ADVANCED PLANNING MODELS FOR TRANSIT ORIENTED DEVELOPMENTS

by

Arsalan Faghri
A Dissertation
Submitted to the
Graduate Faculty
of
George Mason University
in Partial Fulfillment of
The Requirements for the Degree
of
Doctor of Philosophy
Civil and Infrastructure Engineering

Committee:

_____________________________________ Dr. Mohan M. Venigalla, Dissertation Director

_____________________________________ Dr. Michael J. Casey, Committee Member

_____________________________________ Dr. Laurie A. Schintler, Committee Member

_____________________________________ Dr. Burak Tanyu, Committee Member

_____________________________________ Dr. Deborah J. Goodings, Department Chair

_____________________________________ Dr. Lloyd J. Griffiths, Dean, Volgenau School of Engineering

Date: _____________________________ Spring 2012
George Mason University
Fairfax, VA

Advanced Planning Models for Transit Oriented Developments

A dissertation submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy at George Mason University

By

Arsalan Faghri
Master of Science
University of Delaware, 1997
Bachelor of Science
York University, 1995

Director: Mohan Venigalla, Professor
Department of Civil, Environmental & Infrastructure Engineering

Spring 2012
George Mason University
Fairfax, VA

Dedication

To my late father who was "*vast but lone, humble but hard*."

Acknowledgements

I would like to thank my dissertation committee for their encouragement and support throughout this effort. In particular I am gratified by the guidance and technical support of my advisor, Dr. Venigalla. Dr. Michael Casey's responsiveness and Dr. Laurie Schintler's patience with me is an inspiration to be a good teacher and guide. I would also like to thank Dr. Aimee Flannery for her initial vital role in this effort. I wish her success and happiness.

My gratitude extends to the Commonwealth of Virginia and in particular the Virginia Department of Transportation (VDOT) that provided the funding for my doctoral program. I would like to thank my supervisor and mentor Mr. Paul J. Kraucunas, P.E., and my colleagues Dr. Bahram Jamei, P.E., and William R. Sitterle for the support they provided to get this project off the ground. Without their encouragement and support I would not have had the drive to initiate this task.

Finally, I would like to thank my family especially my mother for she neither bended nor budged unless it was for education; my brother, for he opened the wonderful world of transportation to me; my wife, Fereshteh, for her healthy nourishments, and my daughter, Rudy, for she taught me perseverance and determination. Thank you.

Table of Contents

List of Tables

List of Figures

ABSTRACT

ADVANCED PLANNING MODELS FOR TRANSIT ORIENTED DEVELOPMENTS

Arsalan Faghri, PhD

George Mason University, 2012

Dissertation Director: Dr. Mohan Venigalla

Transit Orientated Developments (TODs) have been recognized as a promising proposition for transportation policy makers and land developers to meet the challenges of urban sprawl. Recent land developments in the United States focus on creating livable and walkable communities, concentrated along transit corridors. The rapid pace with which TODs are being developed across the United States has left policy makers and transportation planners looking for methods aimed at modeling travel characteristics of TODs. The travel demand parameters necessary to predict trip generation rates, develop trip distribution tables, identify mode choice characteristics, and determine the trip assignment of TODs are yet to be fully explored.

A methodology has been developed to assess trip generation and mode choice characteristics in transit oriented developments based on activity based 24-hour household travel survey. This will enable transportation professionals forecast vehicular trips and modal choice of transit oriented developments. Multinomial regression models are developed and validated relating TOD trip ends to the size of the development.

Model validation is performed by checking for normality, multicollinearity and heteroscedasticity of the independent variables.

Stochastic mode choice utility models using multinomial logit regression are also developed and validated to show modal split patterns within the 0.25 mile radius of transit stations in the Washington Metro area. The likelihood of taking transit in a TOD environment based on vehicle ownership is determined.

Furthermore, there are many questions associated with the travel characteristics of TODs that need further examination. Vehicle ownership in TODs are identified and compared with non-TOD environments. The use of personal vehicle as a primary mode of travel for several trip purposes such as work, shop, and entertainment trips is explored and compared against traditional suburban communities where the use of personal vehicle is the predominant mode of travel.

The data used for this dissertation is from the 2007/2008 household travel survey obtained from the National Capital Region Transportation Planning Board of the Metropolitan Washington Council of Governments (MWCOG). The activity-based survey data provides a wealth of transit-oriented corridors, and diverse land use. The use of this data mitigates loss of computational information frequently ensued by aggregate data, hence providing a more accurate quantitative forecast.

CHAPTER 1. Introduction

1.1. Concept Description and Background

As unbalanced sprawl takes its toll on urban areas and residents experience enduring congestion in their travels to perform daily activities, transportation planners and policy makers are recognizing the need to alter transportation investment strategies. Accessibility, as an integral part of mobility, is now the focal points in planning for transportation improvement strategies.

Recognition of strong association between transportation network and the adjacent land use is fundamental in transportation planning and engineering research and policy. The number of vehicles utilizing a roadway is partially generated from the adjacent land use. Depending on the type of land use, the number of vehicles utilizing a roadway differs. For example, a million square foot administrative office building generates significantly more trips than office building used as a data center with the same amount of floor area. In the context of urban planning, the concept of smart growth has been recognized as a robust alternative to the status quo. The basic tenet of smart growth is to slow the decentralization process from urban areas to suburban areas. Smart growth promotes higher density, mixed use developments that are concentrated along transit corridors. Smart growth policy requires reinvestment in urban areas through reconstruction of existing communities and brown fields to promote higher density developments, open spaces, and a reliable public transit.

Consistent with smart growth policies, TODs, as a form of land use, attempt to reduce the amount of travel by car by promoting use of public transit and higher density mixed use developments. Transit Oriented Developments, thus, are fundamental for a successful smart growth policy. They are increasingly seen as a viable alternative to sprawl and suburban development. Research has shown that transit-oriented developments are effective in shifting the mode choice from personal vehicles to transit which would result in numerous benefits that ranges from congestion relief to improved air quality and land conversation.

From a supply side perspective, TODs are fundamental for a successful congestion management strategy in urban areas that are served by mass transit. Transit oriented developments are increasingly seen as a viable alternative to sprawl and suburban development. They are especially considered desirable developments for restoring the sense of community.

The rapid pace in developing TODs and the novelty of this land use phenomenon has left policy makers and transportation planners with a lack of knowledge related to trip characteristics of TODs. The travel demand parameters necessary to predict trip generation rates, develop trip distribution tables, identify mode choice characteristics, and determine trip assignment of TODs are yet to be fully explored. This research seeks to address the gaps in analytical methods to be utilized in planning for the TODs as it relates to trip generation and mode choice characteristics in travel demand forecasting.

1.2. Problem Statement

One of many roles of a transportation engineer and planner is to determine the traffic impacts of a variety of land uses. The industry standard approach in the United States is the Traffic Impact Study or Analysis (TIA). The Institute of Transportation Engineers (ITE) Trip Generation Handbook is the primary source for calculating trip rates associated with a variety of land uses. Trip rates are determined based on different variables including area of the land use, number of dwelling units, or number of employees. The association between the trip rates, as the dependent variable, and the mentioned variables, as the independent variable, is shown through the use of regression models that are presented for each specific land use in the ITE Trip Generation Handbook. The selection of the independent variables is usually based on accuracy, ease of collection and reliability of the data.

While ITE's Trip Generation Handbook contains a trip rate for over 150 different type of lane use it lacks a suitable methodology for transit-oriented developments.

Most recently ITE attempted to develop a methodology to forecast the number of vehicular trips for mixed use developments. The proposed methodology does not necessarily include the element of transit and was not the primary focus in the development process. Furthermore, the data utilized for the study primarily came from suburban sites with abundant parking space.

The methodology has been noted by many to overestimate trip generation numbers. A California Department of Transportation (Caltrans) study noted that the ITE proposed model for TODs is not applicable to urban infill sites as the locations used to develop the

ITE proposed model for TODs were typically "isolated locations with ample free parking with little transit and pedestrian accessibility." The report also indicated that the ITE proposed model does not include methods for estimating non-vehicle mode share (Caltrans, 2008).

Furthermore, a comparative analysis of ITE methodology and actual observed trips generated by transit-oriented developments was performed by Cervero. The study was based on empirical data from 17 transit-oriented developments in five U.S. metropolitan areas. According to the authors, the actual observed trips were 44 percent lower than ITE estimations (Cervero, 2008).

There is also an apparent lack of analysis associated with the modal choice characteristics of transit-oriented developments. The additional intent of this research work to fully utilize the activity based data and further explores the mode choice characteristics of TODs. The mode choice models show the relationship between the probability of utilizing a specific mode of travel (transit, cars, bus, subway) for a particular type of trip (i.e., home, work, shop). The question of whether utilizing transit as the primary mode of travel in a transit-oriented development community is therefore need to be investigated. Utilizing the 2007 – 2008 activity based household travel survey data, utility model is developed to examine the assumption that the probability of taking transit in TODs is higher than any other mode of travel in transit-oriented developments. Travel time as the variable that is most likely to impact the mode choice is selected to be used in the utility model.

Finally, there are many questions associated with the travel characteristics of transit-oriented developments that need further examination. Questions such as: How much proximity to a transit station matters, do TODs indeed reduce vehicular trips, do TOD residents own fewer vehicles, and do work trips take longer for TOD residents? Vehicle ownership in TODs are identified and compared with non-TOD environments. The use of personal vehicle as a primary mode of travel for several trip purposes such as work, shop, and entertainment trips is explored and compared between TOD and non-TOD communities. These models and analysis are a testament to how much presence of transit matter for variety of daily trips, and if proximity to transit in a TOD environment matters.

1.3. Definition of TOD

There is no single definition of transit-oriented developments. Several agencies and organizations have offered definitions including the Center for Transit Oriented Development (CTOD), the Transportation Research Board through their Transit Cooperative Research Program (TCRP), the Washington Metropolitan Area Transit Authority (WMATA) and the American Public Transportation Association (APTA). The Center for Transit Oriented Development (CTOD) defines it as a mix of housing, retail and/or commercial development and amenities – typically referred to as mixed-use development – integrated into walkable neighborhoods within a half-mile of quality public transportation (CTOD, 2010).

The Washington Metropolitan Area Transit Authority (WMATA) defines TODs as "projects near transit stops which incorporate the following smart-growth principles:

reduce automobile dependence; encourage high shares of pedestrian and bicycle access trips to transit; help to foster safe station environments; enhance physical connections to transit stations from surrounding areas; and provide a vibrant mix of land-use activities." (WMATA, Development Related Ridership Survey, 2005). WMATA further notes potential benefits of TOD as:

- Reduced automobile trips and greenhouse gas emissions,
- Reduced transportation costs,
- Improved access to local and regional amenities,
- Improved workforce access to job opportunities, and
- Creation of a sense of community and place.

The Transit Cooperative Research Program (TCRP) Report 95 chapter 17 that strictly deals with TODs and defines such developments as "TODs generally refers to higher-density development, with pedestrian priority, located within easy walking distance of a major public transit station or stops. TODs are viewed as offering the potential to boost transit ridership, increase walking activity, mitigate sprawl, accommodate growth, and create interesting places. TOD is a form of development that attempts to reduce the amount of travel by car through promoting use of public transit. The TOD potential depends more on the design and quality of service than it does on the transit technology. High-quality service for all transit technologies is defined as high-frequency service along dedicated lanes or rights of way" (TCRP 95, 2007).

TCRP Report 95 identifies three elements that best characterizes TODs. These are as follows:

- “Regional Context. TODs may exist in a long-established city center or in a suburban context. Although locating TODs in either area type may result in boosted transit ridership and increased walking, the regional context plays a role in determining the overall traveler response. City center TODs generally have higher levels of transit service to more travel markets than suburban TODs and consequently have higher transit ridership generation potential. However, the difference TOD represents from the status quo in suburban contexts is likely more pronounced than in city center contexts, one of the reasons suburban applications receive more attention in the literature.
- Land Use Mix. TODs come in a variety of flavors with different mixes of office, retail, and residential space. The travel behavior response to TOD may be influenced by the type and quantity of uses present. For example, TOD that enables its occupants to address daily needs within the project may result in fewer automobile trips and lower automobile ownership rates than less diverse TOD.
- Primary Transit Mode. TOD has been planned or constructed around metrorail and bus transit stations and stops. Modal characteristics may factor into both the development feasible at the station and the ability of public transit to serve the travel markets created by the TOD. Although TOD around stations of light metrorail transit (LRT) and heavy metrorail (metrorail rapid) transit (HRT/Metro) is the most prominently discussed in the literature, TOD can also be served by commuter metrorail (CRR), bus rapid transit (BRT), and good-frequency traditional bus services” (TCRP 95, 2007).

The TOD potential is also determined by the walkability and bike-ability of station areas, the presence of retail amenities, and the local and regional housing market (CTOD, 2010).

A Transit Oriented Corridor (TOC), on the other hand, is best defined as the walkable areas around the transit station along a transit line within the influence area. The influence area depends on the transit technology. For example, the area of influence along light and heavy metrorail corridors is typically a half mile radius around the transit station. Because streetcars can stop as often as every street corner they tend to have a wider area of influence which can be up to three blocks on either side of the transit station. Any transit technology can define a transit corridor – heavy or light metrorail, streetcar, trolley or bus (CTOD, 2010).

Transit Cooperative Research Program (TCRP) Research Results Digest Number 52 provides the following as sample of TOD definitions found in the literature:

- "The practice of developing or intensifying residential land use near metrorail stations" (Boarnet and Crane 1998A).
- "Development within a specified geographical area around a transit station with a variety of land uses and a multiplicity of landowners" (Salvensen 1996).
- "A mixed-use community that encourages people to live near transit services and to decrease their dependence on driving" (Still 2002).
- "A compact, mixed-use community, centered around a transit station that, by design, invites residents, workers, and shoppers to drive their cars less and ride mass transit more. The transit village extends roughly a quarter mile from a transit station, a

distance that can be covered in about 5 minutes by foot. The centerpiece of the transit village is the transit station itself and the civic and public spaces that surround it. The transit station is what connects village residents to the rest of the region. The surrounding public space serves the important function of being a community gathering spot, a site for special events, and a place for celebrations—a modern-day version of the Greek agora" (Bernick and Cervero 1997, p. 5).

- "Moderate to higher density development, located within an easy walk of a major transit stop, generally with a mix of residential, employment, and shopping opportunities designed for pedestrians without excluding the auto. TOD can be new construction or redevelopment of one or more buildings whose design and orientation facilitate transit use" (California Department of Transportation 2001).
- "A place of relatively higher density that includes a mixture of residential, employment, shopping and civic uses and types located within an easy walk of a bus or metrorail transit center. The development design gives preference to the pedestrian and bicyclists, and may be accessed by automobiles" (Maryland Department of Transportation 2000).

The TCRP Report 52 further provides categories of Transit Oriented Corridors (TOC) as follows:

1. Single-Use Corridors: concentrations of single transit-intensive uses (e.g., office or retail) in transit corridors;
2. Mixed-Use Corridors: concentrations of a variety of land uses on a single parcel or group of parcels within a transit corridor;

3. Neo-Traditional Development: development that primarily focuses on design features that reproduce traditional town or village settings with small lots, narrow streets, detached parking behind houses, reduced setbacks, and front porches;
4. Transit-Oriented Development: compact, mixed-used development concentrated near transit stops (TCRP, Report 52).

The California Statewide TOD Study Technical Advisory Committee defines Transit-oriented Development (TOD) as "moderate to higher-density development, located within an easy walk of a major transit stop, generally with a mix of residential, employment and shopping opportunities designed for pedestrians without excluding the auto. TOD can be new construction or redevelopment of one or more buildings whose design and orientation facilitate transit use" (Statewide Transit-oriented Development Study by Caltrans, 2002).

According to the American Public Transportation Association (APTA), a transit-oriented development (TOD) is a compact, MXD near new or existing public transportation infrastructure that serves housing, transportation, and neighborhood goals. Its proximity to transit services and pedestrian-oriented design encourages residents and workers to drive their cars less and ride mass transit more (American Public Transportation Association. "Transit Resource Guide." Transit-Oriented Development, No. 8. 2005).

From all the various definitions presented thus far, some key features of TOD can be concluded as follows:

- Near new or existing public transportation infrastructure,
- Compact, mixed use, high density developments,

- Within walking distance of a well-served transit station with bicycle access,
- Integrated with walkable neighborhoods, and
- Public and civic spaces near stations.

For the purposes of this research several parameters were used to select an appropriate transit-oriented corridor. These parameters are the common denominator of the definitions of a transit-oriented development found in the literature. They include:

1. Mixed used developments – The variance of land use can be either concentrated in a single parcel, or be spread through a corridor that is well served by transit. The transit technology can include heavy or light metrorail, streetcar, trolley or bus.
2. Walking distance to a well-served transit station – A convenient walkable distance to a transit station, preferably 0.25 mile or less, is probably the most important criteria in defining a Transit-oriented environment.
3. Moderate to high density developments – Increased density of the land use is arguably the most important contribution of TODs in reduction of Vehicle Miles Traveled (VMT) and congestion.
4. Pedestrian and bicycle friendly – In order to satisfy criteria No. 2 above, well connected pedestrian and bicycle facility is necessary.

1.4. TOD Typology

Characterization and classification of TODs is non-uniform and is scattered throughout the literature. The trip generation rate for a TOD vastly differs depending on the type of land use, proximity to transit use and area type that the TOD development is located. Typology of TOD would assist engineers and planners identify the true trip characteristics of the TOD and develop and/or apply the correct trip prediction model for trip generation rates.

The ITE defines Transit Oriented Developments through the use of area types and Context Zones (ITE Parking Generation, 3rd Edition, 2008). These area types are described as follows:

- Central Business District (CBD) is the downtown area for a city. CBD characteristics include good transit service, parking garages, shared parking, an extensive pedestrian sidewalk network, multi-storied buildings, priced parking, and a wide range of land uses (including mixed-use sites).
- Central City Not Downtown (CND) is the area outside the downtown area of a larger city. This area has greater land use density than suburban sites, but is substantially less dense than the CBD. The intent of this area designation is for the places around large central cities (for example, Seattle, San Francisco, Oakland, Atlanta, and Washington, DC) where travel characteristics are likely to be unlike suburban conditions.
- Suburban Center (SBC) areas are those downtown areas of suburbs that have developed CBD characteristics, but are not the central city of a metropolitan region. These activity centers have characteristics that may include good transit service, a mix of surface and structured parking, connected streets, a connected pedestrian network, and a mix of land uses.

Context Zones are development intensity-based descriptions that range from the most rural or undeveloped area to the most urban or developed area (ITE, 2006). The following Context Zone types are proposed to be used in parallel or as alternatives to the more traditional CBD area types to characterize TODs:

- General Urban: Denser and primarily residential urban fabric. Mixed-use sites usually confined to corner locations. Characterized by a wide range of building types: single, side yard, and row houses. Setbacks and landscaping are variable. Streets typically define medium-sized blocks. Typical land uses include medium density residential and home occupations; limited commercial and lodging. Typical buildings include houses and outbuildings, side yard houses, townhouses, live/work units, corner stores, and inns.
- Urban Center: "Main Street" land uses, characterized by building types that accommodate retail, offices, row houses, and apartments. Typically has a compact network of streets, with wide sidewalks, uniform street tree planting and buildings set close to the frontages. Typical land uses include medium intensity residential and commercial uses, (i. e., retail, offices, lodging, civic facilities). Typical buildings include townhouses, apartment houses, live-work units, shop-front buildings and office buildings, hotels, churches, and schools.
- Urban Core: "Downtown" land uses, characterized by the tallest buildings, in the greatest variety, and unique civic buildings in particular. It is the least naturalistic zone type in which street trees are uniformly planted and sometimes absent. Typical land uses include high intensity residential and commercial: retail and offices, lodging, civic buildings. Typical buildings include high and medium-rise apartment

and office buildings, hotels, townhouses, live-work units, shop fronts, churches, and civic buildings.

Transit Oriented Developments are characterized by three main dimensions (J. Evans and R. Pratt, 2007). According to the authors the dimensions are:

- Regional Context. TOD may exist in a long-established city center or in a suburban context. Although locating TOD in either area type may result in boosted transit ridership and increased walking, the regional context plays a role in determining the overall traveler response. City center TODs generally have higher levels of transit service to more travel markets than suburban TODs and consequently have higher transit ridership generation potential. However, the difference TOD represents from the status quo in suburban contexts is likely more pronounced than in city center contexts, one of the reasons suburban applications receive more attention in the literature.
- Land Use Mix. TODs come in a variety of flavors with different mixes of office, retail, and residential space. The travel behavior response to TOD may be influenced by the type and quantity of uses present. For example, TOD that enables its occupants to address daily needs within the project may result in fewer automobile trips and lower automobile ownership rates than less diverse TOD.
- Primary Transit Mode. TOD has been planned or constructed around metrorail and bus transit stations and stops. Modal characteristics may factor into both the development feasible at the station and the ability of public transit to serve the travel markets created by the TOD. Although TOD around stations of light metrorail transit

(LRT) and heavy metrorail (metrorail rapid) transit (HRT/Metro) is the most prominently discussed in the literature, TOD can also be served by commuter metrorail (CRR), bus rapid transit (BRT), and good-frequency traditional bus services (J. Evans and R. Pratt, 2007).

It is important to distinguish between transit oriented developments and transit adjacent developments. A true TOD will include most of the following: (Patrick Siegman, in Tumlin and Millard-Ball, 2003)

- The transit-oriented development lies within a five-minute walk of the transit stop, or about a quarter-mile from stop to edge. For major stations offering access to frequent high-speed service this catchment area may be extended to the measure of a 10-minute walk.
- A balanced mix of uses generates 24-hour ridership. There are places to work, to live, to learn, to relax and to shop for daily needs.
- A place-based zoning code generates buildings that shape and define memorable streets, squares, and plazas, while allowing uses to change easily over time.
- The average block perimeter is limited to no more than 0.25 mile. This generates a fine-grained network of streets, dispersing traffic and allowing for the creation of quiet and intimate thoroughfares.
- Minimum parking requirements are abolished.
- Maximum parking requirements are instituted: For every 1,000 workers, no more than 500 spaces and as few as 10 spaces are provided.

- Parking costs are “unbundled,” and full market rates are charged for all parking spaces. The exception may be validated parking for shoppers.
- Major stops provide bike stations, offering free attended bicycle parking, repairs, and rentals. At minor stops, secure and fully enclosed bicycle parking is provided.
- Transit service is fast, frequent, reliable, and comfortable, with a headway of 15 minutes or less.
- Roadway space is allocated and traffic signals timed primarily for the convenience of walkers and cyclists.
- Automobile level-of-service standards are met through congestion pricing measures, or disregarded entirely.

Another approach in creating a typology is the classification of TOD according to the types of sites and the mode of transit that serves them. This approach, however, does not apply to complex regions with multiple characteristics. In order to address this issue, a new typology was introduced by Dittmar and Poticha (see Table 1).

- Urban downtown TOD – The role of downtown is shifting from being the hub of employment to being a civic and cultural center. Downtown is often served by several types of transit and is typically a primary transfer point for various transits.
- Urban Neighborhood TOD – Urban neighborhoods were built on an extension of the downtown street grid and were served by transit. They form the backbone of a compact, transit friendly region and could form a transit corridor for either rapid bus or light metrorail transit.

- Suburban Town Center TOD – with suburban expansion, small towns are being surrounded by new suburbs and are evolving to include major employments centers. Inclusion of a reliable transit service will alter the suburban town into a suburban center in a region.
- Suburban Neighborhood TOD – a suburban neighborhood community is located along a transit corridor, with a good connection to a suburban town center or the urban downtown. Mixed land use at the center with high density use close to the station and lower density developments further away from the center is among the major characteristics of Suburban Neighborhood TODs.
- Neighborhood Transit Zone TOD – This is a transit stop (bus, streetcar, light Metrorail) with limited neighborhood retail or office space in a largely residential area.
- Commuter Town TOD – a commuter town is a freestanding community, served by metrorail or bus commuter service to the downtown core. The station area can be developed as a "main street" with neighborhood retail, professional offices and some multifamily residential housing within the core of the TOD zone (Dittmar and Poticha, 2004)

Table 1. Sample TOD Typology

TOD Type	Min Housing Density	Housing Types	Regional Connectivity	Transit Modes	Frequencies
Urban Downtown	> 144 units / hectare	Multifamily	High hub or radial system	All Modes	<10 minutes
Urban Neighborhood	>50 units / Hectare	□ Multifamily □ Townhouse □ Single family	Medium access to downtown sub-regional circulation	□ Light-metrorail □ Street car □ Rapid bus □ Local bus	□ 10 minutes (peak □ 20 minutes (off peak)
Suburban Center	> 120 units / hectare	□ Multifamily □ Townhouse	High access to downtown sub-regional hub	□ Light-metrorail □ Street car □ Rapid bus □ Local bus □ Paratransit	□ 10 minutes (peak □ 15 minutes (off peak)
Suburban Neighborhood	>30 units / hectare	□ Multifamily □ Townhouse □ Single family	Medium access to suburban center and Access to downtown	□ Light-metrorail □ Rapid bus □ Local bus □ Paratranist	□ 20 minutes (peak □ 30 minutes (off peak)
Neighborhood Transit Zone	>17 units / hectare	□ Townhouse □ Single family	Low access to a center	□ Local bus □ Paratranist	□ 25 – 30 minutes. □ demand responsive
Commuter Town Center	> 30 units / hectare	□ Multifamily □ Townhouse □ Single family	Low access to downtown	□ Commuter □ Metrorail □ Rapid bus	□ Peak Service □ Demand responsive

Source: Dittmar and Ohland, The new transit town: Best practices in transit-oriented development, 2004.

Most recently, the Center for Transit-Oriented Development (CTOD) has designed the performance-based TOD typology as a user-friendly tool that gives the ability to evaluate the performance of the transit zones. The typology creates distinct place types by identifying the number of miles the typical household within each transit zone will travel in a year and whether the area is primarily residential, employment, or a balance of the two (See Figure 1). Understanding where an individual transit zone sits in this spectrum, or how all of the transit zones in a region compare to one another can make it easier for stakeholders to identify strategies to reduce VMT or to take advantage of existing low VMT places. In this typology the performance of TOD is measured at the neighborhood scale. As a result, the performance-based TOD Typology defines the half-mile radius around each transit station as a unique transit zone. The characteristics of all households within this radius are averaged together, and those averages are used to define the place types and other characteristics of each transit zone. This analysis includes the approximately 3,760 existing transit station areas in 39 regions across the country. (Performance-Based Transit Oriented Development Typology Guidebook, CTOD, 2010).

Use Mix Type	Percentage of workers relative to workers and residents
1 primarily residential	33.3% or less
2 balanced	33.3% to 66.7%
3 primarily employment	66.7% or more

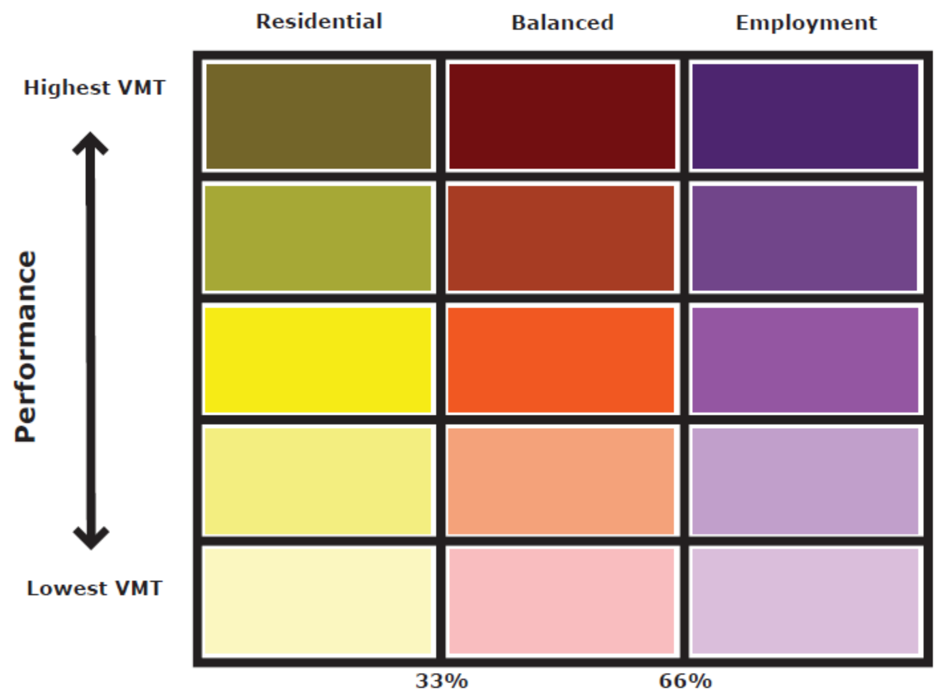


Figure 1. Performance-Based TOD Typology Guidebook (CTOD, 2010)

1.5. State of Practice

Current methods of traffic impact analysis associated with TODs rely on the Institute of Transportation Engineers (ITE) trip generation rate methodology. According to many studies in the literature, the ITE methodology over-estimates the trip generation numbers, which leads to exaggerated roadway impacts and higher impact fees. Consequently, private developers have, thus far, not been encouraged to take advantage of lower impact fees that indeed mixed-use transit-oriented development have to offer and design and build more of this type of development.

A national study for the US EPA, performed by a team composed of both Fehr & Peers and academic researchers developed a new methodology to accurately predict the traffic impacts of mixed-use developments (MXDs). The methodology known as the MXD Methodology depend on the D variables. The original "three Ds," created by Cervero and Kockelman (1997), are density, diversity, and design followed by destination accessibility, distance to transit, and demographics (Ewing and Cervero 2001) which was developed later. The methodology directly aims at adjusting the ITE trip generation rates downward.

The MXD Methodology consists of four steps to determine the daily vehicle trips on external roadways generated by the mixed-use development. The four steps and outputs (Fehr & Peers, 2010) are:

1. Compute daily trip estimates using standard ITE rates or equations.
2. Compute the probability of a trip staying internal to the mixed-use development.
3. Compute the probability an external trip will be made by walking or bicycling.

