within a half mile of a Metrorail Station

5.3.3 Peak Hour Travel Time

Transit system operations do not only have a spatial component, they have a temporal and network dimension as well. Departure times heavily dictate travel times. This model was conducted for the transit peak hour at 8:00 AM. This hour correlates with shorter headways on transit and higher congestion on roads resulting in shorter travel time by transit and longer travel times by automobile. If this model were tested at another time during the day, for example at 11:00 AM, travel times by transit are likely to be greater and travel time by car are likely to be less, thus increasing the likeliness that perceived transit costs would be higher than auto. In this study, the model was run for a time in which the relationship between transit travel time and car travel time would be generally balanced in favor of transit. Of course, it is worth noting that not all home to work commute trips in the region will fall within the peak hour of transit operations.

5.4 Suggested Improvements to Model

The small number of trips studied makes it difficult to make conclusions for the region as a whole. While a single run of this model may show that one travel option is more cost effective than the other for a particular trip, the limited implementation undertaken in this study certainly did not provide an analysis of the commuting experience region wide. It would be ideal to run the model for a much larger group of commuting trips, say 1000 origins and 1000 destinations equaling 1,000,000 trips, however, the need to generate some data manually, missing fare data, and limitations in both Google Transit! and Yay Transit! precluded this from being done at this time. In this section some enhancement that would make this model expansion possible are discussed.

5.4.1 Suggested Enhancements for Yay Transit! Tool

The ability of Yay Transit! to simulate transit operations through ArcGIS is a major stride forward for transit analysis, however as a result of this trial implementation of this model, several improvements can be suggested to improve the tool's value.

The Yay Transit! tool currently automatically selects the first trip to the destination one can take after the designated departure time. The current configuration of the tool does not provide enough flexibility to account for how an individual would choose their trip. Google transit, on the other hand, allows the user the ability to view the travel length of each trip combination within a limited period after the proposed departure time. This is beneficial to the individual because he or she would be able to select the most convenient option available. By using a similar concept, as opposed to automatically selecting a departure/arrival time, the Yay Transit! tool should query for a trip within a departure window which represents the earliest and latest a trip can arrive or depart. The program should then solve the route analysis for all routes within that window and automatically select the most convenient alternative.

On occasion, the Yay Transit! tool solved transit route queries in a manner that poorly reflected the likely travel path of an individual taking transit. For example, the route path between Capitol Hill and Ballston contained two extra transfers. As you can see in Figure 27 below, the route solution traveled along the Orange Line, transferred to the Green Line, followed by the Red Line, in order to get back on the same Orange Line. The overall time saved was two minutes, but it seems likely that in almost all instances, individuals conducting this trip will stay on the Orange Line the entire time. In other instances, route solutions incorporated an additional transit leg between adjacent transit stops because it was quicker than walking, even though these transit trips would only be a quarter mile in length.

Figure 27: Route Solution Recommended by Yay Transit! Versus Realistic Travel Behavior. In order to save two minutes, the route solution traveled along the Orange Line, transferred to the Green Line, followed by the Red Line, in order to get back on the same Orange Line. More likely than not, a typical commuter would remain on the Orange Line despite it taking two minutes more.

In order to solve this issue, the author recommends incorporating algorithms into the Yay Transit! tool to eliminate unnecessary transfers. Route combinations should automatically be eliminated for solutions that propose extra transfers for a comparatively small amount of time savings. Transit trips of less than a mile should also be eliminated unless the equivalent walking distance of the trip would take a significant amount of time. Investigation should go into determining the appropriate thresholds at which the algorithm should avoid recommending additional transit transfers.

The perceived cost of transit contains elements of time and cost, yet within the Yay Transit! application, only time costs are evaluated to solve trips. Even if data for fares existed, the Yay Transit! tool currently lacks the ability to incorporate these fare costs within optimal path calculations. Similarly, the tool lacks the ability to propose separate weights for walking and waiting components. If all of these pieces were customizable within the network route solution, the model would ensure that the most optimal route combination is always selected.

5.4.2 Suggested Enhancements for Google Transit

During the analysis it was found that Google Transit lacked data for some operators in the area. Due to this, the application occasionally failed to simulate accurately the most convenient transit trip. As of March 22, 2014, Google has still not incorporated operations data on Fairfax Connector or the Circulator. Fortunately, GTFS data for both systems was found on the internet which allowed them to be incorporated into the ArcGIS network used in this implementation of the model.

5.4.3 Enhancements Needed for Fare Calculator

A constraint to simulating this model in bulk is the lack of capacity and data to calculate transit fare costs by trip. GTFS data contains very detailed information on transit operations including the time at which a transit vehicle will arrive at any stop in the system on any given day of the year. Unfortunately, both systems, Google and Yay Transit!, lack the capacity to calculate transit fares. In this model, the fare cost of trips was calculated manually for each route based on the selected itinerary and transit operator rules. To do this automatically, a system would need algorithms that decipher the fare rules for each transit operator and incorporates the cost of transfers between select origins and destinations.