4. Compute the probability an external trip will be made by transit.

Once these probabilities are determined the trip generation is calculated as follows:

*Mixed-Use/TOD Development = Raw Trips * (1 – P_internal) * (1 – P_walkbike – P_transit)*

The three probability models (*P_internal, P_walkbike, and P_transit*) depend on variables that are characteristics of the mixed use development. These characteristics include employment, land area, jobs, population diversity, average household size, and vehicles owned per capita.

The MXD methodology was validated using 239 mixed use developments nationwide. The results showed a close correlation between the trip generation numbers derived from the MXD methodology and the actual trip rates generated from the test sites.

A second methodology is called the MTC methodology which is based on San Francisco survey data. The methodology focuses only on TODs near high capacity rail and ferry services. The MTC methodology is still in the experimental phase and is not in widespread use (Handy, 2011).

1.6. Description of Data

With the emergence of tour-based travel demand models as the new state-of-the practice to analyze travel characteristics of a region, the need for 24-hour activity-based household travel survey is determined by many planning organizations. Tour-based travel demand models are gradually replacing the traditional four-step travel demand models that have been used to forecast trip numbers and characteristics of a region since 1960's. Several major planning organizations, including Portland, San Francisco, Sacramento, Denver, Atlanta, and Dallas-Fort Worth have either developed the tour-based models or are in the process of transitioning from the traditional four-step travel demand model to tour-based models.

In the conventional four-step trip based Travel Demand Modeling (TDM) the unit of analysis in individual trips. The trip generation portion of the model estimated home-based and non-home based person trips that are attracted to or produced from a TAZ. Trip generation is followed by trip distribution which identifies trip interchanges between zones. Mode choice splits person trips, that were derived in the previous stage, between different travel modes. The last step in the traditional trip-based TDM is to take the vehicular trips that were obtained in the previous step and assigns them to the travel network based on various types of algorithms.

In a tour based TDM, however, the tour is the basis of analysis. A tour is defined as "a closed chain of trips that begin and end at the same location. Trips are intermediary stops along the tour" (CTR 0-6210-2, University of Texas, Austin, 2009).

In terms of data input to the two modeling approach, one of the major differences is the travel data. Aggregate models are based on household interview that has been aggregated into zones. Average zonal productions and attractions are determined from this data. The data for disaggregate models, however, is based on large samples of individual households, demographics, and travel behaviors. This individualized data is readily available from the aforementioned planning agencies and can be used for all parameters of a four step demand model.

In a trip-based TDM each trip is independent of other trips which may result in ignoring the spatial and temporal linkages between the trips, thus unreasonable trip chain prediction.

Table 2 shows the status of trip-based TDM in some of the major planning organizations in the nation (NCHRP 406, 2010).

The data used for this paper is based on the 2007/2008 household travel survey obtained from the National Capital Region Transportation Planning Board of the Metropolitan Washington Council of Governments (MWCOG). The activity-based survey data provided a wealth of transit-oriented corridors, and diverse land use. The use of this data mitigates loss of computational information frequently ensued by aggregate data, hence providing a more accurate quantitative forecast. The data includes a survey of 24-hour activity based travel patterns for 11,000 households in the greater Washington area which includes northern Virginia and parts of Maryland. The survey was conducted between February 2007 and March 2008 and includes more than 25,000 person records, 16,000 vehicle records, and 130,000 trip records (MWCOG, 2009). Figure 1 shows the traffic analysis Zones (TAZ) in the Greater Metropolitan Washington area. Figure 2 shows the data and file structure associated with this data.

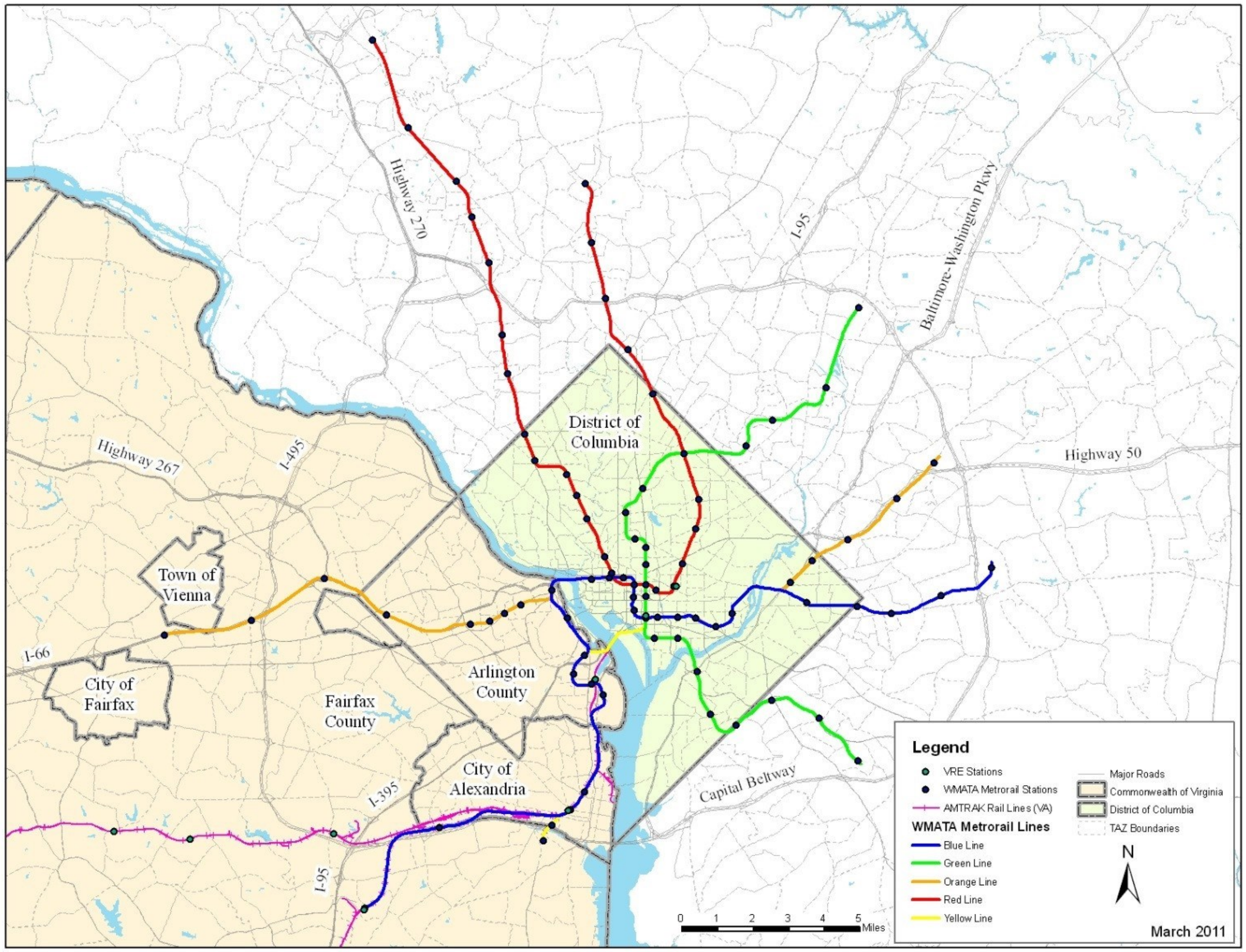


Figure 1. Greater Washington Metropolitan Area – Traffic Analysis Zones

Table 2. Activity Based Modeling Nationwide Status

Region	Population	ABM Status
New York-Northern New Jersey-Long Island	19,069,796	In use
Los Angeles-Long Beach-Santa Ana, CA	12,874,797	In development
Chicago-Joliet-Naperville, IL-IN-WI	9,580,567	In planning
Dallas-Fort Worth-Arlington, TX	6,447,615	No current plans
Philadelphia-Camden-Wilmington	5,968,252	In planning
Houston-Sugar Land-Baytown, TX	5,867,489	In development
Miami-Fort Lauderdale-Pompano Beach, FL	5,547,051	No current plans
Washington-Arlington-Alexandria	5,476,241	In planning
Atlanta-Sandy Springs-Marietta, GA	5,475,213	In use
Boston-Cambridge-Quincy, MA-NH	4,588,680	In planning
Detroit-Warren-Livonia, MI	4,403,437	No current plans
Phoenix-Mesa-Glendale, AZ	4,364,094	In development
San Francisco-Oakland-Fremont, CA	4,317,853	In use
Riverside-San Bernardino-Ontario, CA	4,143,113	In development
Seattle-Tacoma-Bellevue, WA	3,407,848	In use
Minneapolis-St. Paul-Bloomington, MN-WI	3,269,814	?
San Diego-Carlsbad-San Marcos, CA	3,053,793	In development
St. Louis, MO-IL	2,828,990	?
Tampa-St. Petersburg-Clearwater, FL	2,747,272	In planning
Baltimore-Towson, MD	2,690,886	In planning?
Denver-Aurora-Broomfield, CO	2,552,195	In use
Pittsburgh, PA	2,354,957	?
Portland-Vancouver-Hillsboro, OR-WA	2,241,841	In development
Cincinnati-Middletown, OH-KY-IN	2,171,896	?
Sacramento–Arden-Arcade–Roseville, CA	2,127,355	In use
Cleveland-Elyria-Mentor, OH	2,091,286	?
Orlando-Kissimmee-Sanford, FL	2,082,421	No current plans
San Antonio-New Braunfels, TX	2,072,128	No current plans
Kansas City, MO-KS	2,067,585	No current plans
Las Vegas-Paradise, NV	1,902,834	No current plans
San Jose-Sunnyvale-Santa Clara, CA	1,839,700	In use
Columbus, OH	1,801,848	In use
Charlotte-Gastonia-Rock Hill, NC-SC	1,745,524	?
Indianapolis-Carmel, IN	1,743,658	?
Virginia Beach-Norfolk-Newport News	1,674,498	No current plans
Providence-New Bedford-Fall River, RI-MA	1,600,642	?
Nashville-Davidson–Murfreesboro–Franklin,	1,582,264	?
Milwaukee-Waukesha-West Allis, WI	1,559,667	?
Jacksonville, FL	1,328,144	In development

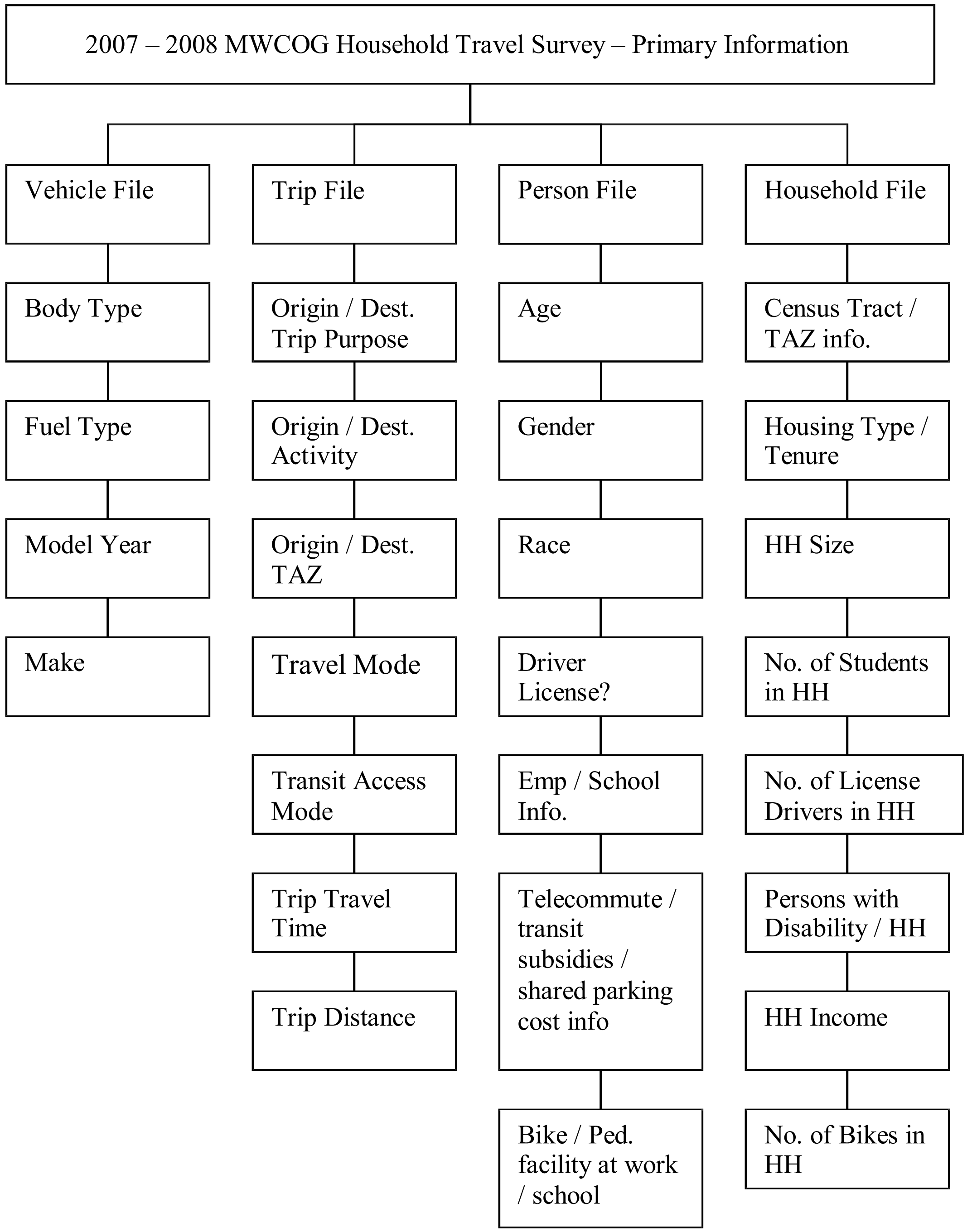


Figure 2. MWCOG 2007/2008 Household Travel Survey Data Structure

1.7. Research Hypotheses

1.7.1. Travel Characteristics of TODs

The basic premise of the research being investigated is that presence of transit facilities tends to reduce vehicular trip rates in commercial, office, and residential developments. In order to investigate this argument the vehicular mode of travel is extracted from all other modes of travel (including but not limited to transit, walk, bike, car pool) and the rates are compared between TOD and non-TOD environments. It is obvious that the TOD and non-TOD environments must have similar characteristics (in terms of number of employment and number of household) to make the comparison a fair and unbiased analysis. Consequently the first step in the analysis is to show that the number of employment and number of households in the selected TOD and non-TOD environments are similar.

The data from the MWCOG is examined to verify this claim. Vehicle ownership data from two areas are compared and contrasted. A non-TOD area is elected in the Loudoun County, Northern Virginia which is typically known for its suburban type environment. The house lots are normally in acres and minimum double-car garages are a fixed feature. There is either minimum or no transit service in this area and the primary mode of travel, whether it is work trips, shop trips or otherwise is vehicular.

Another conclusion normally driven by intuition is that the rate of use of transit within TOD zones far exceeds non-TOD zones. From another perspective it can be argues that the rate of use of personal vehicles in non-TOD zones is higher than trips to, from, and between TOD zones. To assess the accuracy of this claim detailed travel mode is examined using the MWCOG data for the TOD area and is compared with non-TOD areas. It is important to note that the TOD trips include trips within the TOD zone, as well as to and from non-TOD zones. Similarly, Non-TOD trips include all trips within non-TOD areas as well as trips to and from TOD areas.

Utilizing the MWCOG data, the primary travel mode and detailed travel mode for home-based work trips are examined. The data needed to be refined to only include home-based work trips. Work trips are especially important as the travel mode for commuters which make the majority of trips can best be determined. The selection of TOD vs. Non-TOD area for this assessment is based on the 0.25 mile radius of all 86 Washington Metro transit stations. All home-based work trips within the 0.25 mile radius of a transit station are selected as the TOD zone. All home-based work trips beyond 0.25 mile radius of a transit station are considered a non-TOD zone. To ensure a truly TOD behavior, the 0.25 mile radius is deliberately selected as this is the ideal walking distance to a transit station (see Figure 3).

Finally, all trips (home, work, shop, entertainment) to and from a TOD zone is examined and is compared with the rates of a non TOD zone. Consistent with previous section the TOD zone is based on 0.25 mile radius of all 86 Washington Metro transit stations. All home-based trips within the 0.25 mile radius of a transit station is selected as the TOD zone.

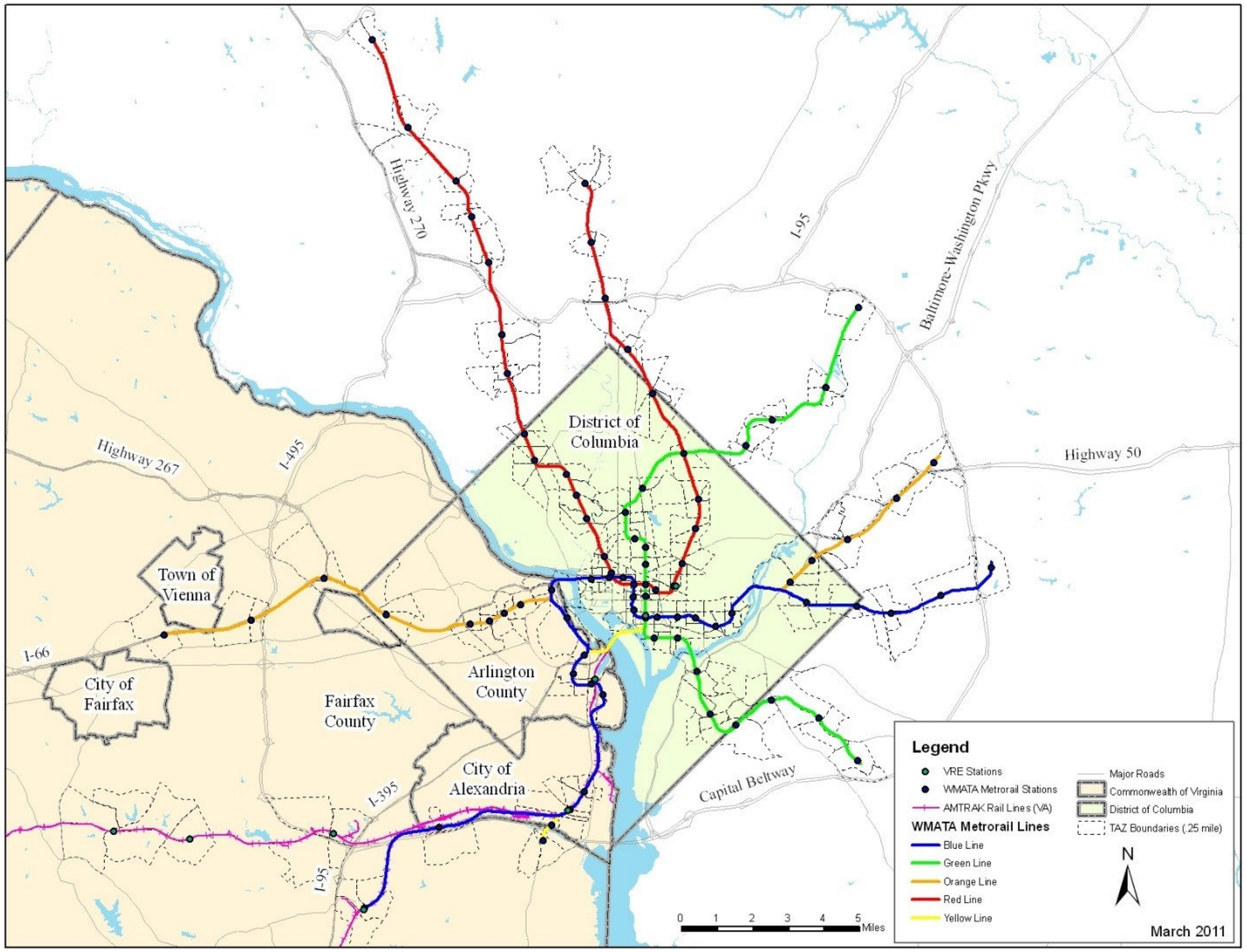


Figure 3. 0.25 Mile Radius TAZ from a Metro Station

1.7.2. Trip Generation Estimations of TODs

The primary purpose of this research is to develop a methodology for determining vehicular trip generation rates of transit-oriented developments using activity-based 24-hour household travel survey data from travel survey data for the Washington D.C. Metropolitan area. This activity-based survey data provided a wealth of transit-oriented corridors, and diverse land use. The use of this data mitigates loss of computational information frequently ensued by aggregate data, hence providing a more accurate quantitative forecast.

The Rosslyn-Ballston Metro Corridor in Arlington, Virginia which is selected as the test site for this portion of the research exemplifies a transit-oriented corridor . The corridor contains five metro transit stations that are well served by a reliable high speed underground Metrorail. Each transit station is the center of high density development within 0.25 mile radius. The corridor as a whole contains diverse land use from residential, office, retail to institutional and entertainment use. All transit stations are accessible through well connected pedestrian and bicycle network.

The trip generation characteristics of TODs are best described by two linear regression models that are developed as part of this research. An initial simple regression model used the development area foot-print (in square feet) in a 0.25 mile buffer of a transit station in a transit-oriented corridor, as the independent variable. The vehicular trips in the same buffer zone served as the dependent variable. For the development of this model guidelines of the ITE Trip Generation Handbook were utilized.

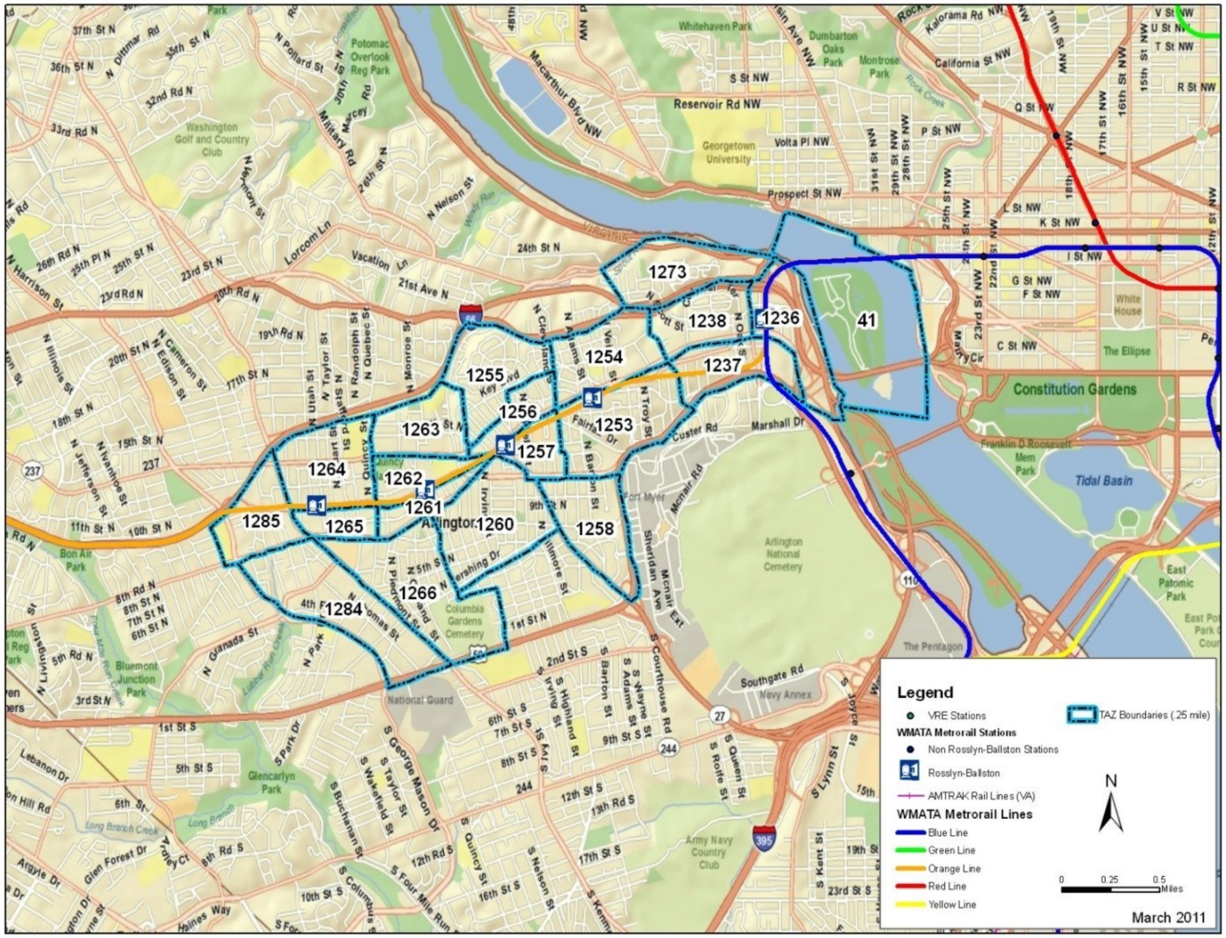


Figure 4. Rosslyn-Ballston Corridor 0.25 Mile Radius TAZ Map

The research hypothesis for this univariate linear regression model is:

Let H_0 = There is no relationship between the size of the development in terms of Gross Floor Area (GFA) and the number of vehicular trips to in a transit-oriented corridor within 0.25 mile buffer zone of a transit station.

Let H_A = There is significant relationship between the size of the development in terms of Gross Floor Area (GFA) and the number of vehicular trips to in a transit-oriented corridor within 0.25 mile buffer zone of a transit station.

A second model associated with the trip generation analysis of TODs is developed to explain the relationship of trip rates and several household attributes in a transit-oriented corridor. Through the use of statistical elimination of lesser significant variables, the multiple linear regression is used to reduce the initial selection of variables to only include significant variables that would aid in predicting trip rates of TODs.

The data for this analysis encompassed travel and household characteristics of 0.25 mile radius of all transit stations in the MWCOG study area which included 117 observations. The independent variables included in the data are:

X_1 = Average income per household,

X_2 = Average vehicles per household,

X_3 = Average number of students per household,

X_4 = Average number of licensed drivers per household,

X_5 = Average number of workers per household, and

X_6 = Average number of bikes per household.

The criteria for eliminating lesser significant variables included $\alpha = 0.05$. P-values of 0.05 or less were eliminated one at a time and the value of regression coefficient R^2 is observed until a reasonable regression coefficient is derived. The p-value of less than 0.05 leads to rejection of null hypothesis and in effect indicates the predictor variable is significantly associated with the dependent variable.

The research hypothesis for this multivariate regression model is:

Let H_0 = There is no relationship between the number of vehicular trips in a transit oriented development, which is the area defined by 0.25 mile buffer zone of a transit station, and any of these independent variables, which include average income, number of vehicles, number of students, number of licensed drivers, number of workers, and number of bikes per household.

Let H_A = There is significant relationship between the number of vehicular trips in a transit oriented development, which is the area defined by 0.25 mile buffer zone of a transit station, and any of these independent variables, which include average income, number of vehicles, number of students, number of licensed drivers, number of workers, and number of bikes per household.

As in previous sections we will let $\alpha = 0.05$

1.7.3. Mode Choice of TODs

A stochastic mode choice utility model is developed using multinomial logistic regression to show the modal split in the 0.25 mile radius of all transit stations in the Washington Metro area.

The intent of this section of the dissertation is to develop two stochastic mode choice models. The first model shows the mode choice amongst six different modes in a transit oriented development environment. Consistent with previous sections, the TOD environment is defined as the 0.25 mile radius of a Washington Metro transit station. All work trips within the 0.25 mile zone are included in the analysis and are the basis of the data for this model.

Additionally, a utility function for the transit mode is developed. The attributes that represent the attractiveness (or the cost) associated with transit mode in the greater Washington area are assumed as transit travel time (min), average wait time (min), transit fare cost (dollars), and average walk time to a transit station (min). Average household income is assumed as the characteristic of traveler.

The framework for the choice process is that an individual first determines the available alternatives to make a decision; next evaluates the attributes for each alternative, and then uses a decision rule to select the most appropriate (least cost) alternative (Ben-Akiva and Lerman, 1985, Chapter 3).

The alternatives are a finite set of choices that is available to the decision maker. Alternatives are characterized by a set of attributes. The attractiveness of an alternative is determined by the value of its attributes (Lancaster 1971). If a certain attribute contains a level of uncertainty, then the level of uncertainty itself can be included as an attribute. For example if average travel time is used as an attribute, as opposed to travel time for individual travelers, then the uncertainty associated with the average value itself can be included as an attribute.

Mode choice models are used to predict mode choice of travelers in a region. In travel demand forecasting it is important to be able to predict a traveler's mode choice from a set of alternatives. These alternatives include transit, personal vehicle, car pool, walk, and bike.

Mode choice models also provide the relative impact of different attributes amongst alternatives when the choice is made. For example the importance of walk time towards a transit station, or the travel time to and from work in the decision making process is measured.

There are normally two ways of modeling mode choice behaviors. The first model is the aggregate mode choice modeling which relies on aggregate data and uses a group of travelers to collectively determine their mode choice based on the average of the whole. Alternatively, the disaggregate model uses data from individual mode selection and thus better identifies characteristics of the mode choice behavior and the associated attributes. The data used for this work is the 24-hour activity trip diary data amongst the Greater Washington D.C. area travelers that is disaggregate in nature. Therefore the disaggregate mode choice model is the natural modeling selection for this work.

Consistent with the state-of-practice, home-based work trips are the focus of mode choice modeling for this dissertation. They constitute the majority of trips in daily travel activities and are the major contributing factor to traffic congestion in urban areas.

The utility maximization rule states that an individual will select the alternative from a set of available alternatives that maximizes his or her utility (Koppelman and Bhat, 2006).

The utility function, U, has the property that an alternative is chosen if its utility is greater than the utility of all other alternatives in the choice set. This can be expressed as:

$$if\ u(X_i, s_t) \geq u(X_j, s_t)\ \forall_j \quad => \quad i > j\ \ \forall_j \in C$$

Where $u(X_i, s_t)$ is the utility function,

X_i, and X_j are attributes (travel time, travel cost, wait time and walk time) describing alternatives i, and j (car, transit, carpool, etc.).

s_t represents the characteristics that influence one's preference amongst alternatives such as household income, or number of automobiles owned.

A utility function using Logit model is developed using travel time, waiting time and walk time as the user cost. The probability of taking different modes of travel in a TOD is determined. The modes include transit, auto driver, auto passenger, walk, bike and other modes of travel.

1.8. Organization

This document seeks to provide a systematic approach to determine travel characteristics of transit-oriented developments.

In chapter 1 is an abridged version of the entire dissertation as it presents a preparatory view of the material ahead. In this chapter, the concept of transit-oriented development as the land use consistent with guidelines of a smart growth strategy is defined. Current travel demand modeling issues associated with TODs and the lack of a clear guideline and methodology for trip generation estimation and mode choice characteristics of TODs are described. A definition of TOD and various typologies of TODs are presented. The chapter continues with introduction of the data used for the research and provides narrative on the test corridor utilized. Chapter 1 continues with an introductory description of each trip generation and mode choice mathematical model that are developed as part of this research.

Chapter 2 pertains to literature search. An extensive literature search associated with inaccuracy of the current ITE-prescribed methodology for mixed-use developments is presented. Lack of a quantifiable trip generation model in the literature is presented. Furthermore, the literature search includes research to-date associated with the modal choice and available, or lack thereof, a utility model for transit oriented developments. The chapter also includes available research on TOD typology.

Chapter 3 challenges myths and/or intuitions by examining the travel behavior of TOD residents and compares them with non-TOD areas in the National Capitol Region. Vehicular mode of travel is extracted from all other modes of travel (including but not limited to transit, walk, bike, car pool) and the rates are compared between TOD and non-TOD environments. Furthermore, detailed travel mode is examined using the MWCOG data for the TOD area and is compared with non-TOD areas.

Chapter 3 concludes with assessment of the primary travel mode and detailed travel mode for home-based work trips and all-trips. The data needed to be refined to only include home-based work trips. Work trips are especially important as the travel mode for commuters which make the majority of trips can best be determined.

The selection of TOD vs. Non-TOD area for this assessment is based on the 0.25 mile radius of all 86 Washington Metro transit stations. All home-based work trips within the 0.25 mile radius of a transit station is selected as the TOD zone. All home-based work trips beyond 0.25 mile radius of a transit station are considered a non-TOD zone. To ensure a truly TOD behavior, the 0.25 mile radius is deliberately selected as this is the ideal walking distance to a transit station.

The purpose of Chapter 4 is to explore vehicular trip characteristics of transit oriented developments by determining their trip generation rates. This will enable traffic engineers and transportation planners accurately forecast vehicular trips associated with TODs. Based on activity based 24-hour household travel survey, regression model is developed and validated relating TOD trip ends to gross floor area (GFA), in square feet, for mixed land use. The validation of the regression model is performed by checking for normality of the distribution of data, multicollinearity and heteroscedasticity of the independent variables.

Chapter 5 presents trip generation based on multivariate regression analysis with the number of vehicular trips as a function of one or more independent variables. Household attributes are selected as the independent variables to accurately depict travel behavior in transit oriented developments. The household attributes assumed include average household size, average number of vehicles, students, licensed drivers, workers and bikes per household.

Mathematical validation of the final model is performed by checking for multi-collinearity between the dependent variables (number of vehicular trips) and with each independent variable individually. While collinearity amongst the dependent and independent variables ensure validity of the model, it must be noted that the linear relationship between independent variables are fatal. Linearity amongst independent variables can cause erroneous regression coefficients which can also be detected by large quantities of residual error.

Chapter 6 presents a stochastic mode choice utility model using multinomial logistic regression to show the modal split in the 0.25 mile radius of all transit stations in the Washington Metro area. The primary focus of the mode choice model is on home-base work trips which predominantly constitute the number of trips in the 24-hour activity based data. The attributes of the primary mode of travel include transit, auto-driver, auto-passenger, walk, bike and other. The outcome of the logit model is the mode of travel. The independent variables which constitute the deterministic portion of the utility model are number of vehicles per household, household income, and trip travel time.

An accurate estimation of trip generation and mode choice prediction is important to public agencies and private developers. It ensures accuracy when determining impact fees and determines the magnitude of transportation improvement required by the development. Therefore over or under estimation is not beneficial to either the public and local governments or the private developers.

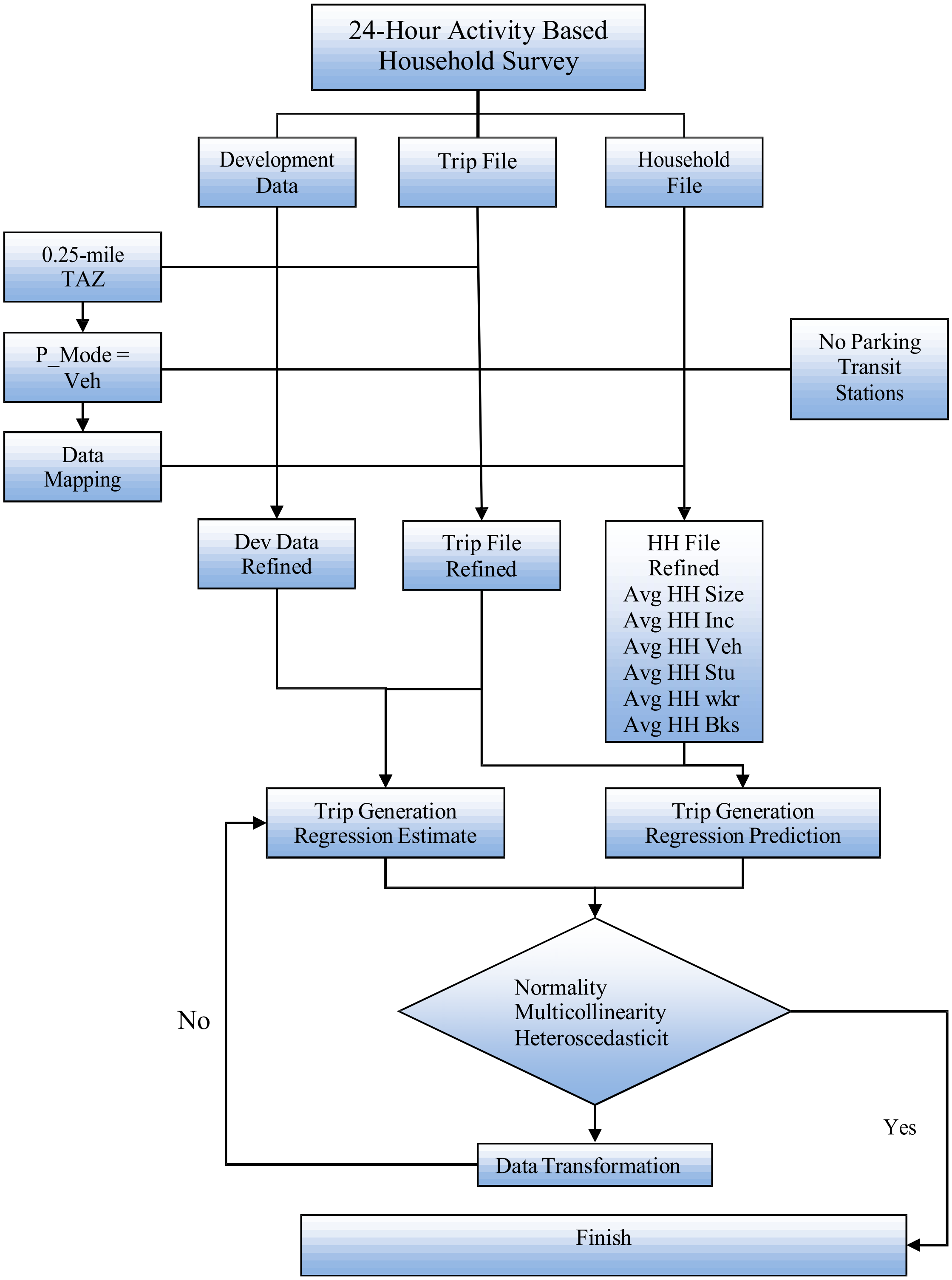


Figure 5. Trip Generation Methodology

CHAPTER 2. Literature Review

This section provides an extensive literature search associated with the work done to-date for trip generation methodologies and mode choice behavior of transit-oriented developments.

Transit-oriented developments have several distinguishing characteristics in terms of the land use and the geographic area which they are located. A literature search without a proper classification of TODs is not beneficial. An essential intent of this section, then, is to present the research work done to-date on the typology of TODs and the different types and classifications of TODs that they may encompass.

An important component of this research work is the mode choice characteristics of TODs and development of mathematical models that explain or predict the modal choice associated with transit oriented developments. This chapter provides the research efforts pertaining to mode choice characteristics of transit oriented developments and the development process of mode choice mathematical models to date.

The chapter concludes with a summary of all findings, identifies areas that require further investigation, and highlights areas where this dissertation fulfills.

2.1. Transit-Oriented Developments and Trip Generation Methodologies

A comparative analysis of ITE methodology and actual observed trips generated by transit-oriented developments was performed by Robert Cervero to determine accuracy of

ITE estimates (Cervero, 2008). The study was based on empirical data from 17 transit-oriented developments in five U.S. metropolitan areas. According to the study, the actual observed trips were 44% lower than ITE estimations. The study is an indication that a more accurate methodology based on reliable data is needed. The set of data should include factors that impact trip rates in a transit-oriented environment which include density of the land use, diversity of the use, scale of the development, demographics, and distance to transit.

On a separate exploration of transit-oriented developments associated mostly with demographics, household and personal attributes, Cervero performed a study which showed living near transit stations and the use of transit as a primary commute vehicle is predominantly dependent upon the individual's conscious decision to live near transit stations (Cervero, 2008). Cervero developed a nested logit model, based on proximity of workplace to transit station, job accessibility index, travel time station, vehicle ownership, and certain personal attributes. The model estimated the probability that a resident of a TOD utilizes transit as the primary mode of travel to commute. The study was based on year 2000 data and was limited to San Francisco, California.

The Transit Cooperative Research Program, Research Results Digest Number 52, provides a comprehensive literature review associated with transit-oriented developments. The report elaborates on institutional issues and explains planning and policy aspects of TOD. The report examines institutional issues amongst various stakeholders including the federal, state and local governments, transit agencies and the developers. Potential impacts and benefits to these stakeholders are discussed and implementation strategies associated with tax and financing, land based initiatives, and zoning and regulation policies are identified. Successful design principles, station area design and community service integration have also been discussed by examination of various TODs throughout the United States.

While the literature overwhelmingly agrees on transit-oriented developments as a promising land use proposition to combat urban sprawl and congestion, yet the rate of increase and success of TODs, in terms of saturating the real estate market, has been sluggish. Cervero claims one of the reasons for the slow increase is excessive supply of parking in TODs even in the urban areas.

In “Are We Over-parked?” (Cervero, 2009), the author found the mean parking supply of 1.57 spaces per unit were 31% higher than the 1.2 spaces recommended in ITE Parking Generation, and 37% higher than the weighted-average peak demand of 1.15 parked vehicles per unit at 31 residential projects near BART metrorail stations. The study shows that the over-supply of parking spaces would result in an increase in vehicle ownership (Cervero, 2009).

A primary question, however, in the study of TODs is how much transit is indeed used by residents of TODs for various trip purposes. In a study performed by Chatman, this question is explored by randomly choosing households and workers within 0.4 mile radius of transit stations in San Diego and San Francisco, California and collecting 24-hour activity and trip diary via phone survey. The study concluded that “people living or working near metrorail stations have a higher non-auto share of commuting and non-work travel” (Chatman, 2006). The study further determines that the non-auto share dissipates as the proximity to transit stations increases or even in outlying suburban transit stations.

Consistent with Cervero, Chatman also argues that improved built environment such as safe walking facilities and convenient transit access are as major contributing factor for use of transit as congestion and longer travel times by auto is. TODs with wide streets and plentiful parking are less likely to be successful in terms of use of transit.

The use of transit at TODs was also explored by Jennifer Dill. Dill surveyed 300 residents of TODs near four light metrorail stations in the Portland area. The study attempted to answer the following questions:

- Do residents of transit-oriented developments (TODs) drive less, use transit more, and/or walk and bicycle more than residents of other neighborhoods?
- To what extent can TODs increase transit ridership?
- How do the features of the TOD influence travel choices?

From a demographic perspective, the study found that the household size tend to be smaller. The data showed older adults and household with fewer children than the suburban areas. Furthermore, the study examined vehicle ownership amongst the residents and found that while the use of transit is significantly higher than non-TOD areas, however, the residents were not transit dependent. A significant finding of the study was the increase of transit ridership amongst the residents within the study area. The study showed that majority of respondents use transit and walking more compared to when they were living in a non-TOD environment (Dill, 2006).

The Transit Cooperative Research Program (TCRP) Report 95 is a series of 19 chapters associated with many aspects of transit including transit facilities and services; transit operation and pricing; land use and travel demand management. Chapter 17 of this report that deals strictly with transit-oriented developments and examines the land use strategy and transportation impact of TODs from three different yet related perspective which the authors believe strongly characterizes TODs, namely regional context, land use mix and primary transit mode that serves the development.

Based on a comprehensive set of existing research findings and some developed analysis, the TCRP 95 report discusses automobile ownership in transit-oriented developments. Given that auto ownership or equivalently the number of licensed drivers in a household is a major factor in mode choice, the report examines three studies in California to determine the association between vehicle ownership and transit ridership at TODs. The report indicates a strong association between transit ridership and vehicle ownership. In fact, TOD residents with no vehicles made 79% of all trips by transit, while this number drops to 27% when surveyed from the residents with one vehicle and 10% transit share if residents had two or more vehicles.

An important finding of the TCRP 95 report however, is the development of a TOD index which assesses the “TOD-ness” of a project near transit station. The report defines TOD Index as “a way to characterize the degree to which a project functions as TOD and contains the important elements of a successful TOD” (TCRP 95, 2007). Some of the “essential indicators” mentioned in the report include centrally located transit, pedestrian priority, high-quality transit, mix of uses, supportive density, and parking management (TCRP 95, 2007).

An alternate look at measuring the performance of a TOD is based on liveability and sustainability. In a study performed by Renne, performance indicators in six categories have been identified. The indicators include travel behavior, the local economy,, the natural environment, the built environment, the social environment, the social and the policy context (Renne, 2007).

In the analysis and/or implementation of transit-oriented developments a decision support tool was much needed to evaluate the land use policy decisions made by local governments. Common travel demand models perform macroscopic / regional analysis and were not sensitive enough to land use changes at the macro level that was required by a single TOD. Furthermore, the amount of time needed to run a typical travel demand model made the proposition of developing a custom-made tool tailored towards TODs and their policy implications even more interesting. Fox and Bowlby, developed such a decision support tool which is spreadsheet based, and at the corridor level, screens land use policies associated with TODs to support investment in Light Metrorail Transit (LRT) and TODs (Fox and Bowdly, 2010). The tool was validated using the Memphis Regional Travel Forecasting Model. The inputs to the spreadsheet and the data flow mimic the traditional four step travel demand model. Figure 6 shows the transit oriented decision support tool data flow.

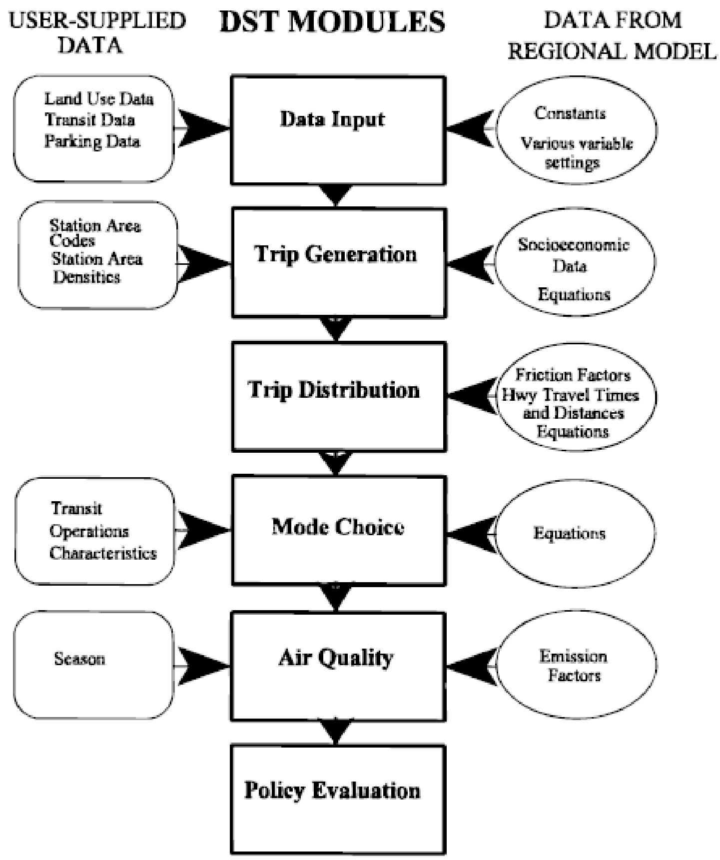


Figure 6. TOD Decision Support Tool System Flow (Fox and Bowdly, 2010)

Once the data is provided to the model, the output is the percentage of new developments in the corridor, increased transit ridership, forecasted annual transit operating cost and air quality benefits.

Travel behavior along transit corridors is extensively studied in the Washington D.C. area by the Washington Metropolitan Area Transit Authority in their 2006 Development-Related Ridership Survey report (WMATA, 2006). Mode choice and potential factors that may impact transit ridership is also assessed in this report and is compared with the results of an earlier similar report in 1989.

The 1987 and 1989 studies found a relationship between the distance at which a building (office, residential, retail or hotel) is located and the transit ridership it generates. The 2005 study not only performed the same analysis but also determined if there are other variables, beyond what was initially considered, which may impact transit ridership. These additional variables include

quality of the pedestrian environment, housing density in the station area, job density in the station area, attractiveness of automobile access, and the availability of transit subsidies.

The results of the study were very consistent with the results of earlier studies. It basically concluded that the walking distance between a site and the transit station positively impact transit ridership. In general, the closer a site is to the station, the

greater likelihood those traveling to and from or within a site choose transit as their travel mode. Based on the survey results, this relationship was stronger for residential sites than for office sites (WMATA, 2006).

A recent research project by the California Department of Transportation (Caltrans) to study travel characteristics of infill development in California's metropolitan areas is very similar to the principal intent of this dissertation. The Caltrans' research was primarily intended to establish data collection methodologies associated with infill land uses and also to develop a database of trip generation studies of infill developments in California. The ultimate goal, however, was to determine trip generation rates for urban infill developments. The study consistently followed the guidelines of ITE Trip Generation Handbook, 2nd Edition for establishing local trip rates. The specific objectives of the research were to:

- Develop a methodology for identifying and describing urban infill locations suitable for collecting infill trip rate data,
- Define and test a methodology for collecting trip generation rate data in urban infill areas,
- Develop trip generation rates for common infill land use categories in urban areas of California,
- Establish a California urban infill land use trip generation database, and Supplement ITE trip generation data (Caltrans, 2008).

The study was completed in two phases. The first phase determined a data collection methodology for urban infill land uses. The report indicated that it has been successful in identifying and testing data collection methods. The preliminary data collected and evaluated from 27 sites indicate that the studied land use categories have lower trip generation characteristics in urban infill contexts than ITE trip generation rates (Caltrans, 2008).

The second and final phased of the study developed trip generation rates based on the empirical data that was collected from the 27 sites in the first phase. The results of the study showed that the trip rates were substantially lower than the trip rates recommended by the ITE methodology.

Travel characteristics of transit-oriented developments and comparing the trip generation rates with the proposed ITE methodology was also studied by Lund and Cervero in Travel Characteristics of TOD in California (Lund, 2004). The study determined that the use of transit as a primary mode choice amongst TOD residents is substantial. The use of transit for home-based work trips is five times more likely than non-TOD areas. The study also showed that the use of transit is very much dependent on the type and maturity of the transit system and that the majority of transit trips were commute trips as opposed to non-work trips (Lund, 2004).

Other very important findings of the Lund study was that "TOD residents are more likely to use transit if there is less of a time benefit for traveling via highways (compared to transit), if there is good pedestrian connectivity at the destination, if they are allowed flexible work hours, and if they have limited vehicle availability. TOD residents are less likely to use transit if the trip involved multiple stops (or "trip chaining"), if there is good job accessibility via highways, if they can park for free at their workplace, and if their employer helps to pay vehicle expenses (such as tolls, fuel, etc.)" (Lund, 2004).

The Hacienda Business Park TIA also revealed the discrepancy between the ITE recommended rates and actual trip generation rates obtained from the TIA. Hacienda Business Park is a 900 acre mixed used job center and housing development in Pleasanton, California. The TIA showed that the office and apartments in Hacienda Business Park generated 20% fewer trips compared to the standard trip rates used by the City of Pleasanton.

There have been a number of researches associated with how to promote transit-oriented developments. One particular research that is more focused on the promotion of TODs from a public policy perspective is performed by Gihring in 2002. Gihring argues that land value property tax is an effective way to promote transit-oriented developments and collect the adequate public funding required for improvements to transit stations and their infrastructure. Gihring demonstrates a case study of a proposed transit-oriented development special assessment district in Seattle, Washington and shows how changing the general property tax to a Land Value Tax (LVT) would provide incentives to utilize sites more intensively. Gihring discusses various value capture mechanisms, and offers two possible land value capture methods to support public bond financing (Gihring, 2002).

An intuitive deduction from the nature of transit-oriented developments would be the impact of such land use on vehicle miles traveled (VMT). Using a four step travel demand model, Zhang determined future (2030) VMT in the Austin, Texas region had a reliable transit system and TOD land use been implemented. The findings are substantial savings in VMT in the range of 10 – 12 million vehicle miles which is translated in 2.2 percent reduction in VMT region wide. Zhang also examined the change in mode choice from single-occupancy vehicle to transit with and without the presence of transit-oriented developments (Zhang, 2010). The study examined three scenarios, with a base assumption of no regional or commuter Metrorail, 10 TODs along a commuter Metrorail line and finally a transit oriented corridor that is primarily served by bus. While the analysis found minimal diversion from single-occupancy to other modes, however the overall transit trips reduced the VMT by approximately 10 million vehicle miles per day, which would have substantial impact on congestion. Zhang also documents a number of potential issues with TODs one of the most important of which is that the non-TOD areas usually benefit more than the TOD areas. This is primarily because a major characteristic of a TOD region is the concentration of jobs, retail and entertainment activities in a certain confined area that focuses on pedestrian, bicycle and transit facilities and limits roadway construction to and from the site. It is therefore natural that the region wide VMT is reduced while the TOD areas face congestion.

The walkability distance of 0.25 mile has been determined as an ideal walking distance for a successful transit-oriented development throughout the literature. Transportation Research Record 1538 indicates "For the city of Calgary the average walking distance to suburban stations is 649 meters with a 75th-percentile distance of 840 meters. At CBD stations the average walking distance is 326 meters and the 75th-percentile distance is 419 meters" (O'Sullivan, 1996).

While the 0.25 mile distance has been identified as the ideal walking distance, Canepa (2007) determined that longer walking distances are also possible for transit riders given certain variables such as housing and employment density and urban design are accounted for.

A quantitative study in the suburban city of North York, Canada examined the relationship between distance to transit and mode choice and auto ownership (Crowley, 2002). Results of the study indicate a strong positive relationship between distance from a planned transit station and subway mode share for either peak trips or total daily trips.

The subway mode share decreased from 36% to 16% as the distance from the transit station increased from less than 200 meters to 800-1600 meters for peak trips. Furthermore, the number of vehicles per household increased from 0.69 to 1.04 vehicles per household as the distance from the transit station increased from less than 200 meters to 800-1600 meters for peak trips. The study shows that even in suburban type environments, proper design and planning of transit stations and the adjacent land use can lead to increased transit shares.

The literature mostly correlates transit-oriented developments with metrorail and subway transit. However, in El Monte, California a transit oriented village was developed in proximity of the bus station. In a study performed by Wayne D. Cotterll called "Transforming a Bus Station into a Transit-Oriented Development: Improving Pedestrian, Bicycling, and Transit Connections" (Wayne D. Cottrell, 2007) the transit village in El Monte was examined and the increase in bus transit ridership was identified. Important attributes such as pedestrian connectivity, lighting improvements to enhance aesthetics and safety of transit ridership and multimodal access (walk, bike, bus) to the transit station was identified.

A model is developed by the San Francisco Bay Area Rapid Transit District (BART) in California to facilitate station planning and development of transit-oriented developments and is designed to streamline decision making about TOD and commuter parking. The model examines ridership impacts, fiscal impacts, and qualitative factors (Wilson and Menotti, 2008). The authors show the conditions under which positive ridership occur if BART deviates from its current policy of providing commuter parking for every transit commuter. The study utilized the MacArthur and San Leandro stations as case studies and determined the substantial cost of retaining transit agency land in surface parking. The spreadsheet-based methodology is adaptable to a wide variety of situations.

Available research shows that availability and convenience of using transit encourages its use. In a study in 1987 by JHK and Associates, it was determined that 50% of employees in Washington D.C. whose workplace in within 1000 feet of a transit station use transit for work trips (JHK and Associates 1987).

On the same note, Robert Cervero determined that the number of residents in the Bay Area who moved to ½ mile radius of a transit station and switched their mode of travel from personal passenger car to transit exceeds 50 percent (Cervero 1993).

In the study of how much transit is indeed used by residents of TODs for various trip purposes, Chatman explored this question by randomly choosing households and workers within 0.4 mile radius of transit stations in San Diego and San Francisco, California. The research included 24-hour activity and trip diary collection via phone survey. The study concluded that "people living or working near metrorail stations have a higher non-auto share of commuting and non-work travel" (Chatman, 2006). The study further determined that the non-auto share dissipates as the proximity to transit stations increases. Consistent with Cervero, Chatman also argues that improved "built environment" such as safe walking facilities and convenient transit access are as major contributing factors for use of transit as congestion and long travel times ensued by the use of personal auto. The study concludes that TODs with wide streets and plentiful parking are less likely to be successful in terms of use of transit.

In terms of data for transit-oriented developments, the National TOD Database contains the latest set of data provided by the Center for Transit-Oriented Development. Intended as a tool for planners, the database provides economic and demographic information for every existing and proposed fixed guide-way transit station in the U. S. The database includes 3776 existing stations and 833 proposed stations in 47 metropolitan areas at three geographic levels; the transit zone (the 1/2 mile or 1/4 mile buffer around the individual station), the transit shed (the aggregate of transit zones), and lastly, the transit region (aligns with the Metropolitan Statistical Area boundary). Over 40,000 variables are derived from nationally available data sets including the 2000 Decennial Census, the Census Transportation Planning Package, and Longitudinal Employment Data (TOD Database, 2010).

The 2005 Development Related Ridership Survey conducted by the Washington Metropolitan Area Transit Authority (WMATA) updated a 16-year old study that surveyed the travel behavior of persons traveling to and from office, residential, hotel and retail sites near Metrorail stations. The 2005 effort sought to determine if modal splits for these land uses have changed over time and whether certain physical site characteristics still impact transit ridership. In 2005, 49 sites of the land uses listed above plus entertainment venues near 13 Metrorail stations participated in the study, which was designed to mimic the earlier efforts as a way to provide some context for comparison (WMATA, 2005). Some of the data in the WMATA includes:

- Percent of Workers from Office Industries who Commute by Auto
- Percent of Workers from Office Industries who Commute by Transit
- Percent of Workers from Office Industries who Work at Home
- Percent of Workers from Shopping and Entertainment Industries who Commute by Auto
- Percent of Workers from Shopping and Entertainment Industries who Commute by Transit
- Percent of Workers from Shopping and Entertainment Industries who Work at Home
- Percent of Workers from non-Office Industries who Commute by Auto
- Percent of Workers from non-Office Industries who Commute by Transit
- Percent of Workers from non-Office Industries who Work at Home

During the course of the literature review several independent traffic impact studies associated with transit oriented developments performed throughout the nation have been identified. The data from these studies were not used for this dissertation. They may, however, be used in TOD research to provide data sufficiency.

Transportation Research Board projects include projects within the National Cooperative Highway Research Program (NCHRP) and Transit Cooperative Research Program Panel (TCRP). Research projects associated with trip generation rates for multi-use developments and / or transit-oriented developments that lay within these programs are identified below.

- Trip Generation Studies for Special Generators sponsored by the Maryland Department of Transportation. The manual will provide guidance when travel forecasting is needed for unconventional land use types that are not covered in the ITE Trip Generation Manual.

- Vermont Trip Generation Manual: This research project, sponsored by the Vermont Agency of Transportation, will measure trip generation for the most widely proposed types of development in Vermont. The end product of this effort will be a Vermont Trip Generation Manual to provide guidelines for preparing and reviewing Traffic Impact Studies in Vermont.
- Enhancing Internal Trip Capture Estimation for Mixed-Use Developments: This manual, led by the Texas Transportation Institute at Texas A&M, is close to completion. The manual will develop methodology for estimation of internal capture trip rates associated with mixed-use developments. The manual will include a classification of mixed-use developments and identifies the site characteristics, features, and contexts that distinguish various types of mixed use developments. A second intent of the manual is to develop a methodology for data collection to quantify internal trips in mixed use developments.
- Trip Generation Rates for Transportation Impact Analyses of Infill Developments (NCHRP Project 08-66): This national-level research, proposed to NCHRP by Caltrans, will develop an easily applied methodology (for trip generation, modal split, and parking generation) in the preparation of site specific transportation impact analyses of infill development projects located within higher-density urban and suburban areas (NCHRP 08-66).

- Ensuring Full Potential Ridership from Transit-Oriented Development (TCRP H-27A): This study is a national assessment of TOD issues, barriers, and successes. This project included case studies from a variety of geographic and development settings with objectives to: (1) determine the behavior and motivation of TOD residents, employees, and employers in their mode choice; (2) identify best practices to promote TOD-related transit ridership; and (3) recommend contextual use of best practices. This study collected empirical trip generation data at 16 TOD sites nationally (TCRP H- 27A).

An applied methodology for the determination of trip generation of mixed use developments with the element of transit as an option is known in the industry as the "MXD Methodology". The methodology is sponsored by the United States Environmental Protection Agency (EPA) and various local governments and state transportation agencies have adopted it. The following studies have also been funded through EPA that relates to the functionality of mixed use and/or transit oriented developments:

- The Transportation and Environmental Impacts of Infill vs. Greenfield Development – A Comparative Case Study Analysis (EPA 231-R-99-005): The objective of this study, prepared in 1999, was to determine which type of development site (Infill or Greenfield) provided better or more efficient transportation services, and which site produced fewer transportation-related burdens on the environment. Comparing Methodologies to Assess Transportation and Air Quality Impacts of Brownfields and Infill Development (EPA 231-R-01-001): The objective of this study, conducted in

2001, was to provide guidance on applicable methodologies to account for the benefits of infill developments in State Air Quality Implementation Plans and transportation conformity determination.