5.5 Recommendations for Further Developments

Although it is difficult to draw conclusions for the region as a whole through this limited implementation of the model, the methodology presented provides a framework for a larger regional model of commuting choices. If the Yay Transit! tool can be enhanced as suggested above and a means for automatically calculating fares can be devised, the model could be conducted in batch mode for areas across the entire region. Summaries of the results could be hosted in an online application with a dashboard similar to that of Figure 21 which would allow the user to personalize formula variables and parameters to understand how transportation policies and sentiments would change their own perceived cost of travel.

The author conceptualizes an application similar to “Transit Score” developed by Walkscore (Walkscore.com). In Transit Score, the user can select a location on the Google map and receive a score for the site indicating the connectivity of the site within the context of the transit system. A general outline is drawn around the area to show the distance one can travel on transit given a window of time.

Similar to Transit Score, the application the author envisions would be based on an online map. Individuals would be able to select an origin or destination point and visually observe the perceived costs of taking transit or driving from that point to the entire region. The application would inform the individual where perceived costs for transit are higher than for car and vice-versa. The author conceptualizes a dashboard with the map to allow users to customize their perceived cost based on their own sentiment. For example, the individual would insert their own income to evaluate their personal time cost, or enter their vehicles miles-per-gallon to more accurately reflect their own travel cost per mile. Over time, this map application can expand on the additive models used here by incorporating additional variables which impact travel conditions, such as comfort on transit, reliability perceptions, safety, availability of transit arrival phone apps (ex. Nextbus,).

The author foresees multiple parties utilizing this application. Local government users such as city officials and transit operators could use the application to understand how policy changes impact the attraction of transit in the region. Land and property developers could use the application to understand where employment or residential areas are best connected, attracting potential tenants and ensuring their developments are located in well-connected areas. Potentially, renters and buyers would be able to see where they should consider housing based on the lowest costs of travel to work or through preferences for one mode over another. This application will have the power to educate everyone on mode accessibility and travel affordability.

CHAPTER 6 - CONCLUSION

Drive alone commuting has been found to be harmful for society, human health, the American economy, and the environment, but despite these known repercussions, 76 percent of Washington region commuters choose to drive alone for their daily travel. This analysis modeled the components of travel mode choices for 30 of these commute trips and identified through an aggregative cost formula the true cost of travel for both driving and transit. Of the 30 trips, transit had lower perceived cost than driving for 11 trips, driving perceived costs were lower for 18 trips, and one trip only made sense to travel by walking. Three of 11 origin and destination locations were calculated to have on average lower perceived cost travel access by transit than driving.

The average difference in perceived cost value between transit and driving for all origins and destinations examined in this study was six percent. Analysis of the results suggested Transportation Demand Management Strategies that could be used to balance the desirability of commuting via transit. These strategies include increasing the price of parking, promoting the benefits of walking for transit commutes, and marketing the attractiveness of multitasking on transit.

The true travel cost for transit and driving was derived by using an aggregative utility model based on the MWCOG Model. This model took into account the out of pocket cost of travel and the aggregate time related to travel on transit and driving. By using the ArcGIS toolkit,” Yay Transit!” and the ArcGIS Network Extension, this model was able to successfully transform GTFS data into a transit operations network inside ArcGIS. Route queries were conducted to simulate actual transit itineraries. Automobile travel times were produced from Google’s Waze application which calculates real travel times based on live traffic conditions.

Sample origin and destination points used in this model were chosen by using a Hot Spot analysis of population and employment densities in the region. Six residential neighborhoods and 5 employment centers were selected. These sample locations generally presented favorable transit conditions including high density, which tends to increase the cost and time of driving, and close proximity to Metrorail, which provides comparable travel speeds to driving. Despite these benefits, transit costs on average failed to measure up to driving suggesting a lack of perceived cost convenience region-wide for transit commuting.

Although it is difficult to draw conclusions for the region as a whole based in the limited analysis conducted, the model provides a framework for the implementation of a larger regional analysis of travel preferences. If certain limitations to the Yay Transit! tool are addressed and data is created for fares, this model can be conducted in batch for all areas in the region. The results from this model can be hosted on an online application similar to "Transit Score" which will inform public and private entities of the complexities of urban accessibility.

It will not be easy to change the commuting habits of three quarters of Washington DC commuters, but with an understanding of current travel options and some insight into ways to shift travel choice attraction, meaningful steps may be taken to encourage transit usage and reduce overall drive alone commutes.

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