- Although the two EPA sponsored studies described above did not estimate trip generation rates for urban infill areas, they presented qualitative and quantitative information about the advantages of infill development, including reductions in travel-time; increases in non-auto mode share; reduced air-pollutant emissions rates; reduced loss of open space; lower commute and infrastructure costs; and improved measures of community quality of life.
- California-Specific Trip Generation Research San Diego Association of Governments Smart Growth Trip Generation and Parking Demand Guidelines: The purpose of this project is to determine observed trip generation rates for automobile, transit, and non-motorized modes of travel, and to observe parking demand associated with smart growth development. The findings are intended to be published in the form of guidelines for use by local agencies in the San Diego region.

2.2. Extent of Proximity to Transit Stations

Planning exercises aimed at making transit as a primary mode of travel will not be successful unless an ideal walking distance to the transit is identified. Transit agencies have performed significant amount of research to determine optimal walking distance to the transit station as the relationship between the number of stations built and the rate of return on investment is obvious.

The literature search predominantly identifies a walking distance of 0.25 mile from the station. Transportation Research Record 1538 indicates "For the city of Calgary, the average walking distance to suburban stations is 649 meter with a 75th-percentile distance of 840 meter. At CBD stations the average walking distance is 326 m and the 75th-percentile distance is 419 meter" (O'Sullivan, 1996).

A quantitative study in the suburban city of North York, Canada examined the relationship between distance to transit and mode choice and auto ownership (Crowley, 2002). Results of the study indicate a strong positive relationship between distance from a transit station and transit mode. The transit mode, in comparison to auto, walk and bike share, decreased from 36 percent to 16 percent as the distance from the transit station increased from less than 200 meters to 800-1600 meters for peak trips. Furthermore, the number of vehicles per household increased from 0.69 to 1.04 vehicles per household as the distance from the transit station increased from less than 200 meters to 800-1600 meters for peak trips. The study is a testament to the fact that proper design and planning of transit stations can lead to increased transit shares even in suburban type environments. The walkability distance of 0.25 mile as an ideal walking distance for a successful transit-oriented development is also confirmed in a study by O'Sullivan. It was found that the average walking distance to suburban stations in Calgary was 649 m with a 75th-percentile distance of 840 meters. Central Business District (CBD) stations the average walking distance was found to be 326 meters with a 75th-percentile distance of 419 meters (O'Sullivan, 1996).

Available research shows that qualitative measures such as proximity, availability, reliability and convenience of using transit increase its market share. In a 1987 study, JHK and Associates determined that 50 percent of employees in Washington D.C. whose workplace is within 1000 feet of a transit station use transit for work trips (JHK and Associates 1987).

Similarly, Robert Cervero determined that the number of residents in the Bay Area who moved to a ½ mile radius of a transit station and switched their mode of travel from personal passenger vehicle to transit exceeded 50 percent (Cervero 1993).

The 2005 study not only performed the same analysis but also determined if there are other variables, beyond what was initially considered, impact transit ridership. These additional variables include quality of the pedestrian environment, housing density in the station area, job density in the station area, attractiveness of automobile access, and the availability of transit subsidies. The results of the study were very consistent with the results of earlier studies. It basically concluded that the walking distance between a site and the transit station positively impact transit ridership. In general, the closer a site is to the station, the greater likelihood those traveling to and from or within a site choose transit as their travel mode. Based on the survey results, this relationship was stronger for residential sites than for office sites (WMATA, 2006).

2.3. Mode Choice Characteristics of Transit-Oriented Developments

There is an apparent lack of analysis associated with the modal choice characteristics of transit-oriented developments. The mode choice models show the relationship between the probability of utilizing a specific mode of travel (transit, cars, bus, subway) for a particular type of trip (i.e., home, work, shop). The question of whether utilizing transit as the primary model of travel in a transit-oriented development community is therefore need to be investigated. The assumption that the probability of taking transit in TODs is higher than any other mode of travel is a function of this research paper.

In the Diagnostic Evaluation of Public Transportation Mode Choice by M. Gebeyehu and Chin-ei of Hokkaido University in Japan and ordered logit model and a binary logit model was utilized to assess the influence factors that impact user perception on the bus service condition. The ordered logit model was utilized because of the ordinal nature of the data used as the independent variable (i.e., 0 = very costly; 1 = costly; 2 = less costly; 3 = not costly). Several parameters was used in the models to assess user satisfaction and three parameters of fare, convenience and frequency were found to have significant impact (M. Gebeyehu and Chin-ei, 2007).

Fox and Bowlby developed an integrated decision support tool to for the evaluation of transit. The tool was further used to assess land coordination policies. The study was performed for the Memphis Area Transit Authority in Memphis, Tennessee. The paper examines transit-oriented developments and use of Light-Metrorail Transit (LRT) to combat congestion, air pollution and urban sprawl and whether the use of state-of-practice demand models are proper tools to assess their impact. The paper concludes that due to the fact that the demand models are often cumbersome and take a long time to build, calibrate and validate, and execute, and summarize the results. Instead the authors had developed a Decision Support Tool (DST) which is spreadsheet based and unlike the demand models the scope of the analysis can be performed at the corridor level. The spreadsheet based DST is a policy-level screening to support investment in LRT in terms of land use, transit service, financing and parking management (Fox and Bowlby, 2010). In an examination of inter-zonal trips and their relevance in demand forecasting particularly mode choice, Bhatta and Larsen concluded the impact is proportional to the amount of inter-zonal trips. If inter-zonal trips make up less than 5% of the total trips, then the impact on mode choice analysis is negligible, but for higher proportions these trips need to be considered. Inter-zonal trips are trips that occur within the same Traffic Analysis Zone (TAZ). They are often shorter in duration and are often performed using non-motorized modes such as walking or biking. Furthermore, they are often not accounted for because of the aggregate nature of the data (Bhatta and Larsen, 2010). In an economic impact assessment of transit-oriented developments performed by Steven Lewis-Workman and Daniel Brod, study of several transit-oriented metro areas including Portland, San Francisco and New York indicated significant economic benefits in terms of real-estate appreciations. In Portland, Oregon property values increase by about $2.49 for every meter closer to light metrorail within 762-1609 meters distance to transit station. In San Francisco examination of more than 4,000 residential properties indicated non-user benefits account for 50% of property value. Moreover, the study determined with every 1% increase in distance from transit station (BART) results in 0.22 percent reduction in home prices. In New York, home prices decline about $75 for every meter further from subway stations. Value of average home within these subway stations areas is about $37,000 greater than home outside station areas (Transportation Research Record, 1576:147–153, 1997).

Household attributes in transit-oriented developments were examined in Taipei by Jen-Jia Lin and Ya-Chum Jen (Jen-Jia Lin and Ya-Chum Jen, 2009). The attributes included household income, household size, floor space needs, and presence of children or elder family members were examined. Using a binary logit model the authors found that household income, household size, and floor space needs are negatively associated with TODs and presence of children or elder family members and preference for mixed land use are positively associated with TODs. The degree of association is related to the preference of living in a TOD environment. For example household income is negatively related to preference to live in a TOD because higher income people tend to prefer to live in suburbs where land is more generous and privacy is abundant. The results of the study indicated that consistent with the hypotheses, household income and size had a negative impact on the decision to live in a TOD community. However, in contrast to the hypothesis having children or elder family members were positively associated with the preference to live in a TOD.

The study recommended land use policy and property development strategies based on the results of the study. Included in the policy development was supplying TOD and mixed use developments in lower income small size families. Secondly, since the study found that households with children and elder family members were positively associated with the decision to live near a TOD, then it would make sense to provide facilities that accommodate children and elder family members near transit stations (Jen-Jia Lin and Ya-Chum Jen, 2009).

2.4. Conclusion

It is evident that significant amount of effort has been performed on the planning side of transit oriented developments and less on the output such as trip generation rates, ridership and traffic conditions. There is an abstract understanding of what constitutes a TOD in terms of land use and transit, however, given the vast variety of land use and transit types a methodical and comprehensive typology of transit oriented developments is beneficial. Furthermore, trip characteristics of TODs including levels of walking, cycling, public transit utilization and Vehicle Mile Traveled (VMT), and how these impact pollution emissions and traffic fatality rates need further examination. The literature clearly showed lack of mathematical models that accurately predicts trip generation rates and asses mode choice behavior of transit oriented developments. While there is substantial research on common understanding of transit oriented developments and their benefits, a standard classification and characterization of TODs do not exist.

CHAPTER 3. Transit Oriented Development Travel Behavior

The wealth of information contained in the 2007-2008 Household Travel Survey Data from the Metropolitan Washington D.C. Council of Governments (MWCOG) that is utilized for this dissertation is substantive enough to encourage examination of travel behavior of TOD residents and compare them with non-TOD areas in the National Capitol Region (NCR). While the data refinement is an extensive effort and requires a solid knowledge of database manipulation and GIS, the end result provides valuable information associated with the travel behavior of transit oriented developments. In the subsequent sections of this chapter myths and/or intuitions about TODs is challenged and examined.

The data used for this section is based on the 2007/2008 household travel survey obtained from the National Capital Region Transportation Planning Board of the Metropolitan Washington Council of Governments (MWCOG). The use of this activity-based survey data mitigates loss of computational information frequently ensued by aggregate data, hence providing a more accurate quantitative forecast. The data includes a survey of 24-hour activity based travel patterns for 11,000 households in the greater Washington area which includes northern Virginia and parts of Maryland. The survey is conducted between February 2007 and March 2008 and includes more than 25,000 person records, 16,000 vehicle records, and 130,000 trip records (MWCOG, 2009).

The data included a household file which contained information for household size of various sizes having one, two, three, or more vehicles, household income, number of vehicles, number of students per household, number of licensed drivers per household and number of bikes and workers per household amongst other data fields. Since the data pertained to an individual person, totals and averages for each TAZ needed to be determined. For this reason, all data points (persons) who resided in the 0.25 mile buffer were extracted from the total of 25,000 person records.

Furthermore, the data included a trip file which contained information on 87,000 trips that was gathered throughout the data collection process. The file contained various trip attribute such as primary travel mode, and detailed travel mode which is particularly valuable for this dissertation.

In subsequent sections of this chapter the data from the household file and trip file is refined to illustrate vehicle ownership in transit oriented environments. Additionally primary and detailed travel mode is examined in transit oriented zones and is compared with areas that are not serviced by a reliable high speed transit service and the land use architecture is often pictured as half acre lots or larger with double car garages and a suburban life style where the use of personal vehicle is necessary for most trip activities.

3.1. Data Refinement

In the analysis of data for TOD vs. non-TOD zones, it is important to realize that a trip may have six potential destinations which as listed as follows:

1. A trip may start in a TOD zone and end in the same TOD Zone.
2. A trip may start in a TOD zone and end in a different TOD zone.

3. A trip may start in a TOD zone and end in a non-TOD zone.
4. A trip may start in a non-TOD zone and end in the same non-TOD Zone.
5. A trip may start in a non-TOD zone and end in a different non-TOD zone.
6. A trip may start in a non-TOD zone and end in a TOD zone.

3.2. Vehicle Ownership – TOD vs. Non-TOD

The use of vehicle as a primary mode of travel is fundamental in trip generation. The state-of-practice regression models for trip generation have the vehicular trips as the dependent variable. It is therefore prudent to examine vehicle ownership in transit-oriented communities. It is often thought that availability of a reliable transit system in the community in addition to strict parking regulations that limits the required number of parking spots leads to the use of transit usage as the primary mode of travel and hence reduces vehicle ownership.

The basic premise of this research that is being investigated is that presence of transit facilities tends to reduce vehicular trip rates in commercial, including office, and residential developments. In order to investigate this argument the vehicular mode of travel is extracted from all other modes of travel (including but not limited to transit, walk, bike, car pool) and the rates are compared between TOD and non-TOD environments. It is obvious that the TOD and non-TOD environments must have similar characteristics (in terms of number of employment and number of household) to make the comparison a fair and unbiased analysis. Consequently the first step in the analysis is to show that the employment data and number of households in the selected TOD and non-TOD environments are comparable.

The data from the MWCOG is examined to verify this claim. Vehicle ownership data from two areas are compared and contrasted. A non-TOD area is elected in the Loudoun County, Northern Virginia which is typically known for its suburban type environment. The house lots are normally in acres and minimum double-car garages are a fixed feature. There is either minimum or no transit service in this area and the primary mode of travel, whether it is work, shop or otherwise, is vehicular.

The TOD area is selected as the Rosslyn Ballston corridor in Arlington, Virginia which is the showcase of a transit oriented corridor in the nation. The reliable high speed Metro transit service coupled with the interconnecting bus transit system provides a well-connected network of public transit for home-based work, shop and entertainment trips as well as non-home-based trips in the National Capitol Region.

The two areas are somewhat identical in terms of the employment population. They are within 10% of each other. Figure 7 compares the two areas in terms of employment population. For the analysis periods 2005 and 2010, the selected two areas show similar employment population.

Once we have the employment population established as equivalent, vehicle ownership is examined. The MWCOG data shows the "number of vehicles in household" as an ordinal variable. The categories for the ordinal data are "0 vehicles", "1 vehicle", and incrementally increase to 6 vehicles.

Examination of the data indicates that vehicle ownership is much less in the TOD area than the Non-TOD area. In the Rosslyn-Ballston corridor where the strong TOD community exists, the date terminates after the "5 vehicle" category indicating that no household in that area has 5 or more vehicles in the household. Furthermore, the number of households in the TOD with no vehicles far exceeds the same category in the non-TOD area. Figure 8 shows graphical results of the analysis.

	2005 Employment	2010 Employment
TOD	93265	101107
Non-TOD	91257	100193

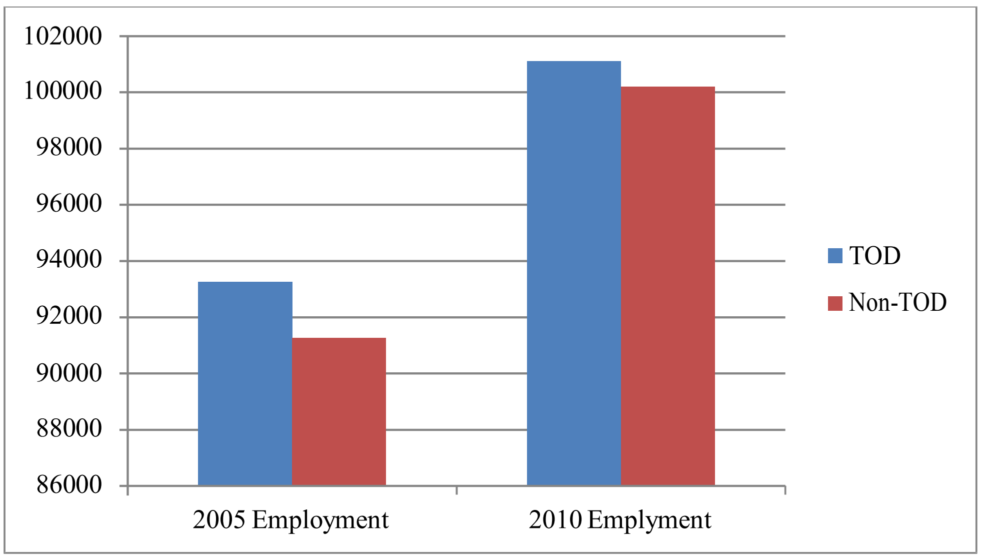


Figure 7. Employment Population – TOD vs. Non-TOD

hhveh	TOD	Non-TOD
0	3700.010626	456.8387214
1	15610.09706	17631.85317
2	7341.670825	27503.07631
3	2043.331382	8646.196959
4	110.45632	2892.54591
5	0	774.8853661
6	0	282.0792758
7	0	0
8	0	0
9	0	0
10	0	0

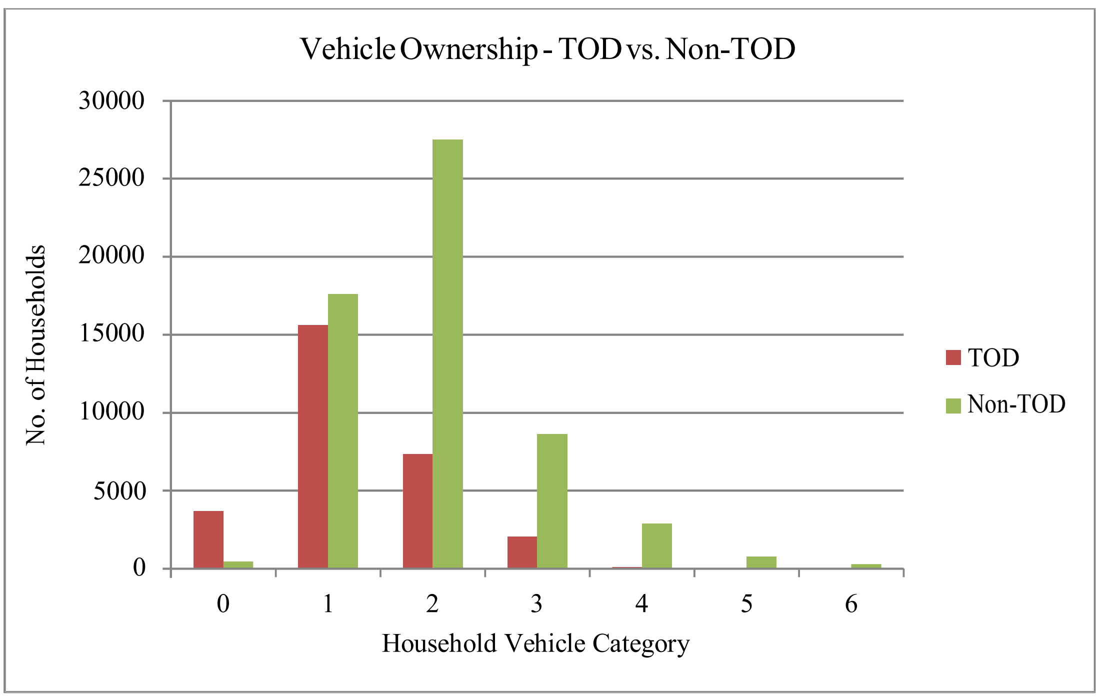


Figure 8. Vehicle Ownership – TOD vs. Non-TOD

3.3. Detailed Travel Mode – TOD vs. Non-TOD

Detailed travel mode is examined using the MWCOG data for the TOD area and is compared with non-TOD areas.

It is important to note that the TOD trips include trips within the TOD zone, as well as to and from non-TOD zones. Similarly, Non-TOD trips include all trips within non-TOD areas as well as trips to and from TOD areas.

As Figure 9 shows, and consistent with intuition, the rate of use of transit within TOD zones far exceeds non-TOD zones. Similarly, the rate of use of personal vehicles in non-TOD zones is higher than trips to, from, and between TOD zones. However, a surprising element in the data is that when the rate of use of personal vehicles is compared inside vs. outside TOD zones, one can observe a higher rate for personal vehicle as opposed to transit usage. One reason that may contribute to this is the TOD zone data includes trips to and from non-TOD areas. In other words, while the trip origin may be in a TOD zone, the trip destination may be in a non-TOD zone. In such cases, the traveler is forced to take personal vehicle even though he resides in a TOD zone. This is a testament to the fact that while the MWCOG area enjoys one of the widely used public transit systems in the nation, it's lack of complete service coverage to all areas of MWCOG results in higher use of vehicle mode even in TOD areas.

Detailed Travel Mode	0.25 Mile Buffer TAZ	> 0.25 Mile Buffer TAZ
Subway	13%	4%
Auto Driver	48%	60%
Auto Passenger	15%	23%
Taxi/Limo	1%	0%
Walk	16%	8%
Bike	1%	0%
School Bus	1%	4%
Local Bus	4%	1%
Commuter Rail	1%	0%

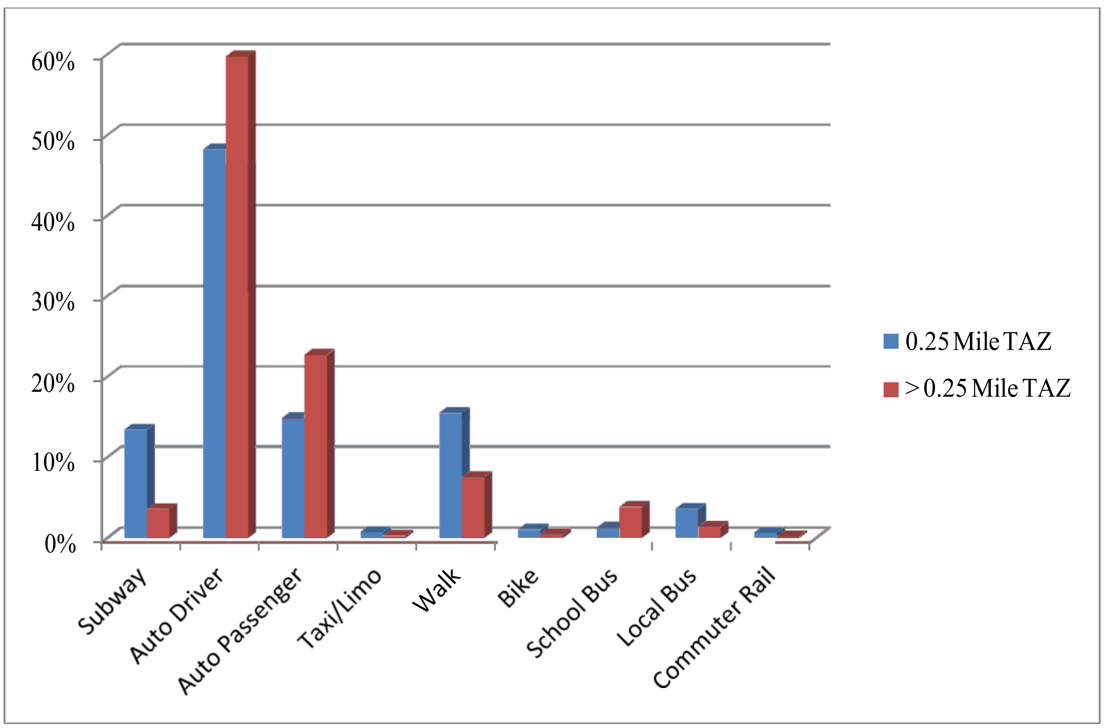


Figure 9. Detailed Travel mode – TOD vs. Non-TOD

3.4. Work Trips per Mode – TOD vs. Non-TOD

Utilizing the MWCOG data, the primary travel mode and detailed travel mode for home-based work trips are examined. The data needed to be refined to only include home-based work trips. Work trips are especially important as the travel mode for commuters which make the majority of trips can best be determined.

The selection of TOD vs. Non-TOD area for this assessment is based on the 0.25 mile radius of all 86 Washington Metro transit stations. All home-based work trips within the 0.25 mile radius of a transit station is selected as the TOD zone. All home-based work trips beyond 0.25 mile radius of a transit station are considered a non-TOD zone. To ensure a truly TOD behavior, the 0.25 mile radius is considered ideal walking distance to a transit station as shown in section 2.2.

Figure 10 and Figure 11 show the result of the data associated with primary travel mode and detailed travel mode respectively. As the figures show all transit, walk, and bike travel modes are much larger in the TOD zone. The non-TOD zone show larger share of auto mode.

The results verify the assumption that travelers who live beyond the comfortable walking distance of 0.25 mile from a transit station have a higher chance of using personal vehicles for home-based work trip which constitute majority of daily trips.

Primary Travel Mode	Work Trips (0.25 Mile Buffer TAZs)	Work Trips (Beyond 0.25 Mile Buffer TAZs)	All COG Work Trips
01 = Transit	320,436	35,185	355,621
02 = Auto Driver	556,333	1,630,619	2,186,953
03 = Auto Passenger	54,811	104,684	159,494
06 = Walk	187,027	58,018	245,045
07 = Bike	14,472	5,993	20,464
09 = Other	19,849	14,114	33,963
Total:	**1,152,927**	**1,848,613**	**3,001,541**

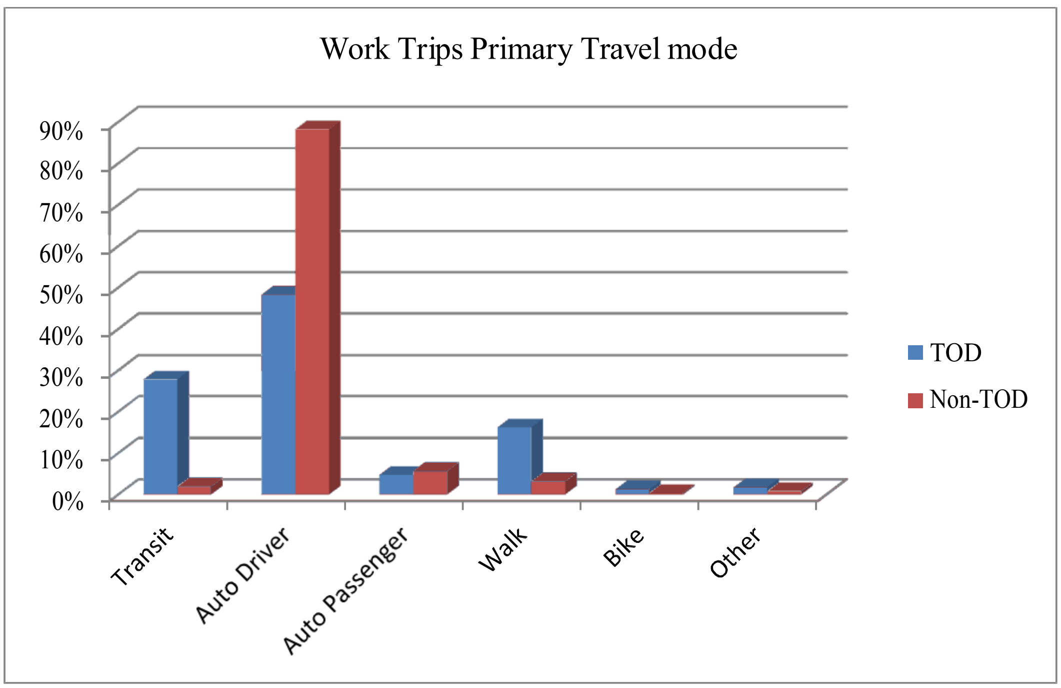


Figure 10. Work Trip Estimation Per Primary Travel Mode – TOD vs. Non TOD

Table 3. Work Trip Estimation by Detailed Travel Mode – TOD vs. Non-TOD

Detailed Travel Mode (mode)	Work Trips (0.25 TAZs)	Work Trips (Beyond 0.25 TAZs)	Work Trips (All COG)
Subway	252,983	16,708	269,691
Auto Driver	556,333	1,630,619	2,186,953
Auto Passenger	54,811	104,684	159,494
Taxi/Limo	8,770	3,628	12,397
Motorcycle	2,309	2,945	5,254
Walk	187,027	58,018	245,045
Bike	14,472	5,993	20,464
School Bus	1,401	1,876	3,277
Heavy Truck	1,060	1,485	2,545
Local Bus	43,661	14,874	58,535
Commuter Metrorail	15,270	2,822	18,091
Commuter Bus	8,522	782	9,304
Light Metrorail	0	957	957
MetroAccess	475	506	981
Shuttle Bus	5,835	2,599	8,433
Other	0	118	118
Total:	**1,152,927**	1,848,613	**3,001,541**

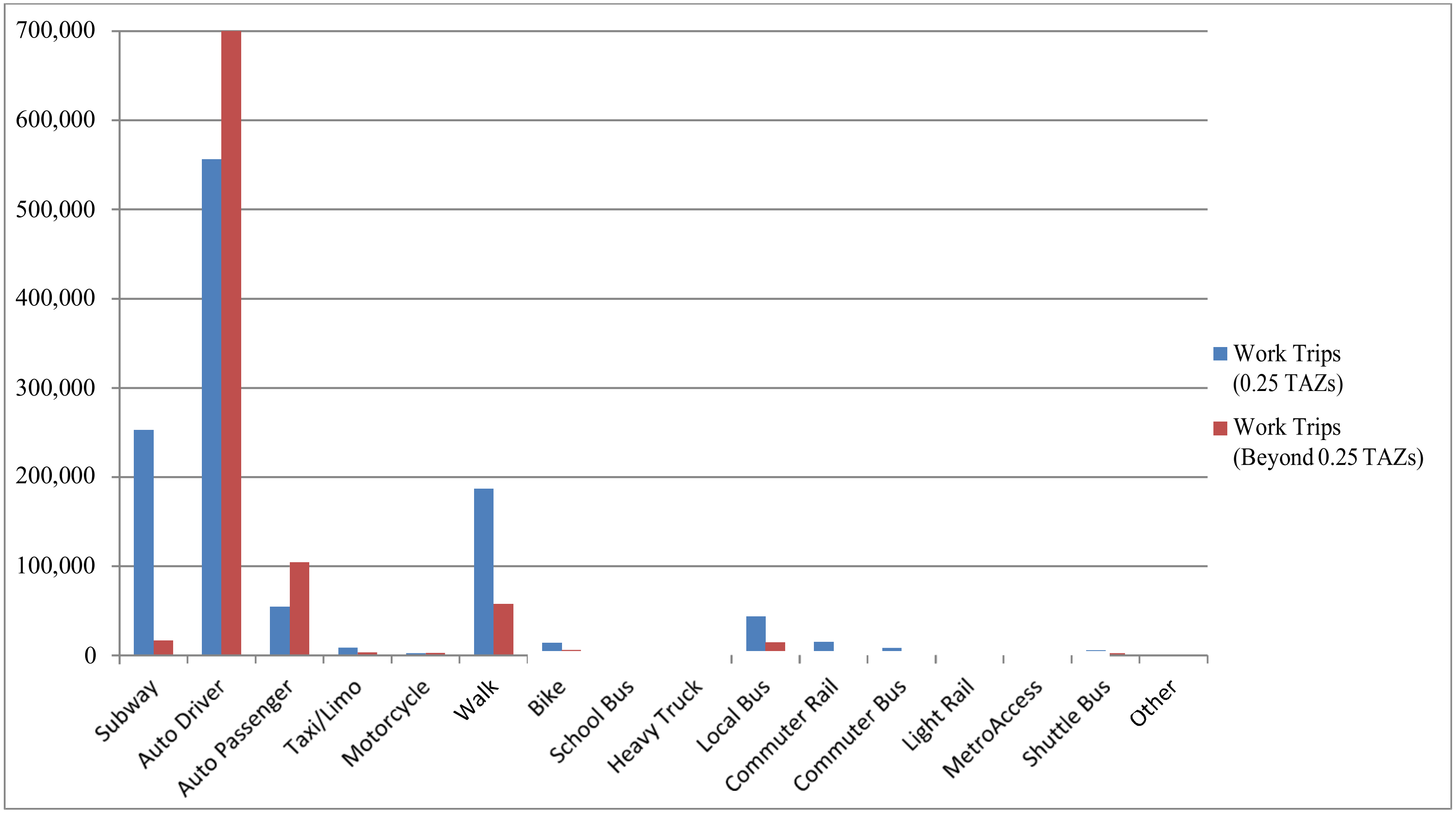


Figure 11. Work Trip Estimation Per Detailed Travel Mode – TOD vs. Non TOD

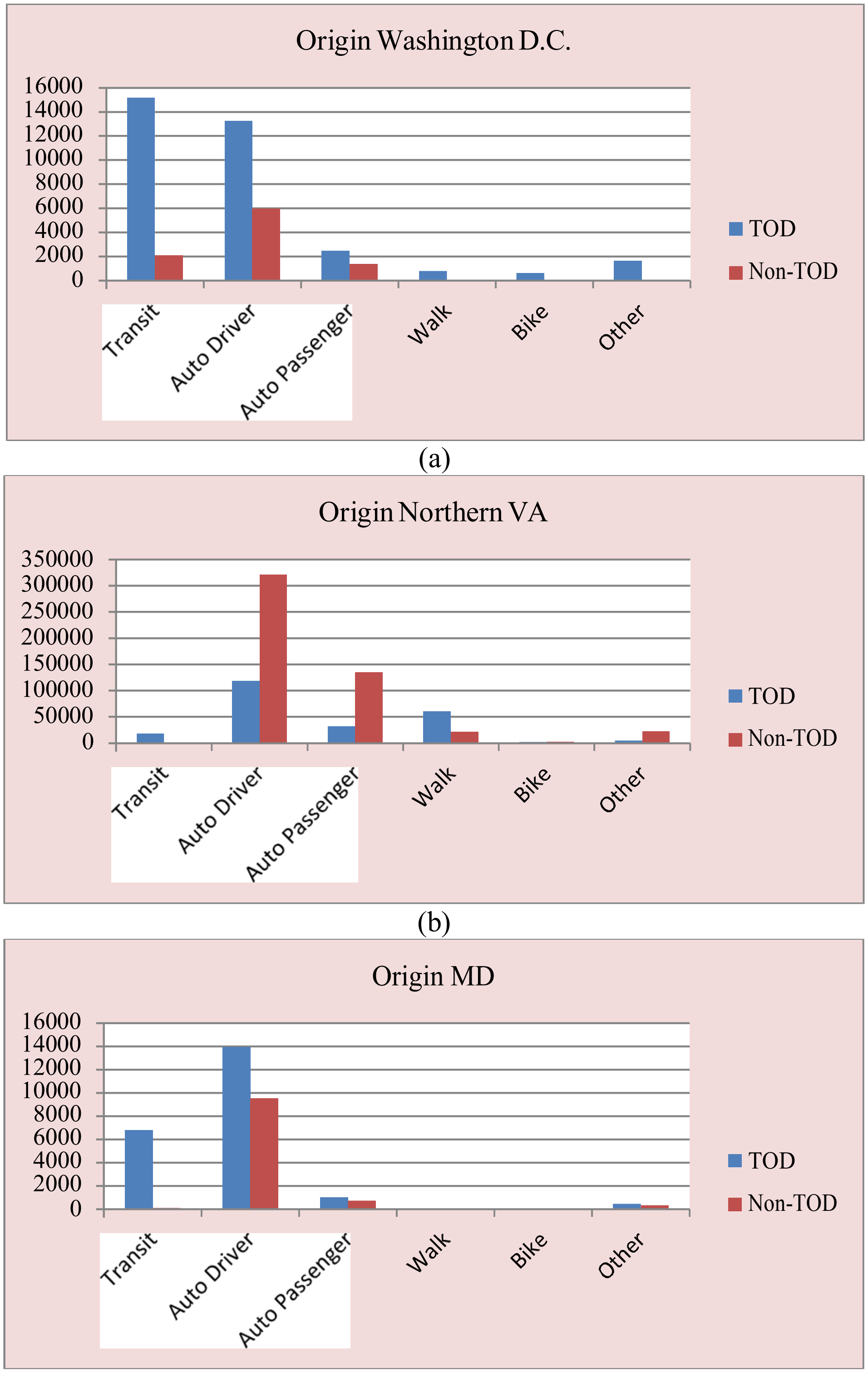
3.5. All Trips per Mode – TOD vs. Non-TOD

This section examines all trips (home, work, shop, entertainment) to and from a TOD zone and compares the rates with a non TOD zone. The primary travel mode is the data attribute that is examined in this section.

Consistent with previous section the TOD zone is based on 0.25 mile radius of all 86 Washington Metro transit stations. All home-based trips within the 0.25 mile radius of a transit station is selected as the TOD zone. All home-based trips beyond 0.25 mile radius of a transit station are considered a non-TOD zone. To ensure a truly TOD behavior, the 0.25 mile radius is deliberately selected as this is the ideal walking distance to a transit station as shown in section 2.2.

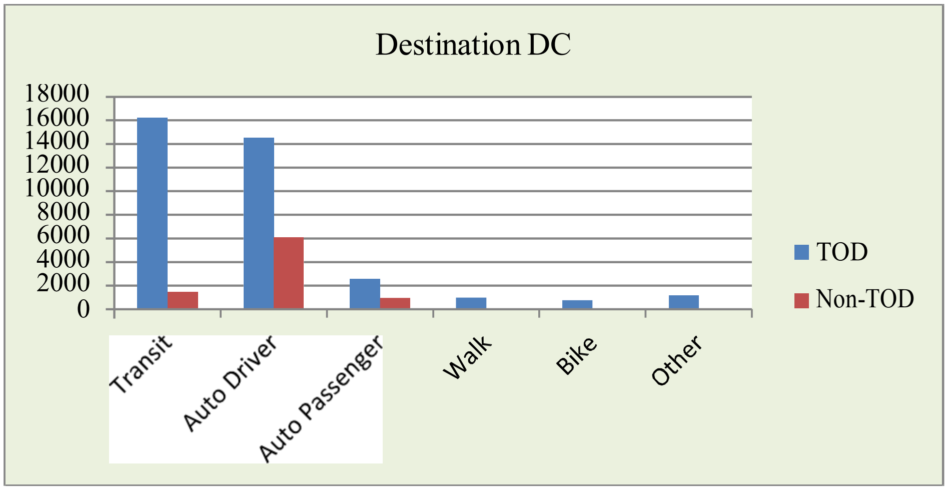
Figure 12 and Figure 13show the result of the data associated with primary travel mode and detailed travel mode respectively. As the figures show all transit, walk, and bike travel modes are much larger in the TOD zone. The non-TOD zone show larger share of auto mode.

The results of the analysis verifies the assumption that travelers who live beyond the comfortable walking distance of 0.25 mile from a transit station have a higher chance of using personal vehicles for home-based work trip which constitute majority of daily trips.

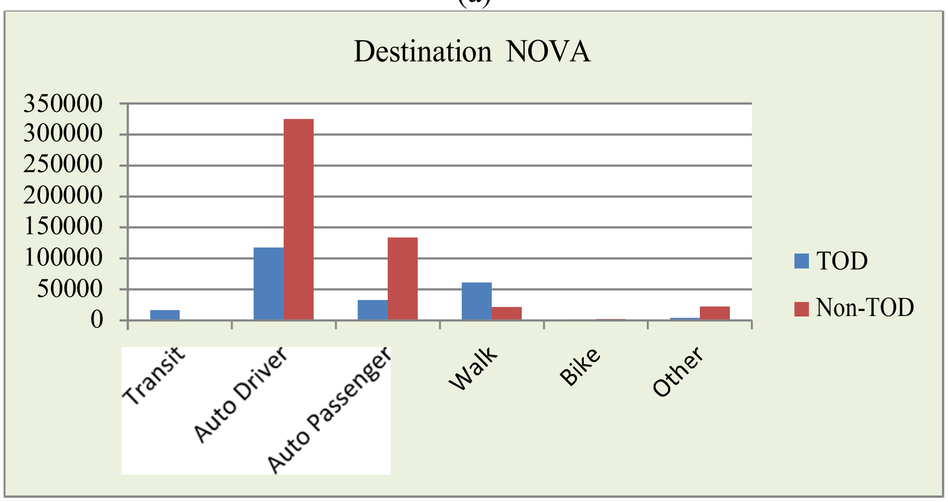


(c)

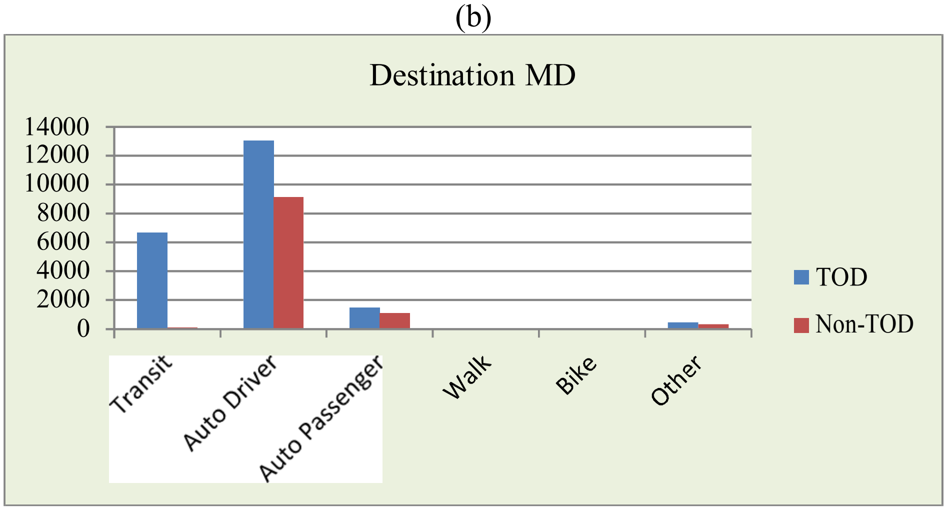
Figure 12. Mode of Travel to TOD / Non-TOD



(a)



(b)



(c)

Figure 13. Trip Destination From TOD / Non-TOD

3.6. Conclusion

Two geographic segments of the greater Washington D.C. area is selected to determine the trip behavior of transit oriented developments. While the two segments are similar in terms of number of employment population, there is a distinct difference associated with the level of transit facility and usage.

The TOD segments contain mixed-use developments located within comfortable walking distance of a reliable transit station. Arlington County, Virginia is the showcase of smart growth strategies in the nation. The mix-use developments adjacent to conveniently spaced transit stations service by the Washington Metro constitute the TOD segment of the analysis.

The non-TOD segment, however, is a typical suburban environment which the land use is predominantly constituted by single family homes and large lots. Home based work trips and shopping trips are often performed by the use of single occupancy vehicles a distant away from the residential zones. The Traffic Analysis Zones (TAZ) selected for the non-TOD segment of this analysis is mostly associated with Loudoun County, Virginia.

Results of the data analysis are consistent with intuition. Basically, there is heavier transit usage in TOD areas. Home based work, shop, and entertainment trips are mainly performed via the use of transit in TOD areas. Furthermore, walk and bike as the primary mode of travel are more predominant in TOD areas than the non-TOD areas.

Another result of the analysis which may not be contrary to intuition is the use of personal vehicles in TOD area is still high. This is because while the greater Washington D.C. area has one of the best transit network systems in the nation, yet the transit network is not saturated and only serves a limited part of the geography. In refinement of the data, if the origin or the destination of the trip is inside a TOD, then the trips were counted as a TOD trip. There are numerous instances which the traveler may reside in a TOD area, but work in a Non-TOD area, which is a cause for use of the personal vehicle as the primary mode of travel for home based work trips, hence the higher use of single occupancy vehicles in the results of the analysis.

CHAPTER 4. Trip Generation Estimation

4.1. Introduction

Trip Generation is the first step in the conventional four-step transportation demand forecasting process. Trip generation is followed by trip distribution, mode choice, and route choice. It predicts the number of trips originating in or destined for a particular traffic analysis zone (TAZ).

A Transportation Impact Analysis (TIA) is a study that assesses the demands and impacts of a particular land development on the surrounding area's surface transportation network. Traffic impact analyses vary depending on the type, size, and location of the development and are often required by local agencies as part of their land development review process. The overall objective of traffic impact studies is to evaluate the traffic generation of new developments and how that traffic impacts current traffic conditions. The need to invest in roadway improvements, whether it is in the form of new roads and highways, traffic signals, turn lanes, or improved safety are also an integral part of the impact analyses.

An accurate estimation of trip generation information is important to public agencies and private developers. It ensures accuracy when determining impact fees and also determines the magnitude of transportation improvement required by the development.

Therefore over or under estimation of trip generation rates is not beneficial to either local governments or the private sector developers.

The purpose of this chapter is to explore vehicular trip characteristics of transit oriented developments by determining their trip generation rates. This will enable traffic engineers and transportation planners accurately forecast vehicular trips associated with TODs. Based on activity based 24-hour household travel survey, regression models are developed and validated relating TOD trip ends to floor area for mixed land use. The validation of the regression model is performed by checking for normality of the distribution of data, multicollinearity and heteroscedasticity of the independent variables.

4.2. Problem Statement

The Institute of Transportation Engineers (ITE) Trip Generation Handbook is the primary source for calculating trip rates associated with a variety of land uses. Trip rates are determined based on different variables including area of the land use, number of dwelling units, or number of employees. The association between the trip rates, as the dependent variable, and the mentioned variables, as the independent variable, is shown through the use of regression models that are presented for each specific land use. The selection of the independent variables is usually based on accuracy, ease of collection and reliability of the data. While ITE's Trip Generation Handbook contains a trip rate for over 150 different type of lane use it lacks a suitable methodology for transit-oriented developments.

Most recently ITE attempted to develop a methodology to forecast the number of vehicular trips for mixed use developments. The proposed methodology does not necessarily include the element of transit and is not the primary focus in the development process. Furthermore, the data utilized for the study primarily came from suburban sites with abundant parking space.

The methodology has been noted by many researchers and public organizations to overestimate trip generation numbers.

A California Department of Transportation (Caltrans) study noted that the ITE proposed model for TODs was not applicable to urban infill sites as the locations used to develop the ITE proposed model for TODs were typically "isolated locations with ample free parking with little transit and pedestrian accessibility" (Caltrans, 2008). Furthermore, a comparative analysis of ITE methodology and actual observed trips generated by transit-oriented developments was performed by Cervero. The study was based on empirical data from 17 transit-oriented developments in five U.S. metropolitan areas. According to the author, the actual observed trips were 44 percent lower than ITE estimations (Cervero, 2008).

In an assessment of land use impact on transportation, Todd Litman of the Victoria Transport Policy Institute has made several references to the high trip rates that result from application of the ITE trip generation methodology for both residential and commercial developments. In a parking study performed in Portland, Oregon, he found that transit-oriented developments require 0.73 vehicles per housing unit as opposed to the 1.3 vehicles per housing unit recommended in the ITE Parking Generation Handbook (Litman, 2010).

The unsuitability of ITE's methodology is further described and analyzed by "Trip-Generation Rates for Urban Infill Land uses in California" report sponsored by Caltrans. The unsuitability of the method is noted to be contributed to the differences between infill developments and the suburban data presented in the trip generation (Kimley Horn and Associates, 2009).

The Alternative Mode (Non-Auto) Final Report Trip Reductions Database Study prepared for the Virginia Department of Transportation (VDOT) also recognizes the unsuitability of using the ITE recommended practice to develop trip generation forecasts for TODs (HNTB, 2009).

4.3. Level of Analysis

The two kinds of trip generation models are trip production models and trip attraction models. Trip production models estimate the number of home-based trips to and from zones where trip makers reside. Trip attraction models estimate the number of home-based trips to and from each zone at the non-home end of the trip. Different production and attraction models are used for each trip purpose. Special generation models are used to estimate non-home-based trips.

Consistency with industry standards is a primary factor in the development of trip generation model throughout this dissertation. Therefore, following the guidelines for variable selection in the ITE Trip Generation Handbook which most traffic engineers and planners are familiar with is a primary factor. The ITE Trip Generation Handbook uses the number of trips as the dependent variable and other parameters such as gross floor area, number of employees, or number of residential units is used as the dependent variable. Linear regression models are developed based on these variables. The R^2, as the measure of goodness of fit, is used in these models for validation purposes.

4.4. Measurement

The dependent variable is the total number of trips in a well-defined transit oriented corridor. The trips include home-based work, home-based shop, home-based entertainment and non-home based trips.

The independent variable is the gross floor area of developments within the 0.25 mile radius of the transit stations within the transit oriented corridor. The independent variable set is deliberately selected so that it is consistent with ITE's definition as a "physical, measurable and predictable unit describing the study site" (ITE, 2008).

The data from a well-defined transit-oriented corridor is needed to develop the linear regression model for this chapter. Several parameters are used to select an appropriate transit-oriented corridor. These parameters are the common denominator of the definitions of a transit-oriented development found in the literature, which include:

1. Mixed used developments – The variance of land use can be either concentrated in a single parcel, or be spread through a corridor that is well served by transit. The transit technology can include heavy or light rail, streetcar, trolley or bus.
2. Walking distance to a well-served transit station – A convenient walkable distance to a transit station, preferably 0.25 mile or less, is probably the most important criteria in defining a Transit-oriented environment.

3. Moderate to high density developments – Increased density of the land use is arguably the most important contribution of TODs in reduction of Vehicle Miles Traveled (VMT) and congestion.
4. Pedestrian and bicycle friendly – In order to satisfy criteria No. 2 above, well connected pedestrian and bicycle facility is necessary.

The Rosslyn-Ballston Metro Corridor in Arlington, Virginia selected as the test site which exemplifies a well-defined transit-oriented corridor. The corridor contains five metro transit stations that are well served by a reliable high speed underground metro-rail. Each transit station is the center of high density development within 0.25 mile radius. The corridor as a whole contains diverse land use from residential, office, retail to institutional and entertainment use. All transit stations are accessible through well connected pedestrian and bicycle network (Figure 14).

The Rosslyn station has the highest density with an average intensity of about 1.78 Floor Area Ratio (FAR) , and Clarendon station has the lowest intensity of around 0.60 FAR. The corridor contains a diverse land use. The Arlington General Land use Plan identified a particular use at each transit station referred to as “mixed-use nodes of activity” so that transit can be used for home and work trips, in addition to shop, entertainment, play, and study along the corridor. The Rosslyn station is more focused on high intensity office and residential mixed use, Courthouse has governmental and institutional use, Ballston and Clarendon are focused on restaurant and retail use, and Virginia Square has more educational and institutional use (Fairfax County Department of Planning and Zoning, 2009).

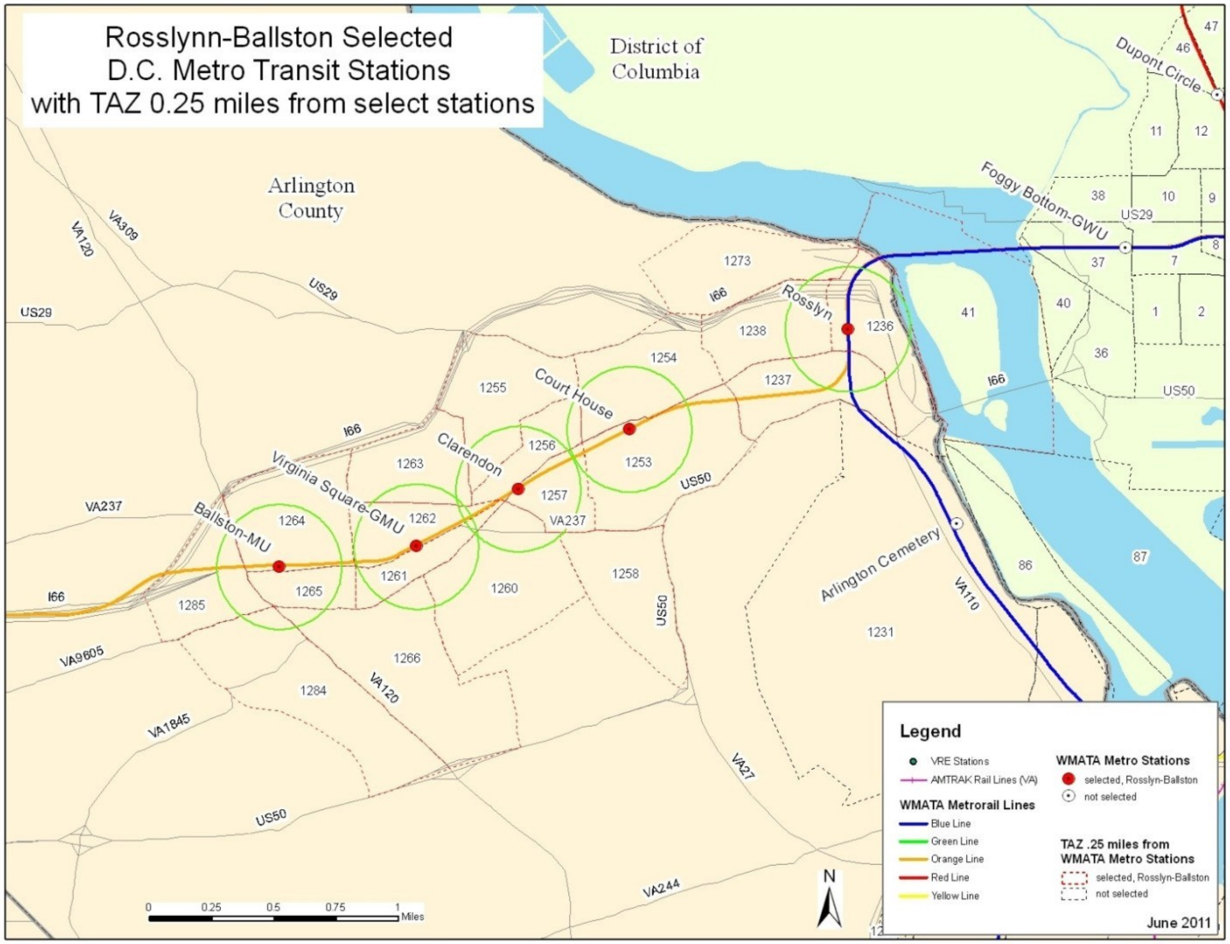


Figure 14. Test Site for Trip Generation Model Development

4.5. Description of Data

A considerable amount of research and development has focused on the area of disaggregate models for improved travel demand forecasting. The difference between the aggregate and disaggregate techniques is mainly in the data efficiency. Aggregate models are usually based on home interview origin and destination data that has been aggregated into zones. Subsequently the average zonal productions and attractions are derived. The disaggregate approach is based on large samples of household types and travel behaviors and uses data directly as opposed to groups of data. The disaggregate approach expresses non-linear relationships and is more easily understood (Kimley-Horn, 2008).

Over time the profession has come to understand that considerable predictive power and accuracy can be gained by disaggregate analysis of influential variables. This means that the models use factors describing individual sample units (e.g., persons, households or workplaces) rather than an average value of each factor for each analysis zone. The result is trip generation models with trip rates for sample units having specific characteristics, such as households of one, two, or more family members, owning one, two, or more vehicles. These models are based on the trip rates for individual sample households having those particular discrete characteristics (Kimley-Horn, 2008).

4.5.1. Conventional Data Collection Techniques

The conventional methodology for collecting trip data for any kind of development is primarily based on the use of pneumatic tube counters that are strategically located at all access points to the site for a one week period to capture variations in vehicular volume that try to ingress and egress the site.

The ITE Trip Generation Handbook outlines the necessary steps in the design of a trip generation study for special generators. Special generators are land uses that are not already identified in the current edition of the Handbook. There may be circumstances where discrepancies in terms of definition of land use or size of the development exist between what is provided in the Handbook and the land use under study. Such circumstances trigger the need for performing a trip generation study (ITE Trip Generation Handbook, 2008).

Transit-oriented developments are an example of special generators that travel data is not readily available and must be collected. The data collection process is expensive and time consuming and may not produce the most accurate data for analysis. The lack of accuracy is partially due to the responses obtained from the interviews which play a great role in the determination of pass by trips.

The approach for collecting vehicular trip generation data for special generators is outlined in the ITE Trip Generation Handbook. The initial step is to determine an accurate sample size to yield a statistically significant trip generation results. ITE recommends a sample size of at least three sites and preferably five sites. Obviously statistical accuracy of the final trip rates will increase as the sample size increases however, cost increase can be a detrimental factor in the determination of sample size. Once the sample size is determined, site selection follows. It is paramount that the sites are consistent with the definition of the land use under study. In the case of transit-oriented developments proximity to a well-served reliable transit station, mixed use nature of the developments, walkability to the transit station are among important factors to consider in site selection. Other criteria to consider in site selection, as identified by the ITE are:

- Reasonable occupancy,
- Maturity of the development (at least two years old) to ensure the characteristics of the development are in place,
- Availability of the data required for the independent variables (such as square footage, number of dwelling units),
- Stand-alone development (no shared parking or driveways, no through traffic and pass-by pedestrian activity), and
- Single use activity with limited or no construction within the limit of study.

Next, one or more independent variables have to be identified that are easily collectable. These may include square footage, number of dwelling units, site acreage, or number of employees.

The survey period is the final step in the preparatory work prior to the actual count. ITE recommends a full 7-day period. This period allows for determination of actual peak hour volumes and eliminates peak hour variations which may ensue from unexpected anomalies such as weekend trips, or roadway accidents.

The actual data count utilizes automatic traffic counters located at site access points to capture all egress and ingress vehicular count data. A typical vehicular count data collection for special generators includes:

1. A week long (seven consecutive days) of directional traffic volume count that encompasses both exiting and entering the site by 15 minute period.
2. Hourly traffic volume data on all adjacent streets to determine peak hour volume on the adjacent street to the site can be determined.
3. All access points to the site must be counted.
4. Data associated with the site can be obtained either from owner or from the site plan.
5. Verification of automatic counts with manual counts.
6. Additional data collection may be needed for transit trips, mixed-use development, pass-by trips and internal capture trips. The pass-by trip data is collected via the use of interviews. An appropriate sample size with a desired confidence level must be initially determined. Once the sample size is determined, interviews are conducted on all access points to the site. Motorists are interviewed upon approaching their vehicles or as they exit the site.
7. For mixed use developments, a combination of automatic traffic counters for a seven consecutive day period on all external and internal streets, plus interviews of workers, shoppers, visitors and residents must be concurrently conducted.

It has been noted that the conventional approach to data collection may not capture all trips as visitors may park off-site and walk to the site if parking is limited or expensive. Furthermore, the conventional approach requires that the site be a stand-alone facility with its parking dedicated only to that site, and isolated enough so that visitors to the site do not park off-site and walk (Caltrans, 2008).

Other data collection techniques have also been developed in the industry. These methods include travel journals, mail-in surveys, telephone surveys, combined telephone and mail-in surveys, and in-person intercept surveys. Table 4 describe these data collection methodologies and discusses its advantages and disadvantages.

4.5.2. Trip Generation Analysis Data

The data used for this paper is based on the 2007/2008 household travel survey obtained from the National Capital Region Transportation Planning Board of the Metropolitan Washington Council of Governments (MWCOG). The activity-based survey data provided a wealth of transit-oriented corridors, and diverse land use. The use of this data mitigates loss of computational information frequently ensued by aggregate data, hence providing a more accurate quantitative forecast. The data includes a survey of 24-hour activity based travel patterns for 11,000 households in the greater Washington area which includes northern Virginia and parts of Maryland. The survey is conducted between February 2007 and March 2008 and includes more than 25,000 person records, 16,000 vehicle records, and 130,000 trip records (MWCOG, 2009).

This data for the gross floor area of developments within 0.25 mile radius of a transit station is obtained from the Arlington County's website. The information is included in the Planning Information Report (PIR No. 63 and 66) published by Arlington County.

For consistency, both sets of data which include the 24 hour activity-diary survey and the development data, applied to the same analysis period of 2007 – 2008. The development data included residential, office, retail, hotel and others for each of the five stations along the Rosslyn-Ballston Metro Corridor. The Geographic Information System (GIS) analysis tool ArcGIS is used to determine the 0.25 mile buffer around the transit station. The data refinement process is a series of data manipulation and extraction via the use of MS Access and Arc GIS. The following is a series of steps taken to extract the trip data and the development data required for trip generation estimation of transit-oriented developments. Figure 15 illustrates the data refinement process.

1. The trip file from the MWCOG trip diary survey data is used to extract trip associated with the Rosslyn Ballston corridor. The TAZ that were associated with the Rosslyn Ballston corridor were identified and filtered through the trip file to obtain the trips inside the corridor.
2. The development data published on a series of Planning Reports by Arlington County is available per transit station.
3. ArcGIS is used to determine the area (in square mile) of the TAZ that is within the 0.25 mile radius zone of a transit station.
4. The percent area of the TAZ that is within the 0.25 mile zone is applied to both the number of trips and the development gross floor area.
5. The result is the number of trips, the dependent variable, and gross floor area, the independent variable both inside the 0.25 mile radius zone.

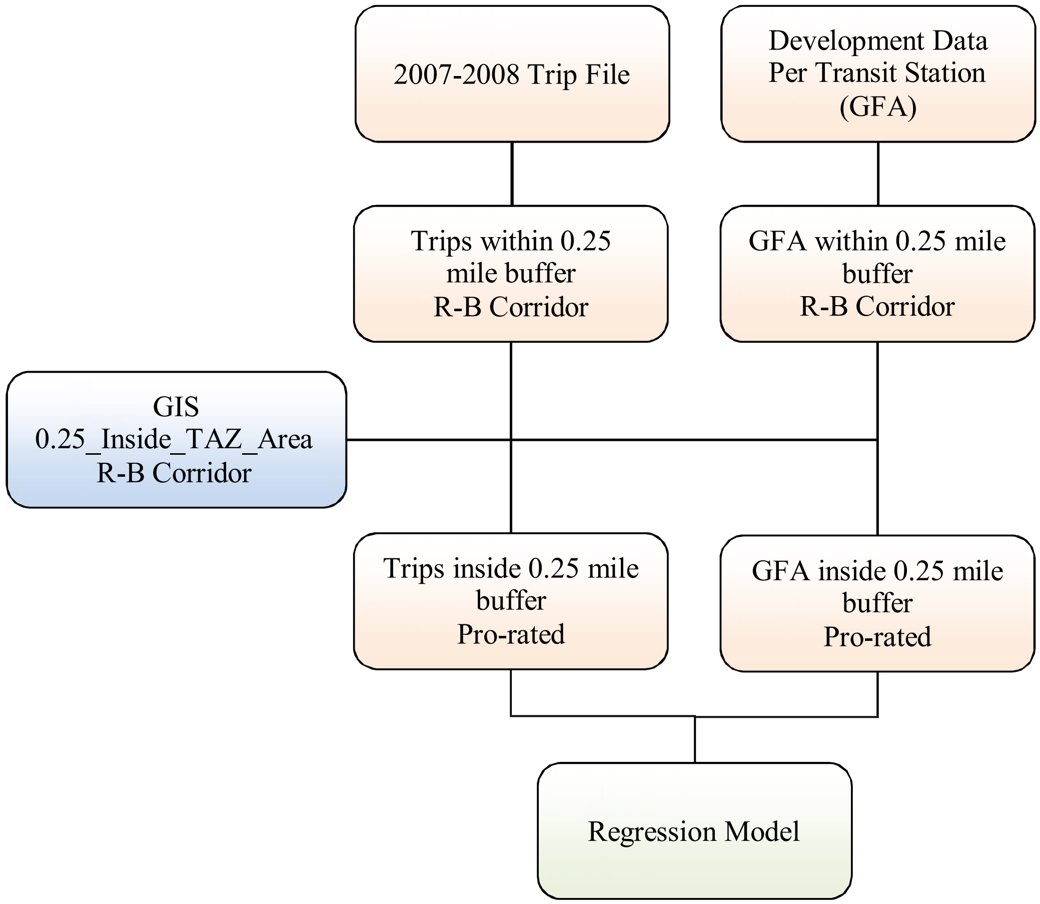


Figure 15. Trip Estimation Data refinement Process

Table 4. Alternative Data Collection Methodologies

Methodology	Advantages	Disadvantages
Travel Journals A daily or weekly diary filled in by an individual traveler to document all trips. These surveys can document information about an individual's socio-economic and demographic status, household information, vehicle ownership, and daily travel choices by purpose and mode§.	□ Effective way of collecting many types of data associated with the traveler.	□ Requires significant commitment from the respondent. □ Requires high response rate. □ Not necessarily associated with a specific land use type. □ High cost
Mail-in Surveys Involves mailing questionnaires with respondents mailing back the completed surveys.	□ Effective way of collecting many types of data associated with the traveler.	□ Data is associated with the residents of the site and not to the visitors of the site. □ Typically low response rate.
Telephone Surveys *Involves calling respondents and asking the questionnaires.*	□ Higher response rate than mail-in surveys.	□ Hard to identify the right individual to survey.
Intercept Surveys Intercept surveys collect data from a sample of the population being surveyed in-person.	□ High statistical accuracy.	□ Must ensure randomness.

§.*Trip Generation Rates for Urban Infill Land Uses in California – Final Report* (CalTrans, 2008)

4.6. Research Design

The primary purpose of this chapter is to develop a regression model to determine vehicular trip generation rates of transit-oriented developments using activity-based 24-hour household travel survey data from travel survey data for the greater Washington D.C. metropolitan area.

The Rosslyn-Ballston Metro Corridor in Arlington, Virginia which is selected as the test site for this portion of the research exemplifies a transit-oriented corridor. The corridor contains five metro transit stations that are well served by a reliable high speed underground metro-rail. Each transit station is the center of high density development within 0.25 mile radius. The walkability distance of 0.25 mile as an ideal walking distance for a successful transit-oriented development is confirmed and established throughout the literature. The test corridor contains diverse land use from residential, office, retail to institutional and entertainment use. All transit stations are accessible through well connected pedestrian and bicycle network.

The trip generation characteristics of TODs are best described by a regression model. The regression model used the development area foot-print (in square feet) in a 0.25 mile zone of a transit station, as the independent variable. The vehicular trips in the same buffer zone served as the dependent variable.

4.7. Modeling Technique

The three major techniques used for trip generation analysis are cross classification, experience based analysis, and multiple regression analysis. While only regression model is used for the trip generation portion of this chapter, each technique is briefly discussed below:

4.7.1. Cross-Classification

Cross-Classification procedures measure the changes in one variable (trips) when other variables, for example land use, are accounted for. Cross-Classification resembles multiple regression techniques. One problem with the Cross-Classification technique is that the "independent" variables may not be truly independent, which may result in erroneous trip predications.

The FHWA trip production model uses Cross-Classification and has the following sub-models.

- Income sub-model which shows the distribution of households within various income levels.
- Auto ownership sub-model that shows the relationship between household income to auto ownership.
- Trip production sub-model which establishes the relationship between the trips made by each household and independent variables.
- Trip purpose sub-model which relates the trip purposes to income so that the trip productions can be divided among various purposes.

4.7.2. Experience Based Analysis

Experience Based Analysis, one of the most commonly used techniques, is founded primarily on experience. The Institute of Transportation Engineer's Manual of Trip Generation is one of the best sources of generalized trip generation rates. The manual is a compilation of data from all over North America on many different types of land uses. The Trip Generation Manual includes productions and attractions for each type of land use and are related to some measurable variable. For example, a shopping center might produce a certain number of trips for each employee. Simply asking for the employment roster would allow a transportation engineer to estimate the total number of trips that are generated by the shopping center employees. A survey of similar land uses in the area may also need to be conducted to validate the model.

4.7.3. Regression Analysis

The trip generation characteristic of TODs is best described by a linear regression models that is developed as part of this chapter. The simple regression model used the development area foot-print (in square feet) in a 0.25 mile zone of a transit station in a transit-oriented corridor, as the independent variable (predictor). The vehicular trips in the same buffer zone served as the dependent variable.

The regression equation expresses the mathematical relationship between the dependent and the independent variable. It is basically the equation of a line that best fits the data. A total of 38 data points were included in the analysis. The ITE Handbook recommends using the regression equation for 20 or more data points to ensure normal distribution of data.

4.8. Research Hypothesis

The research hypothesis for this analysis is as follows:

Let H_0 = There is no relationship between the size of the development in terms of Gross Floor Area (GFA) and the number of vehicular trips to in a transit-oriented corridor within 0.25 mile buffer zone of a transit station.

Let H_A = There is significant relationship between the size of the development in terms of Gross Floor Area (GFA) and the number of vehicular trips to in a transit-oriented corridor within 0.25 mile buffer zone of a transit station.

Assume $\alpha = 0.05$.

4.9. Analysis Results

As shown on Table 5, the p-value is very small (0.0000). This value indicates the significance of the model and shows that there is a strong relationship between the number of trips in the 0.25 mile radius buffer zone of a transit station and the independent variables which is the gross floor area of development within the same zone.

We conclude that the null hypothesis is rejected.

Table 5. Linear Regression Analysis Results

Number of Observations	38	
R^2	0.8918	
Adjusted R^2	0.8076	
Trips	Coef	P > t
GFA	1.096	0.000
Constant	1.05	0.000

Additionally, the R^2, which is the "measure of goodness of fit", is 63%. R^2 is the proportion of variance in the dependent variable (trips) which can be predicted from the independent variable (gross floor area (SF)). The R^2 does not reflect the extent to which any particular independent variable is correlated with the dependent variable.

The association of trips in a TOD corridor and development foot-print in terms of square feet can be represented as follows:

$$ln(T) = 1.05 + 1.096 ln(X)$$

Where:

T = Trip Ends

X = TOD Gross Floor Area in (SF)

Figure 16 shows the regression graph of this analysis.

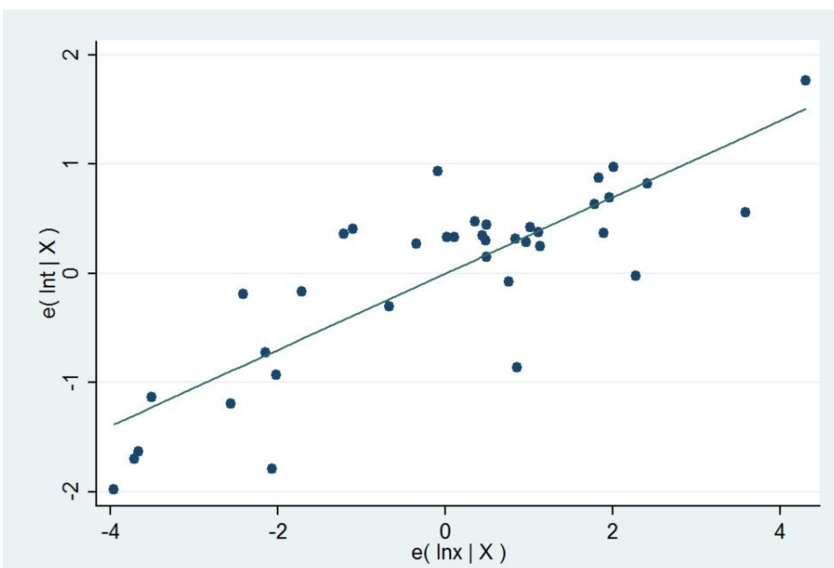


Figure 16. Linear Regression Graph – TOD Trips

4.9.1. Normality

Many researchers believe that multiple regression requires normality. This is not the case. Normality of residuals is only required for valid hypothesis testing, that is, the normality assumption assures that the p-values for the t-tests and F-test will be valid. Normality is not required in order to obtain unbiased estimates of the regression coefficients (Stata® help files).

Furthermore, there is no assumption or requirement that the predictor (independent) variable be normally distributed.

After a regression analysis is executed, the “predict” command, in Stata® is used to create residuals. Then the command “kdensity: is used to verify the normality of the residuals. Figure 17 shows that the residuals are close to a normal distribution, thus we accept the independent variable to be normally distributed.

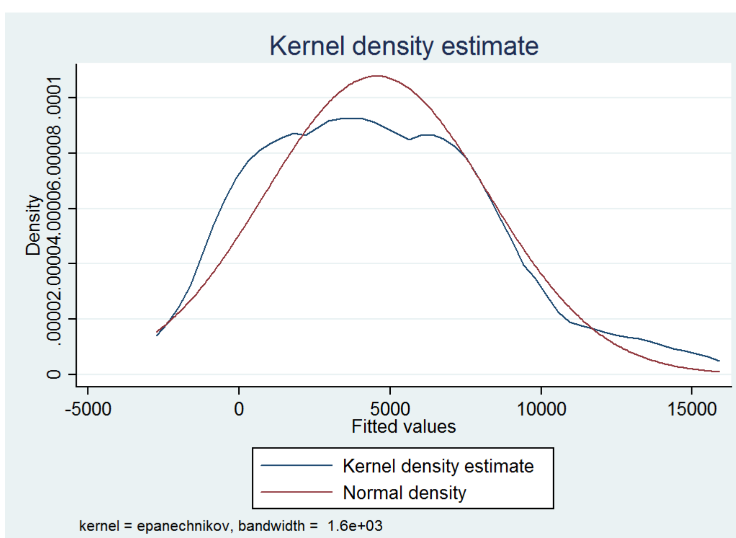


Figure 17. Normality Test of Residuals

4.9.2. Collinearity

A criteria in mathematical validation of the model is linearity between the predictor and the dependent variable. Table 6 shows the result of linearity. The value of 0.79 indicates that approximately 80 percent of the variables maintain a linear relationship with each other.

Table 6. Collinearity Test

	Trips	**Development Foot Print (KSF)**
Trips	1.0000	
Development Foot Print (KSF)	0.7921	1.0000

4.10. Heteroscedasticity

A validation criteria in regression models is to test for homogeneity of variance of the residuals. If the model is well-fitted, then there should be no pattern between the residuals and the fitted values and the model. In this case it is said to be non- heteroscedastic. If the variance of the residuals is non-constant then the residual variance is said to be "heteroscedastic." In order to show the model is non- heteroscedastic we plot the residuals versus fitted (predicted) values. In Stata[1] we do this by issuing the “rvfplot” command.

---

[1] http://www.ats.ucla.edu/stat/mult_pkg/whatstat/default.htm

The heteroscedasticity plot of the model with a reference line y = 0 show there are no pattern between the residuals and the fitted values, thus the model is not heteroscedastic (see Figure 18).

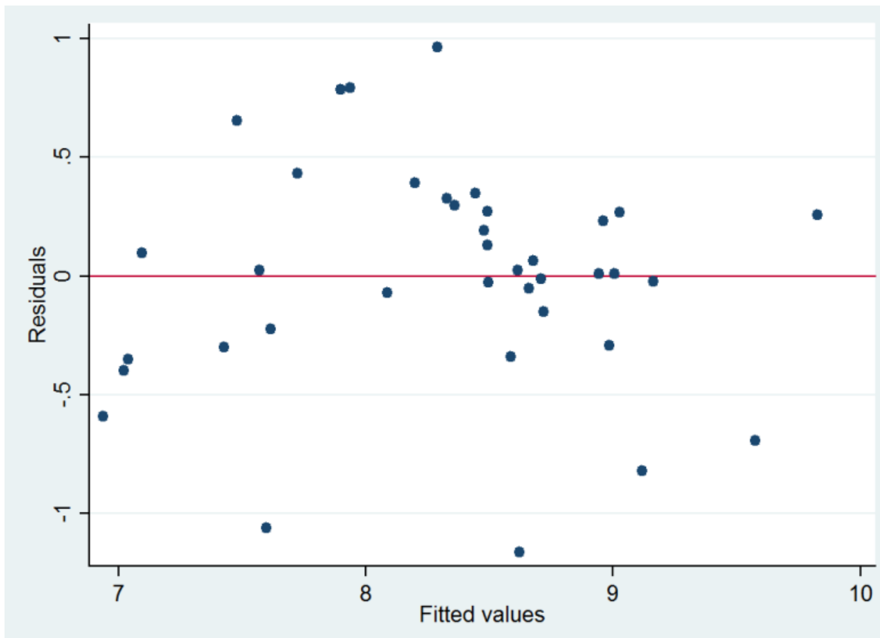


Figure 18. Heteroscedasticity Test

4.11. Model Validation

In addition to the normality test, p-value and R^2 factors that indicate the robustness of association and validity of the model described in previous sections of this chapter, the regression model is tested against two current state-of-practice methodologies. The two methodologies are the non-TOD ITE and the MXD methodology. A 1,000 KSF of office building is assumed as the land use for the validation test.

The non-TOD ITE methodology is referring to the normal trip generation for office use that is calculated based on the conventional methods prescribed by the ITE *Trip Generation Handbook*.

The MXD methodology is developed by the U.S. Environmental Protection Agency (EPA). The methodology is a substitute to the ITE multi use method by reducing the vehicle trip estimates to better illustrate the trip generation behavior of mixed use transit oriented development. The MXD model is validated using data collected at 239 multi-use development sites in six regions (Atlanta, Boston, Houston, Portland, Sacramento and Seattle.)

The MXD methodology is MS Excel spreadsheet based and requires various types of data. Key inputs to the spreadsheet are in the number of intersection within the project; number of employment within one mile radius of the mixed use development, and employment that can be reached from project within a 30-minute transit trip. The output of the spreadsheet is the percent reductions for internal capture trips and external transit and pedestrian / bicycle trips that are reduced from the regular ITE trip rates.

The input to the MXD spreadsheet is cumbersome and is in contrast to the state of practice. Most of the data requirement needs additional complex data refinement process that often involves the use of GIS and robust database analysis software.

Results of the analysis are shown on Table 7 which illustrates the comparison between all three methodologies.

Table 7. Validation Test[2]

	TOD Regression Model	Regular Non-TOD ITE Rate	MXD Methodology
Trips	5546	7856	4617
Difference		30%	7 %

The developed regression model shows a 55% trip reduction for transit oriented developments compared to a non-TOD development. This is consistent with the state of practice. Often times a value of 55% - 65% reduction is applied for presence of a reliable heavy rail transit service. While this number is not justifies by any statistical or mathematical analysis, yet the industry as a whole is comfortable with this quantity. Furthermore, the results of the developed regression model are consistent with the MXD methodology. Since the MXD methodology is currently the only tested, verified and adopted (by multitude of public agencies) model, to predict rip generation numbers of a mixed use development with a strong transit element, then the within 10% difference in trip generation numbers is a good indication of the validity of the developed model.

4.12. Conclusion

A regression model to show the association between trip ends and gross floor area of developments along a transit-oriented corridor is developed and validated. The activity-based 24-hour household travel survey data from travel survey data for the Washington

---

[2] Based on 1,000 KSF of office use.

D.C. Metropolitan area is used as the analysis data. The Rosslyn-Ballston Metro Corridor in Arlington, Virginia which exemplifies an ideal transit-oriented corridor is selected as the test site. The p-value of close to zero, with 4 significant digits, shows the model is significant and independent variables reliably predict the dependent variable. Furthermore, the R^2 of 0.81 is an overall measure of the strength of association and goodness of fit.

The model is further validated against two state-of-practice measures for trip prediction. The developed regression model shows a 55% trip reduction for transit oriented developments compared to a non-TOD development. This is consistent with the state of practice. The less than 10% difference in trip generation numbers between the developed regression model and the MXD methodology is another good indication of the validity of the developed model.

In the absence of a structured sensitivity analysis, it is not clear if differentiating trip generation models for TODs and other land uses will automatically lead to better results from the travel demand modeling process. However, disaggregate trip generation models are widely regarded as better model for travel demand modeling applications. Therefore, whenever travel survey data with spatial resolution are available, it is recommended that separate trip generation models be developed for TODs.

It should be pointed out, while the methodology presented in this dissertation is transferable, the models themselves is limited to greater metropolitan Washington D.C and may not be transferable to other regions of the country.

CHAPTER 5. Trip Generation Prediction

5.1. Concept Description and Background

The previous chapter showed the mathematical relationship between a certain land use and trip ends. The trip ends are normally in terms of sheer magnitude and does not consider direction or length. For trip generation purposes, transportation planners are also interested to assess the relationship of trip ends and certain socio-economic factors such as race, income, vehicle ownership, and employment type among others. For example, in order to adequately determine the number of parking spaces for office land use, a city government is interested to assess the association between number of vehicles in a household and trip ends in a transit oriented development. This chapter establishes the relationship between trip ends and several socio-economic factors focused along transit oriented developments.

To fully utilize the available data, the association between trip rates in a transit oriented environment and number of household characteristics such as household income, number of cars, among others, are of interest. A multinomial regression equation that can describe and/or predict the relationship between trips rates and household characteristics will be useful to transportation planners and engineers.

The trip generation characteristics of TODs are best described by egression models that are developed as part of this dissertation. Trip generation models have been commonly developed by regression analysis because of its power of prediction and ease of use for common practitioners. The trip generation is based on multivariate regression analysis with the number of vehicular trips as a function of one or more independent variables. This is a mathematical approach to trip generation in which all variables are considered random with normal distributions.

The household attributes assumed for the analysis presented in this chapter include average household size, average number of vehicles, students, licensed drivers, workers and bikes per household. These variables which are served as the predictor (independent variable) in the analysis are readily available through the 2007 – 2008 MWCOG data used for this dissertation.

The list of independent variables is all inclusive. In other words, they include all household attributes included in the MWCOG data set. The impact of the variable, however, will be determined through backward elimination presented in the subsequent sections of this chapter. Backward elimination is a statistical process that is initiated with the development of a full multivariate regression model and is followed by an iterative process of elimination of variables with low significance of association until a robust model with strong association is derived.

Mathematical validation of the final model is performed by checking for multi-collinearity between the dependent variables (number of vehicular trips) and with each independent variable individually. While collinearity amongst the dependent and independent variables ensure validity of the model, it must be noted that the linear relationship between independent variables are fatal. Linearity amongst independent variables can cause erroneous regression coefficients which can also be detected by large quantities of residual error.

Normality of the independent variables is a further testament to the validity of the independent variables. While the "central limit theorem" insures normality by the sheer quantity of the data, yet graphical presentation of data is also shown to verify normality. Furthermore, homogeneity of variance (a.k.a heteroscedasticity) which is an indication that the variance amongst errors is constant is shown graphically.

5.2. Level of Analysis and Measurements

A multiple regression model is developed to explain the relationship between trip rates and several household attributes in a transit-oriented environment. Through the use of statistical elimination of lesser significant variables, the multiple regression model is reduced to only include significant variables that would aid in predicting trip rates of TODs given a set of variables.

The independent variables included in the data are:

- *Size* = Average household size
- *inc* = Average income per household,
- *veh* = Average vehicles per household,
- *stud* = Average number of students per household,
- *drvr* = Average number of licensed drivers per household,
- *wrkr* = Average number of workers per household, and
- *bike* = Average number of bikes per household.

Backward elimination technique is used to eliminate variables that do not significantly impact the association. The criteria for eliminating lesser significant variables included $\alpha = 0.05$. Therefore P-values of 0.05 or less were eliminated one at a time and the value of regression coefficient R^2 is observed until a reasonable regression coefficient is derived.

5.3. Description of Data

The data used for this paper is based on the 2007/2008 household travel survey obtained from the National Capital Region Transportation Planning Board of the Metropolitan Washington Council of Governments (MWCOG). The activity-based survey data provided a wealth of transit-oriented corridors, and diverse land use. The use of this data mitigates loss of computational information frequently ensued by aggregate data, hence providing a more accurate quantitative forecast. The data includes a survey of 24-hour activity based travel patterns for 11,000 households in the greater Washington area which includes northern Virginia and parts of Maryland. The survey is conducted between February 2007 and March 2008 and includes more than 25,000 person records, 16,000 vehicle records, and 130,000 trip records (MWCOG, 2009).

The 24-hour activity-diary survey data included a household file which contained the data for household size of various sizes having one, two, three, or more vehicles, household income, number of vehicles, whether the data point is a student, has a driver license, has bike, is a worker and other relevant information. Since the data pertained to an individual person, totals and averages for each TAZ needed to be determined. For this reason, all data points (persons) who resided in the 0.25 mile buffer were extracted from the total of 25,000 person records.

5.3.1. Data Refinement Process

The 2007/2008 24 hour activity-diary survey data obtained from MWCOG required extensive refinement to serve the purposes of this study. The data included a trip file which contained information on the primary travel mode associated with a person in a TAZ. In order to develop a multinomial regression equation, the number of vehicular trips in a TAZ, as the dependent variable, is desired. Consequently, the number of vehicular trips is extracted from other trips such as subway, transit, walk, and bike. Furthermore, all traffic analysis zones (TAZ) associated with Washington Metro stations that do not have an on-site parking facility are extracted and trip rates for each transit station are identified. The deliberate selection of parking facilities with no on-site parking ensures the use of transit as the primary mode of travel. The parking-less stations would also satisfy the deficiency of the methodology for mixed use developments by the ITE. As discussed on section 1.2 of this dissertation one of the main problems associated with the ITE methodology was the plentiful parking at the time of site selection for collection of TOD data. The abundance of parking is practically discouraging travelers to use transit as a primary mode of travel, hence erroneous results. Consequently, additional care has been given to only include transit station with no parking available to commuters for the development of this model. Due to the extensive number of data points, Microsoft Access is used for all data refinements.

The final step in data refinement for the multiple regression equation is to merge the two data sets, namely the trip data from the trip file and the household attributes mentioned above and ensuring the TAZ numbers are mapped correctly between the two files (Figure 19).

Consistent with the data analysis in of the previous chapter, the 0.25 mile radius surrounding the transit station is used as the buffer zone that ensures use of transit as the primary mode. The 0.25 mile buffer is a well-established standard in the industry for walkability to a transit station. TOD manuals from Maryland Mass Transit Administration, New Jersey Transit, New York Tri-metro area Regional Plan Association and the Ontario Ministry of Transportation all define walking distance of 0.25 mile as the industry standard (Fairfax County Planning Commission, 2009).

In the computation of trip numbers, if only a portion of a TAZ is included in the 0.25 mile buffer zone, the trip numbers were pro-rated based on the area of the TAZ. That is the portion of the area of TAZ that overlaps the 0.25 mile buffer zone is computed and is applied to the trip rates for that TAZ (Figure 20).

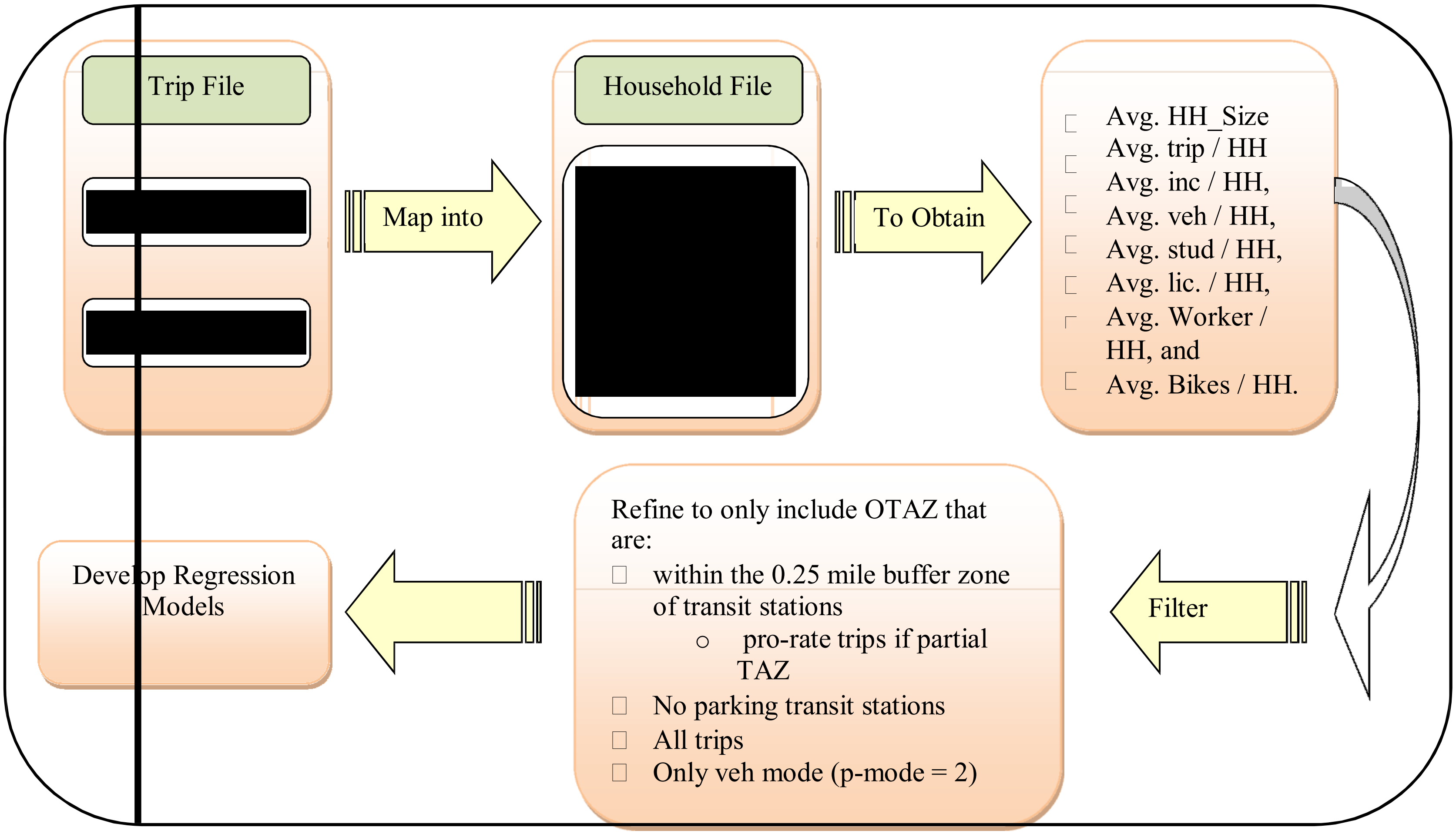


Figure 19. Data Refinement Process for Trip Generation Model

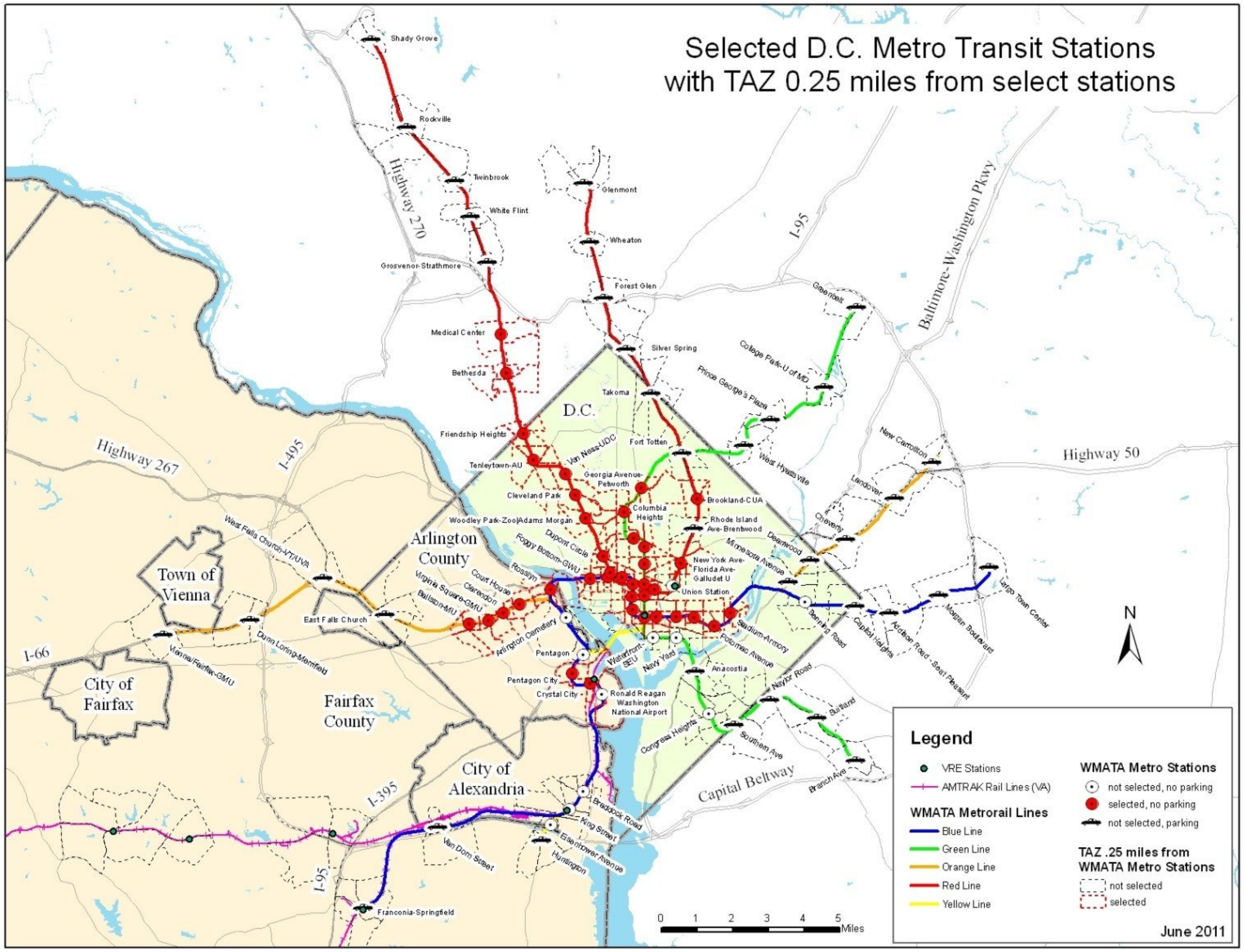


Figure 20. 0.25 Mile Buffer Zone from Metro Stations with no Parking

5.4. Research Hypothesis

The intent of this chapter is to explore the relationship between the number of trips as the dependent variable and several household attributes such as average income, number of vehicles and number of drivers in a household among others. The trips are refined to only include trips made by vehicular mode within the 0.25 mile radius zone from all transit metro stations that do not have on-site parking.

The null hypothesis states that there is no significant relationship between the number of trips and the other household characteristics. Whereas, the Alternative hypothesis states that there is a strong association between the number of trips and household income, number of vehicles and number of drivers and/or students in a household. In other words,

Let H_0 = There is no relationship between the number of vehicular trips in a transit oriented development, which is the area defined by 0.25 mile buffer zone of a transit station, and any of these independent variables, which include average income, number of vehicles, number of students, number of licensed drivers, number of workers, and number of bikes per household.

Let H_A = There is significant relationship between the number of vehicular trips in a transit oriented development, which is the area defined by 0.25 mile buffer zone of a transit station, and any of these independent variables, which include average income, number of vehicles, number of students, number of licensed drivers, number of workers, and number of bikes per household.

As in previous sections we will assume $\alpha = 0.05$.

5.5. Research Design

To learn about the relationship between several predictor, independent, variables that may impact trip rates of transit-oriented developments multivariate regression models is best suited. The model applied the suitable walking distance of 0.25 mile buffer surrounding a transit station and used all transit stations in the MWCOG area that do not have on-site parking facility. A total of 117 data points is used in the development and analysis of the multi-variable regression model. According to the central limit theorem, the multitude data points ensure normal distribution of data.

The 24-hour activity-diary survey data included a household file which contained the data for household size of various sizes having one, two, three, or more vehicles, household income, number of vehicles, whether the data point is a student, has a driver license, has bike, is a worker and other relevant information. Since the data pertained to an individual person, totals and averages for each TAZ needed to be determined. For this reason, all data points (persons) who resided in the 0.25 mile buffer were extracted from the total of 25,000 person records. Utilizing MS Access the following variables were derived from the household file:

- Average household size
- Average income per household,
- Average vehicles per household,
- Average number of licensed drivers per household,
- Average number of workers per household, and
- Average number of bikes per household.

The final step in data refinement for the multiple regression equation is to merge the two data sets, namely the trip data from the trip file and the household attributes mentioned above and ensuring the TAZ numbers are mapped correctly between the two files.

The resultant multiple regression equation depicts the relationship between vehicular trip rates and other household attributes mentioned earlier. However, this is the first cut on the development of the model which may not necessarily be a valid model. Several parameters such as normality of the independent variables, multicollinearity of the dependent and independent variables, and heteroscedasticity of residuals are essential to determine the validity of the model. Figure 21 shows the validation process.

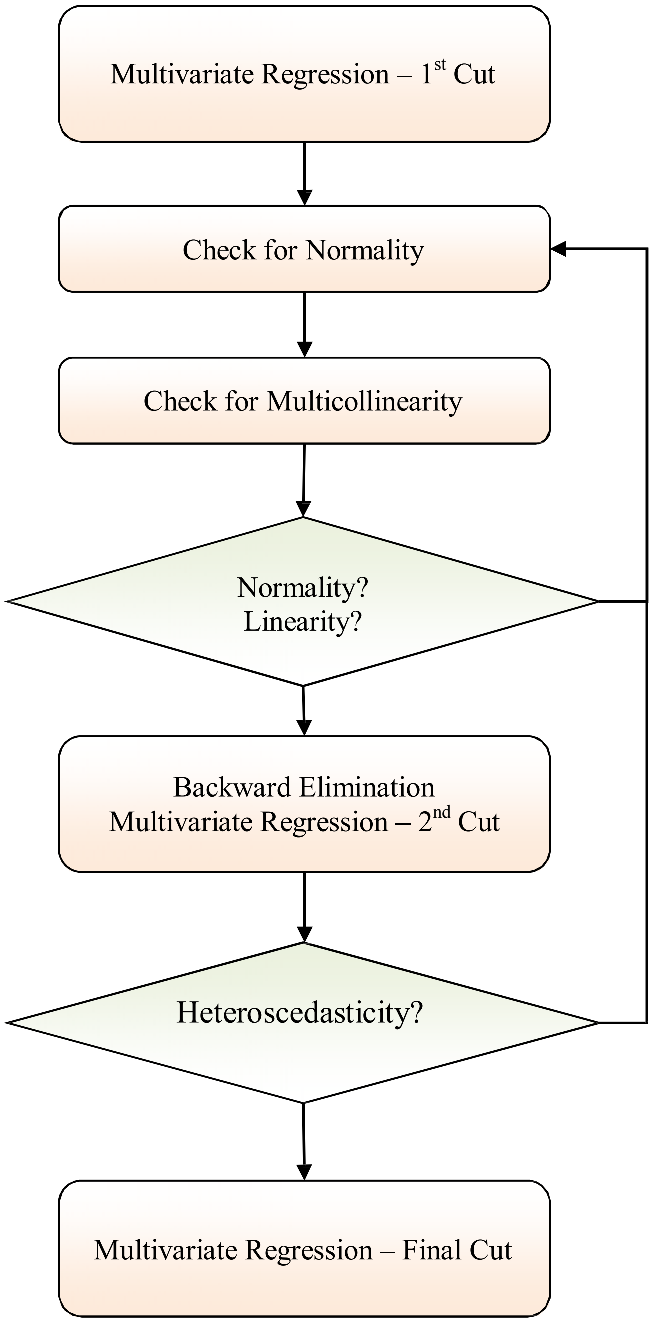


Figure 21. Multivariate Regression Research Design

5.6. Modeling Technique

The relationship of trip rates and several household attributes in a transit-oriented corridor is best described in a multivariate regression model. Through the use of statistical elimination of lesser significant variables, the multivariate regression is reduced to only include significant variables that would aid in predicting trip rates of TODs given a set of variables such as income, number of vehicles, number of licensed drivers, and number of bikes.

The data for this analysis encompasses travel and household characteristics within 0.25 mile radius of all transit stations in the MWCOG study area which included 117 observations.

5.7. Analysis Results – 1st Cut

The summary results of the initial run of the multivariate regression model which all the variables is presented in the Table 8.

Table 8. Multivariate Regression Model – 1st Run

Number of Observations	117	
RMSE	5.72	
Prob > F	0.0000	
R^2	0.6200	
Trips	Coef	P > t
HH_Size	0.5541	0.000
HH_Inc	0.5830	0.225
HH_Veh	-0.6061	0.798
HH_Stud	7.1674	0.139
HH_Drvr	-3.2967	0.463
HH_Wrkr	2.2071	0.584
HH_Bikes	3.4599	0.075
Constant	-0.4121	0.886

In order to ensure validity of the model "linearity" as the linear relationships between the predictors and the outcome variable and "normality" as the normal distribution of errors should be verified. We will then look at the scatter plots of trip rates against each of the predictor variables before the regression. The scatterplot matrix of these variables as shown on Figure 22 illustrates the relationship between these variables.

The scatterplot matrix shows the somewhat linear relationship between the trip rates and all other predictors, while clearly shows there are no linear relationship between predictor variables.

Results show that the first run of the multivariate regression has a strong 'goodness of fit' as shown be the R^2 value of 0.62. However, some of the p-values are larger than the pre-assumed value $\alpha = 0.05$. This large p-value would lead us to conclude that we fail to reject the null hypothesis that there is no significant association between the dependent variable and the predictor variables.

The first model with all independent variables that are perceived as significant can thus be shown as:

$$t = -0.4121 + 0.5541X_1 + 0.5830\ X_2 - 0.6061\ X_3 + 7.1674\ X_4 – 3.2967\ X_5 + 2.2071\ X_6 + 3.4599\ X_7$$

Where:

T = Number of vehicular trips

X_1 = Average household size

X_2 = Average household Income

X_3 = Average number of vehicles

X_4 = Average No. of household students

X_5 = Average No. of household drivers

X_6 = Average No. of household workers

X_7 = Average No. of household bikes

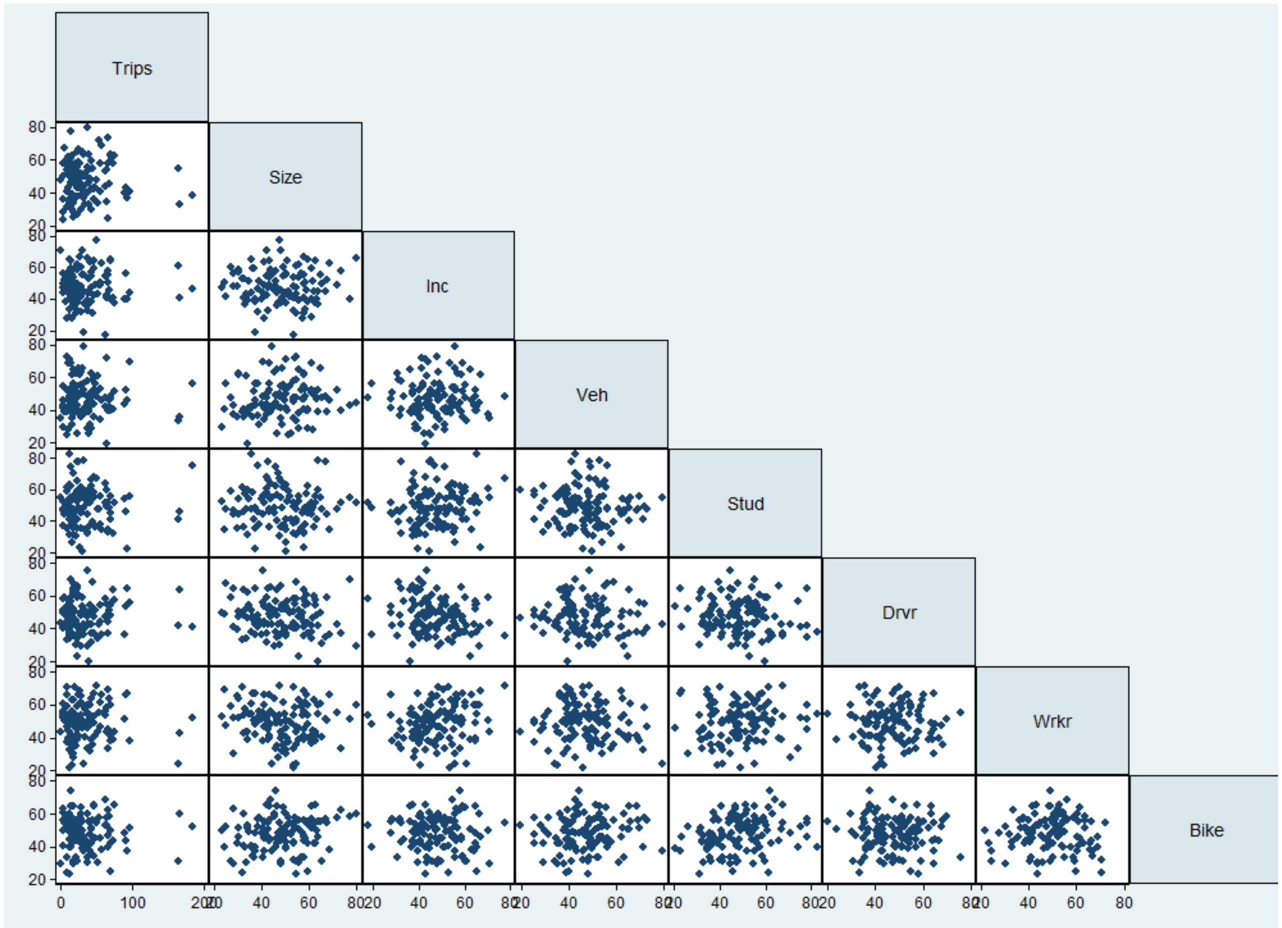


Figure 22. Scatter Plot – 1st Run

5.8. Analysis Results – Final Cut

Since the 1st cut results showed a number of independent variables not meeting the p-value criteria, an attempt will be made to transform these variables so the normal distribution of data is ensured. Subsequently, the model is run again and through the backward elimination technique, variables with lesser significant impact are dropped until a robust multivariate regression model is achieved. The following sections provide detailed description of the process.

5.8.1. Variable Transformation

Before the process of backward elimination is initiated, a further look at the normality of independent variables is essential. The statistical process of transformation of data variables would help us derive at a normal distribution for variables that do not have a normal distribution. While the sheer magnitude of 117 data points ensures normality, "gladder" and "qladder" commands in Stata® is utilized to determine best data transformation to obtain a normal distribution of the independent variable.

Figure 23 to Figure 28 show the transformation necessary for the independent variables to maintain a normal distribution. Table 9 shows the summary of data transformation results.

Table 9. Data Transformation – Summary Table

Variable	Transformation
HH_Size	Natural log (ln)
HH_Inc	Natural log (ln)
HH_Veh	Square root
HH_Drver	Cube
HH_Wrkr	Square
HH_Bikes	Square root

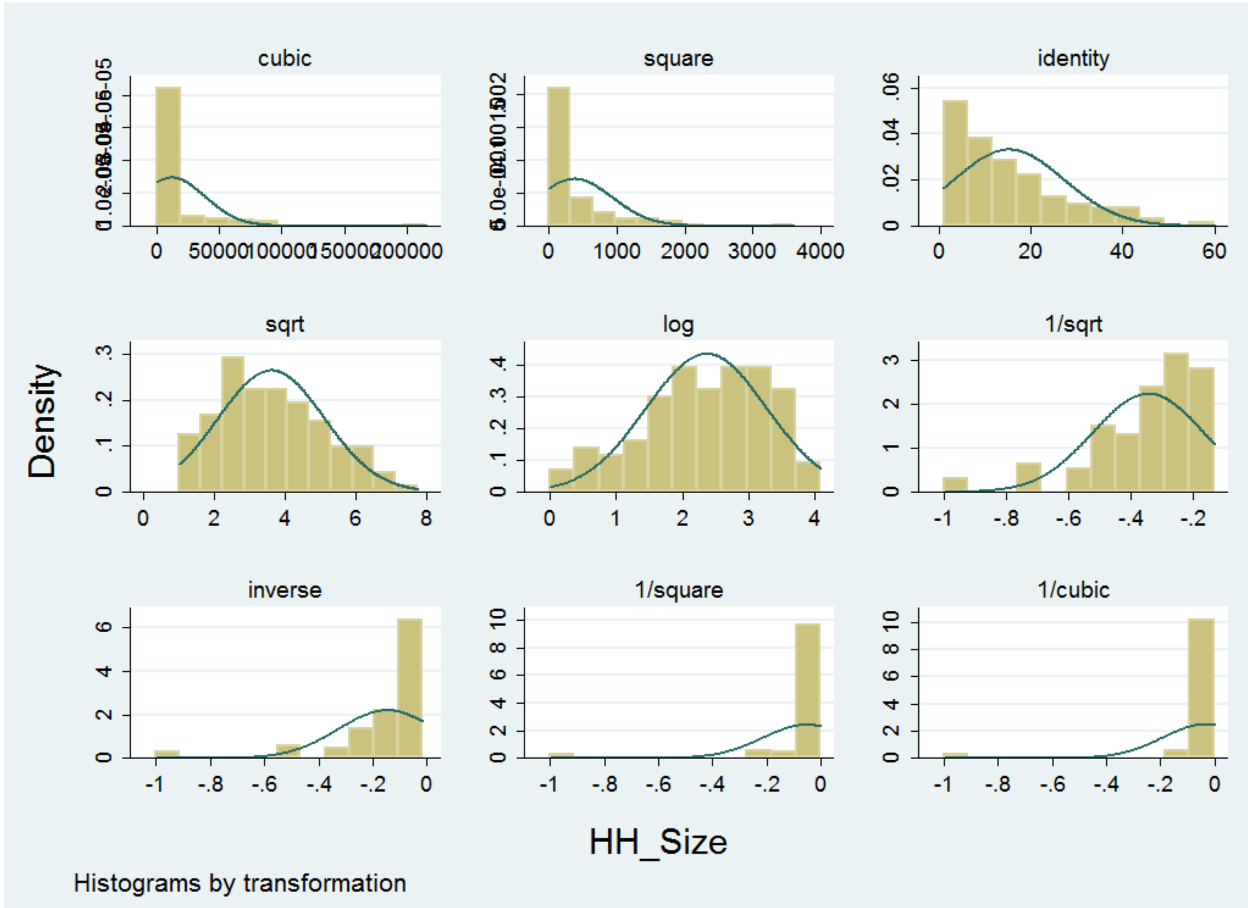


Figure 23. Average Household Size Transformation Histogram

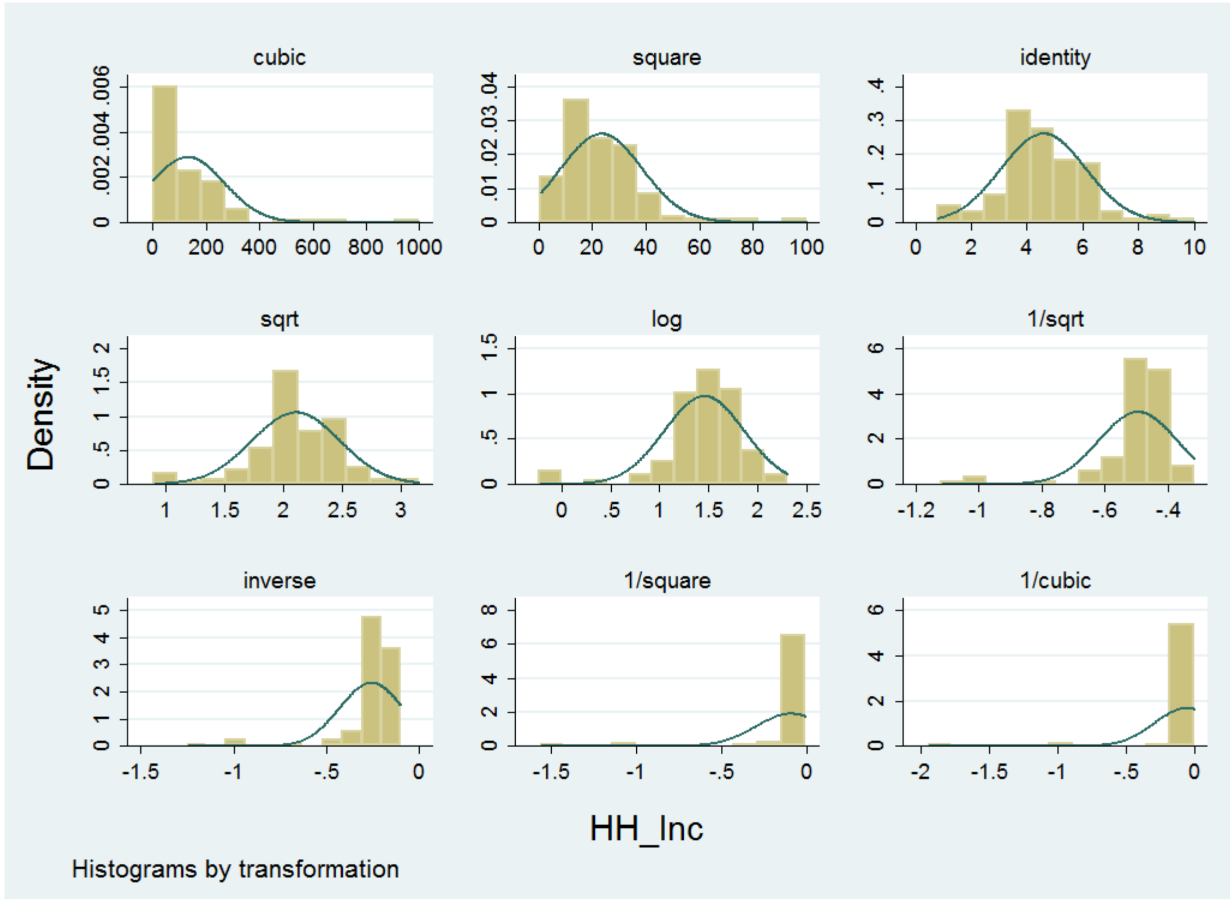


Figure 24. Average Household Income Transformation Histogram

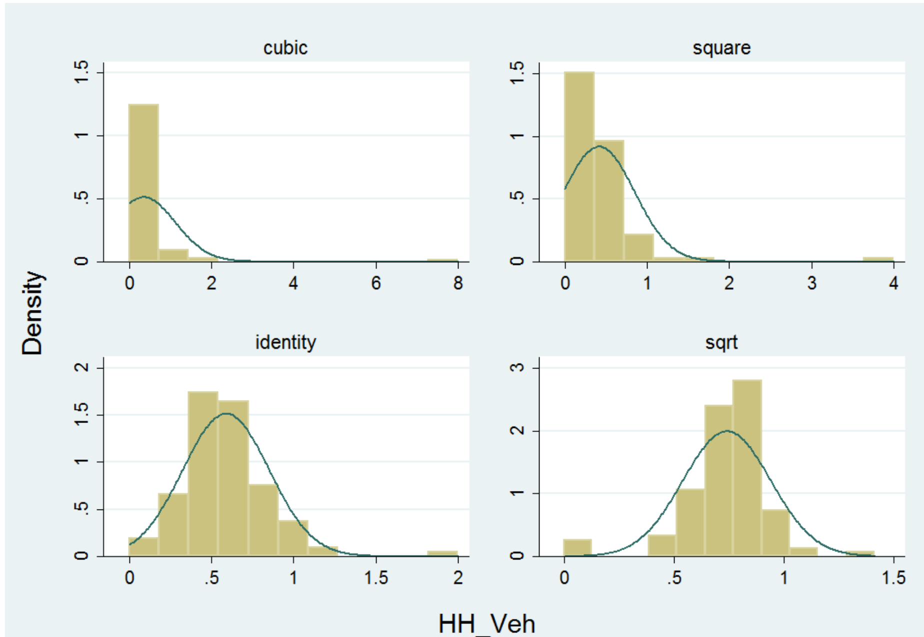


Figure 25. Average No. of Vehicles per Household Transformation Histogram

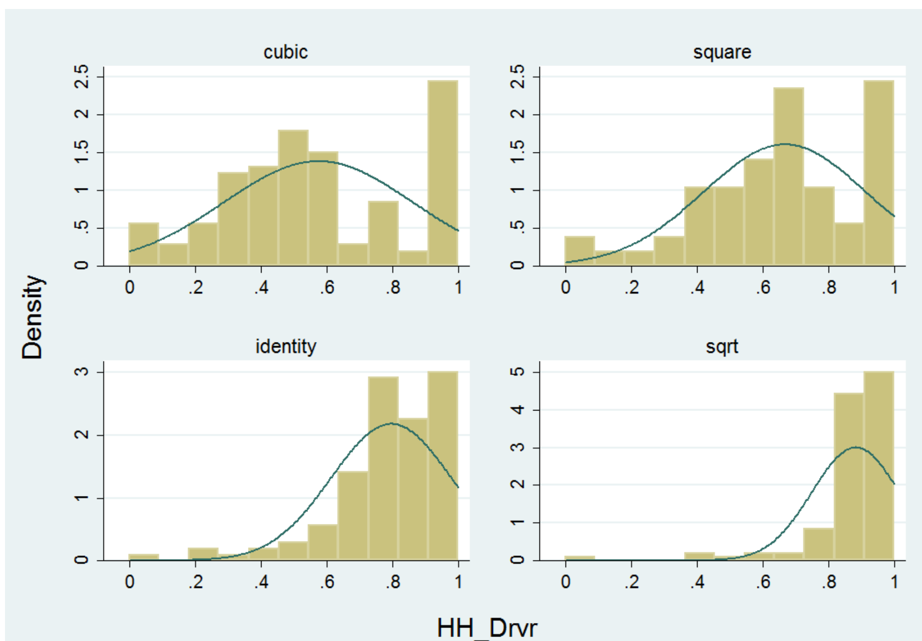


Figure 26. Average No. of Vehicles per Household Transformation Histogram

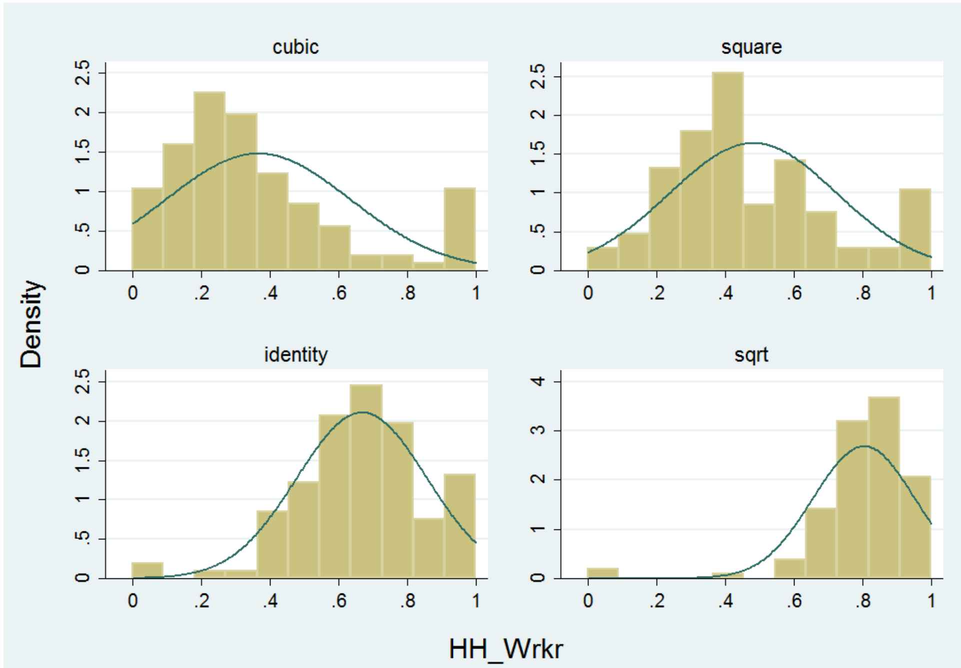


Figure 27. Average No. of Vehicles per Household Transformation Histogram

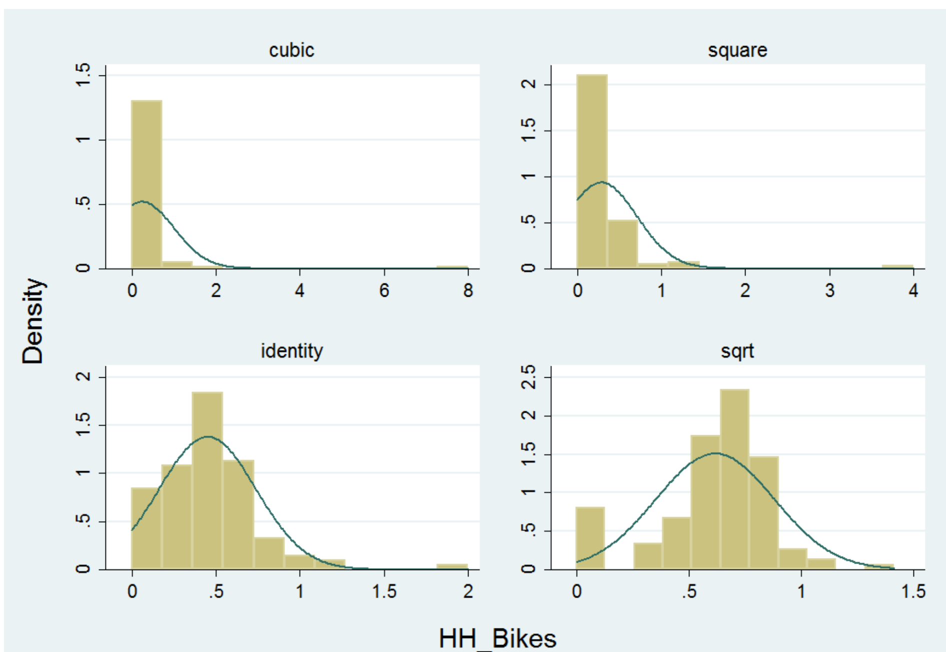


Figure 28. Average No. of Bikes per Household Transformation Histogram

5.8.2. Backward Elimination

Backward elimination technique is used to eliminate variables that do not significantly impact the association. The criteria for eliminating lesser significant variables included $\alpha = 0.05$. Independent variables with P-values of 0.05 or less are eliminated one at a time and the value of regression coefficient R^2 is observed until a reasonable regression coefficient is derived.

The initial model shows encouraging results. Judging from the p-values and assuming an error level of $\alpha = 0.05$, all variables except *stud, inc, drvr, bikes* which corresponds to the average number of students, average household income, licensed drivers, and bikes per household are not significant. The $R^2 = 0.71$ shows the goodness of fit measurement as relatively strong (see Table 10).

Table 10. Multivariate Regression Model – Final Cut

Number of Observations	117	
RMSE	5.72	
Prob > F	0.0000	
R^2	0.71	
Trips	Coef	P > t
HH Size	0.525	0.007
HH_Veh	0.837	0.000
HH_Wrkr	0.767	0.000
Constant	8.458	0.000

The final multivariate regression equation with all significant variables involved can be shown as $t = 8.458 + 0.525\ln(size) + 0.837\,(veh)^2 + 0.767\,(wrkr)^2$

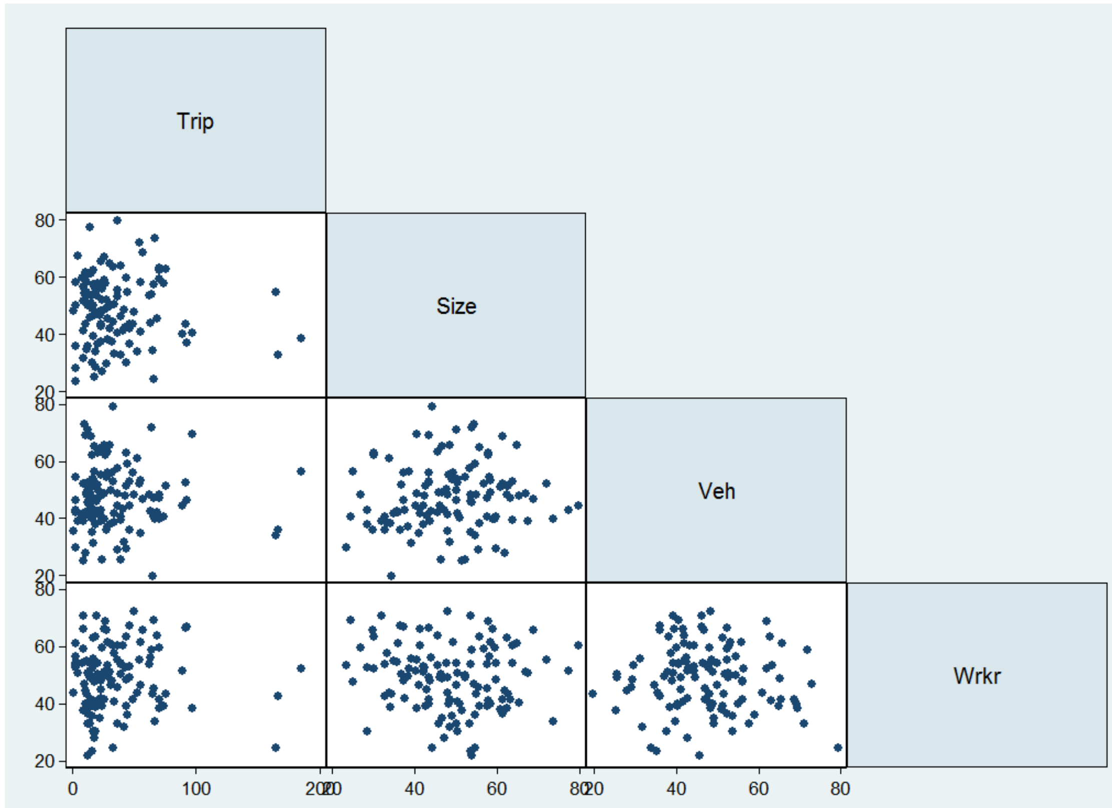


Figure 29. Scatterplot Matrix – Final Cut

5.8.3. Normality

For a valid hypothesis testing normality of residuals (errors) is required. Stata® uses the Kernel density estimate graphs to show normality. Figure 30 thru Figure 32 shows the normality tests for the final predictor variables.

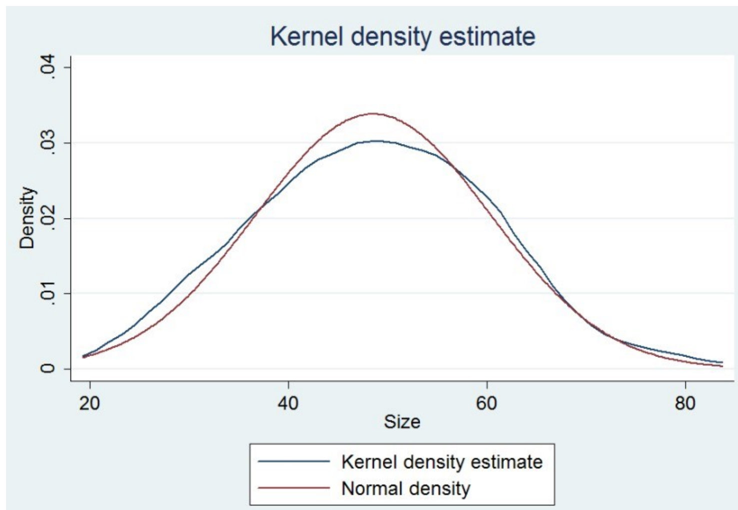


Figure 30. Normality Test for Predictor "size"

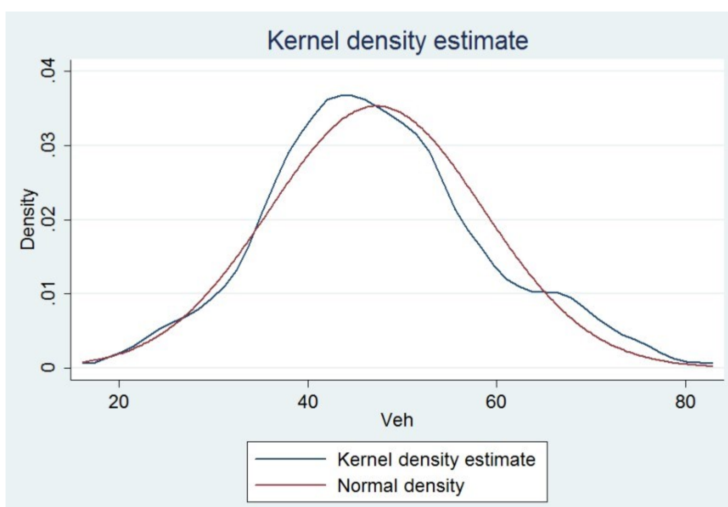


Figure 31. Normality Test for Predictor "veh"

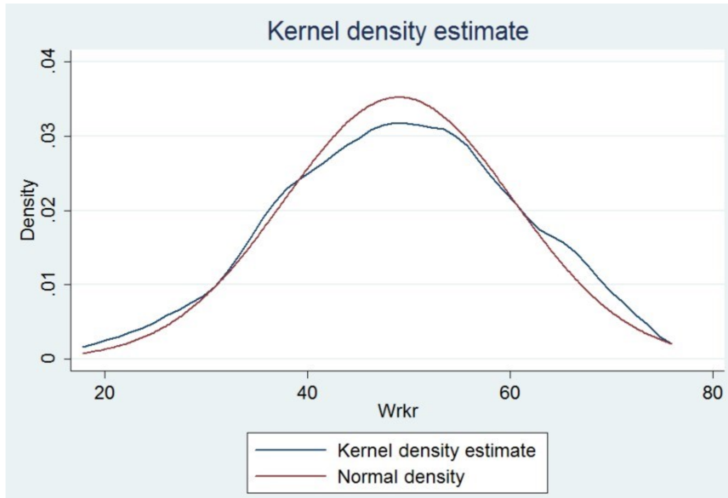


Figure 32. Normality Test for Predictor "wrkr"

5.8.4. Multicollinearity

The term multicollinearity is referred to when two or more variables have approximately a linear relationship with each other.

As one of the validation tools for the polynomial regression model, multicollinearity assist in the validity of the coefficient estimates. As multicollinearity increases, the regression model estimates of the coefficients become invalid, and the standard errors for the coefficients will be overestimated.

We can use the "*vif*" command in Stata after the regression to check for multicollinearity. *vif* stands for "variance inflation factor." A variable whose *vif* values are greater than 10 may merit further investigation. Tolerance, defined as 1/VIF, is used by many researchers to check on the degree of collinearity. A tolerance value lower than 0.1 is comparable to a VIF of 10. It means that the variable could be considered as a linear combination of other independent variables (Stata help files[3]).

Table 11 shows the results of the *vif* test for the polynomial regression model. All 1/*vif* ratio for variables are higher than 0.1, thus none of the variables are a linear combination of other variables.

Table 11. Checking for Multicollinearity

Variable	VIF	1/VIF
Size	1.02	0.9785
Veh	1.02	0.9831
Wrkr	1.01	0.9857
Mean VIF	1.02	

5.8.5. Heteroscedasticity Verification

One of the main assumptions for the multivariate regression models are the homogeneity of variance of the residuals. If the model is well-fitted, then there should be no pattern between the residuals and the fitted values and the model is said to be non-heteroscedastic. If the variance of the residuals is non-constant then the residual variance is said to be "heteroscedastic." In order to show the model is non- heteroscedastic we plot the residuals versus fitted (predicted) values. In STATA we do this by issuing the “rvfplot” command.

---

3 http://www.ats.ucla.edu/stat/stata/webbooks/reg/chapter2/statareg2.htm

The heteroscedasticity plot of the model with a reference line y = 0 show there are no pattern between the residuals and the fitted values, thus the model is not heteroscedastic (see Figure 33).

Other measures to test for heteroscedasticity are the White's test and Breusch-Pagan test that can be developed using the "imest" command in STATA. Both of these test verify the null hypothesis that the variance of residuals is homogenous. If the p-value is very small, then we have to reject the null hypothesis and accept the alternative hypothesis that the variance is not homogenous.

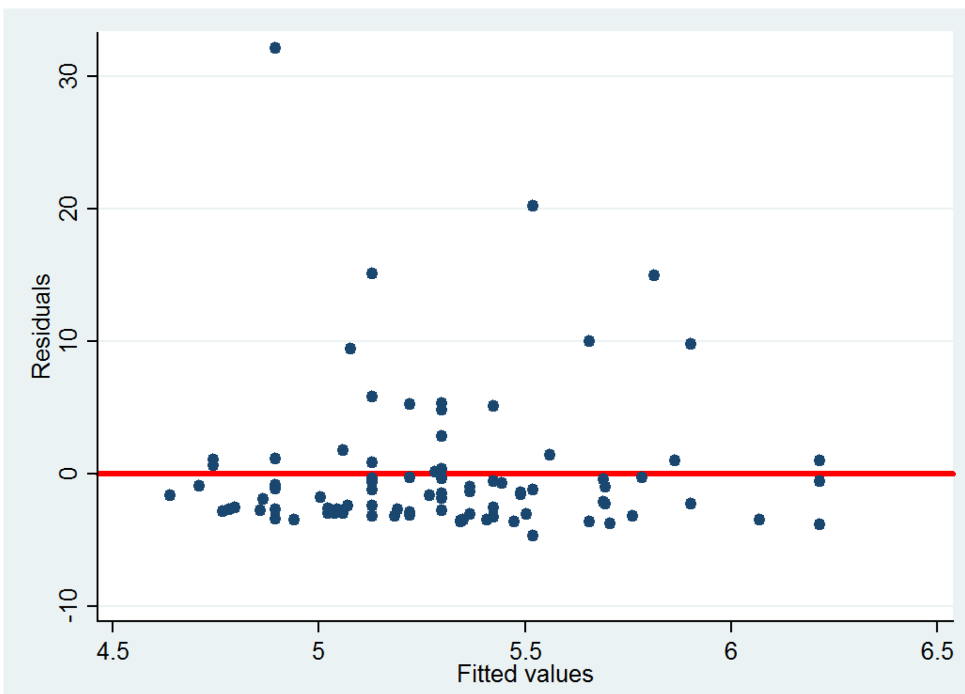


Figure 33. Heteroscedasticity plot of the Model

5.9. Conclusion

A multivariate regression model is developed for estimating trip generation rates associated with transit-oriented developments using 2007-2008 MWCOG activity-based 24-hour household travel survey. The accuracy of the model and reduced cost obtained from the use of this data, as opposed to the use of conventional data collection techniques, is notable.

The multivariate regression model assesses the relationship between various household attributes and vehicular trip rates of within a TOD. Backward elimination technique is used to eliminate variables that do not significantly impact the association. The final model expressed trip rates of transit-oriented developments in terms of size, average number of vehicles and average number of workers in a household.

While normal distribution of the data is ensured by the multitude of data points, the models need to be validated. The model is validated by checking for heteroscedasticity and multicollinearity. The $R^2 = 0.7$ for the final model is a robust indication of goodness of fit.

CHAPTER 6. Transit Oriented Development Modal Choice

6.1. Introduction

Mode choice is the third step in the conventional travel demand model subsequent to trip generation and trip distribution and followed by route choice. Mode choice models show the mathematical relationship associated with the traveler's choice of mode of transport. They show the proportion of person trips, obtained from the previous stage of the demand model, that to the available mode choices such as car, transit, vanpool, walk and bike. Mode choice models are also developed to determine the impact of introducing a new mode of travel such as transit or High Occupancy Vehicle (HOV) lanes or enhancements to an existing mode of travel (again such improvements to an existing transit system) on a transportation network.

The trip distribution part of the demand model generates person trips from a Traffic Analysis Zone (TAZ) to another TAZ. These person trips are the input to mode choice models which subsequently outputs the number of trips per mode. Furthermore, transit trips are further divided to sub-modes (such as local bus, subway, shuttle bus) and access modes (walk or drive to a transit station).

Mode choice models are often based on logit models. Logit models mainly are in two forms the multinomial logit and nested logit. The multinomial logit model would show all the modal choices available to the traveler (car, transit, walk, bike) and let the traveler choose one amongst several modes based on lower cost (travel time, travel cost). However, in the nested logit model the traveler has already chosen the mode of travel (for example transit) and the model would show which sub-mode (i.e., subway, bus, BRT) the traveler would choose. The choice that the traveler makes is based on the utility (cost) of the sub-mode.

The logit mode choice shows the probability of choosing a mode for a given trip. This mathematical relationship is based on the values of a number of attributes (independent variables) such as the cost for travel time, transit wait time, walk time, and travel time. Logit models estimate the coefficients of the variables in the utility function. Stata® statistical software package is used in this dissertation to optimize the accuracy of the coefficients.

Logit models are a non-linear transformation of linear regression models. Linear regression models were extensively used in trip generation chapters 4, and 5 of this dissertation. The non-linear transformation is often the natural logarithmic distribution which is an S-shaped distribution function and constrains the estimated probabilities between 0 and 1 (Figure 34)[4].

Mode choice models can be based on different types of logit models including multinomial, incremental and nested logit models. The multinomial and nested logit models are often used to estimate mode shares for transit strategies (NCHRP 365, 1998)

---

4 http://www.appstate.edu/~whiteheadjc/service/logit/intro.htm#logitmodel

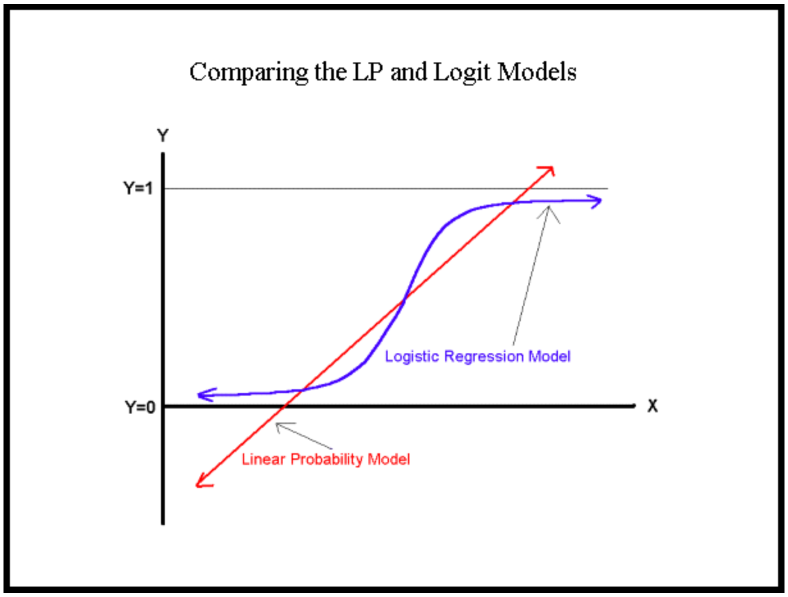


Figure 34. Comparing Linear Regression and Logit Models[5]

The following equation is the basis for logit models to estimate the probability of choosing a mode:

$$P_i = \frac{e^{u_i}}{\sum_{i=1}^{k} e^{u_i}}$$

Where,

P_i = the probability of choosing mode *i*

u_i = utility mode of *i* that describes the cost of attractiveness of mode *i*

5 http://www.appstate.edu/~whiteheadjc/service/logit/intro.htm#logitmodel

6.1.1. Utility Theory

The utility mode of i (u_i) is composed of a set of attributes that with a linear relationship describes the attractiveness of a mode. If the utility function of alternative i which is a linear function of the costs of alternative i (such as travel time, travel cost) is greater than the utility function of alternative j then alternative i is chosen over alternative j for all i and j belonging to a set C of choices. Mathematically this can be represented as:

$$\text{if } u(X_i, s_t) \geq u(X_j, s_t)\ \forall_j \quad \Rightarrow \quad i > j\ \ \forall_j \in C$$

Where:

Where $u(X_i, s_t)$ is the utility function,

X_i and X_j are attributes (travel time, travel cost, wait time and walk time) describing alternatives i, and j (car, transit, carpool, etc.).

s_t represents the characteristics that influence one's preference amongst alternatives such as household income, or number of automobiles owned).

C is the set of mode choices.

The attributes that represent the attractiveness of the mode choice model associated with transit oriented developments are transit travel time, average wait time, transit fare cost, and average walk time to a transit station . Subsequently, the utility function can be illustrated as follows:

$$U_i = a_i + b_i \times TT_i + c_i \times WT_i + d_i \times COST + e_i \times WKT_i$$

Where,

TT_i is the transit travel time for mode i

WT_i is the average wait time for mode i

$COST_i$ is the cost of mode *i*

WKT_i is the average walk time for mode i

a_i is the constant

b_i , c_i , d_i , and e_i are coefficients for each attribute for mode *i*

6.1.2. Deterministic and Stochastic Choice Theory

The linear logistic regression model presented in the previous section indicates that a traveler chooses the mode with the least amount of utility or cost. However in real world there is an element of uncertainty in a traveler's decision beyond the cost. In reality, travelers with similar characteristics may choose different modes of travel. Even the same travelers may choose different mode of travel on a daily basis. Therefore the appropriateness of a deterministic mode choice model, as presented in the previous section is questionable.

The stochastic mode choice theory overcomes this issue by assigning the probability of choosing a mode as opposed to predicting the traveler's mode choice with certainty. The stochastic mode choice is composed of two parts. The deterministic portion and the error associated with the deterministic portion which can be represented as follows:

$U_{it} = V_{it} + \varepsilon_{it}$

Where:

U_{it} = is the true utility of mode I to the traveler t,

V_{it} = is the deterministic portion of the utility estimated based on the observed data,

ε_{it} = is the error associated with the deterministic portion.

The deterministic portion, V_{it}, of the mode choice model is composed of the characteristics of the traveler (S_t), the utility function cost of mode i (X_i) and the interaction between (S_t) and (X_i), which can be written as:

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

Where:

$V_{t,i}$ is the deterministic portion of the stochastic choice model,

$V(S_t)$ is the utility of characteristics of traveler t,

$V(X_i)$ is the utility of attributes of mode i,

$V(S_t , X_i)$ is the utility of the interactions between mode i and traveler t.

The $V(S_t)$*as* the utility of characteristics of traveler t, can be attributes such as:

- Household income of the traveler
- Number of cars in traveler's household
- Number of workers in traveler's household
- Number of bikes in traveler's household
- Age / Sex of the traveler

The $V(X_i)$ as the utility of cost attributes of mode i are attributes such as:

- Total travel time
- Wait time
- Walk time
- Cost

6.1.2.1. The Error Term

As discussed the stochastic mode choice model is composed of two components. The deterministic part which is discussed in the previous section is based on the observed data. There are, however, missing information in the data because the information is simply not available to the traveler at the time of data collection. In other words, the error term is associated with the unmeasured or the unobserved portion of the data. The ε_{it} represents the stochastic component of the mode choice model.

6.1.3. Modeling Technique

When dealing with number of attributes both for the traveler and the mode, the ε_{it} as discussed in the previous section, aggregates. The Central Limit Theorem states that the sum of all these small errors follows a normal distribution. This would lead to Multinomial Probit (MNP) choice model. MNP, however, is complex, hard to predict and has limited use in practice. It is common practice to use the equally applicable Multinomial Logit Model (MNL) for mode choice modeling.

6.1.4. Purpose of This Chapter

The intent of this chapter is to develop two stochastic mode choice models. The first model shows the mode choice amongst six different modes in a transit oriented development environment. The TOD environment is defined as the 0.25 mile radius of a Washington Metro transit station. All work trips within the 0.25 mile zone are included in the analysis and are the basis of the data for this model.

Additionally, a utility function for the transit mode is developed. The attributes that represent the attractiveness (or the cost) associated with transit mode in the greater

Washington area are assumed as transit travel time (min), average wait time (min), transit fare cost (dollars), and average walk time to a transit station (min). Average household income is assumed as the characteristic of traveler.

6.2. Mode Choice Model – TOD

A stochastic mode choice utility model is developed using multinomial logistic regression to show the modal split in the 0.25 mile radius of all transit stations in the Washington Metro area. The primary focus of the mode choice model is on home-base work trips which predominantly constitute the number of trips in the 24-hour activity based data. The attributes of the primary mode of travel include transit, auto-driver, auto-passenger, walk, bike and other. The outcome of the logit model is the mode of travel. The independent variables which constitute the deterministic portion of the utility model are number of vehicles per household, household income, and trip travel time. Table 12 shows the sample data used for this model.

Table 12. Mode Choice Sample Data

Only Work Trips in the 0.25 TAZs opurp=2(Work)										
	Link b/w files		HH file		Trip file Travel Time (in Minutes)					
opurp	sampn	rtripid	hhveh	incom	01 = Transit	02 = Auto D	03 = Auto P	06 = Walk	07 = Bike	09 = Other
2	2100009	21000090103	2	9	60	30	0	0	0	0
2	2100122	21001170103	2	8	57	34	0	0	0	0
2	2100428	21004280106	1	6	0	30	0	15	0	0
2	2100441	21004410203	2	11	0	19	0	13	0	0
2	2100467	21004670103	2	11	68	0	0	0	0	0
2	2100526	21005260105	2	11	0	46	0	0	0	0
2	2100626	21006260204	2	9	10	0	45	0	0	0
2	2100628	21006280103	2	9	0	40	45	0	0	0
2	2100650	21006500104	3	11	0	2	0	15	0	0
2	2100729	21007290203	2	12	0	10	0	3	0	0

6.2.1. Model Specification

Once the data has been refined to include the attributes of a traveler *t* and the mode characteristics *i* , Stata® statistical software is used to determine the utility models. The models can be shown as follows:

$U_T = -0.5046\ hhveh - 0.1141inc + 0.06837TT + 1.784$

$U_{A\_D} = 0.3797\ hhveh - 0.1726inc + 0.0250TT + 3.232$

$U_{A\_P} = 0.1442\ hhveh - 0.1426inc + 0.0223TT + 1.461$

$U_W = -0.5043\ hhveh - 0.0582inc - 0.1147TT + 5.281$

$U_B = -0.4493\ hhveh - 0.0642inc + 0.0247TT - 1.012$

Where,

T = Transit mode

A_D = Auto drive mode

A_P = Auto private mode

W = Walk mode

B = Bike mode

Table 14 shows the results of the multinomial logistic regression. The iteration log show the list of log likelihood at 6 iterations until the model is converged. Multinomial log regression models use the "maximum likelihood estimation" which is an iterative process to reach minimum log likelihood. When the difference between iterations is small, then the model is converged and no smaller value of log likelihood exists.

The likelihood ratio test (LR) uses the log likelihood to determine if a variable or a group of variables should be dropped from the logit model. The log likelihood tests the explanatory effectiveness of a variable. Therefore, if dropping a variable doesn't change the value of the log likelihood then the variable can be dropped.

The likelihood ratio test (LR) is implemented by first estimating the model with all variables. Then a second model is estimated to only include variables that are believed to have an explanatory impact. Subsequently, the value of "likelihood ratio test statistic (LR)" is determined as follows:

$$LR = 2(log\ (log\ likelihood\ of\ Model_1) - log(log\ likelihood\ of\ Model_2\ )$$

In Stata® statistical software package the Likelihood Ratio (LR) test is represented by LR chi^2 and is an indication if the model is significant. Unlike Horowitz, the LR chi^2 is simply twice the difference between the log likelihood of the current model with the intercept model. The log likelihood of the intercept model is shown at the 0^{th} iteration. This value indicates the likelihood ratio that for all equations (1 = Transit, 2 = auto-driver, 3 = auto-passenger, 4 = walk, 5 = bike, and 6 = other) at least one of the predictors' regression coefficient (hh_veh, income, travel time) is not equal to zero.

The degree of freedom (df) for the Chi-Square distribution is also shown in Stata® and is calculated as:

df = the number of models estimated (5) × *the number of predictors in the model (3).*

The null hypothesis is that all of the regression coefficients across all models are equal to zero. The Prob > chi^2 is the p-value that is compared with a pre-set tolerance to accept a Type I error of $\alpha = 0.05$ would reject the null hypothesis and shows that at least one regression coefficient is not equal to zero.

The confidence interval (CI) shown on the output indicated that for a particular predictor we are 95% confident that the "true" coefficient lies between the lower and upper limit of the interval. If the CI includes zero, we'd fail to reject the null hypothesis that the regression coefficient is zero given the other independent variables are in the model.

It must be noted that Stata® output uses the z-test for the confidence interval.

The z-test is used for testing the mean of a population versus a standard, or comparing the means of two populations. Furthermore, the t-test is mainly used for data samples of smaller that 30 items, whereas the z-test is used data samples of greater than 30 items. Thus the use of z-test is more appropriate for the purposes of this chapter.

Table 13. Mode Choice MLR Summary of Results

Number of Obs		5950			
LR chi² (15)		3875.86			
P value		0.000			
Pseudo R^2		0.2502			
Log Likelihood		-5808.9426			
Mode	Variable	Coef	P Value	95% Confidence Interval	
Transit	HH_Veh	-0.5046	0.000	-0.7293	-0.2799
	Inc	-0.1140	0.016	-0.2073	0.0208
	TT	0.0683	0.000	0.05715	0.0795
	Const	1.7847	0.000	0.8976	2.6717
Auto_D	HH_Veh	0.3797	0.000	0.1664	0.5929
	Inc	-0.1726	0.000	-0.2631	-0.0821
	TT	0.0250	0.000	0.0140	0.0360
	Const	3.232	0.000	2.3679	4.0973
Auto_P	HH_Veh	0.0144	0.910	-0.2353	0.2642
	Inc	-0.1426	0.007	-0.2460	-0.0393
	TT	0.0223	0.000	0.0100	0.0346
	Const	1.4615	0.003	0.4864	2.4366
Walk	HH_Veh	-0.5043	0.000	-0.7351	-0.2735
	Inc	-0.05829	0.228	-0.1531	0.03658
	TT	-0.1147	0.000	-0.1292	-0.1002
	Const	5.2810	0.000	4.3771	6.1850
Bike	HH_Veh	-0.4493	0.014	-0.8060	-0.0926
	Inc	0.06421	0.376	-0.0779	-0.2063
	TT	0.02478	0.002	0.0091	0.0403
	Const	-1.0121	0.144	-2.3699	0.3456

Another methodology to evaluate the LR is presented by Horowitz. Based on him, the value of LR is compared against a predetermined Critical value (CV). If LR is greater than CV then the variable retained, otherwise the variable has no explanatory value and should be dropped.

Table 14shows the appropriate values of CV for up to 5 variables (Horowitz, 1986).

Table 14. Critical values of the Likelihood Ratio Test

Number of Variables Being Tested	Critical Value
2	2.408
3	3.665
4	4.878
5	6.064

6.2.2. Goodness of fit

As discussed previously the log likelihood chi-square in Stata® is a good indication if the model is statistically significant. Unlike Horowitz methodology, the LR chi^2 is simply twice the difference between the log likelihood of the current model with the intercept model. The log likelihood of the intercept model is shown at the 0^{th} iteration.

The pseudo R^2 shown in the output of Stata® can potentially be a measure for goodness of fit, however, there are many variations of measuring the R^2 amongst statisticians and its use is cautioned.

6.2.3. Multicollinearity

Multicollinearity occurs when there is a linear relationship between two or more independent variables in the model. In such cases an accurate estimation of regression coefficients are nearly impossible.

Stata® has the ability to automatically drop one of the two variables that have a linear relationship with each other. It must be noted that reasonable multicollinearity does exist in logistic regression models. In cases of strong multicollinearity, the standard errors for the coefficients tend to be very large.

Results of the output indicate low standard errors amongst all variables, hence lack of any evidence of multicollinearity.

6.2.4. Validation

6.2.4.1. The S Shape MNL Property

The S shape of multinomial logit probabilities is shown in Figure 35. The sample data for the graph is shown in Table 15. The S shape graph shows the probability of taking transit when all other alternatives are held constant. The S shape graph is an important property of MNL models. The gradual slope of the curve at extreme ends is an indication that small changes in the utility of the mode does not impact the probability of the mode being chosen, given utility of all other modes are constant. Small increase in the utility of the mode increases the probability of the mode being chosen only when that the utility of the mode is equal to the utility of all other modes combined which is illustrated in the middle of the curve where there is a sharp slope.

Table 15. Probability Values for Transit as a Function of Transit Utility

Case	V_T	V_{A_D}	V_{A_P}	V_W	V_B	Pr(T)
1	2.066	1.0	0.5	-0.5	-1.0	0.596
2	0.516	1.0	0.5	-0.5	-1.0	0.239
3	-0.994	1.0	0.5	-0.5	-1.0	0.065
4	1.632	1.0	0.5	-0.5	-1.0	0.489
5	3.710	1.0	0.5	-0.5	-1.0	0.884

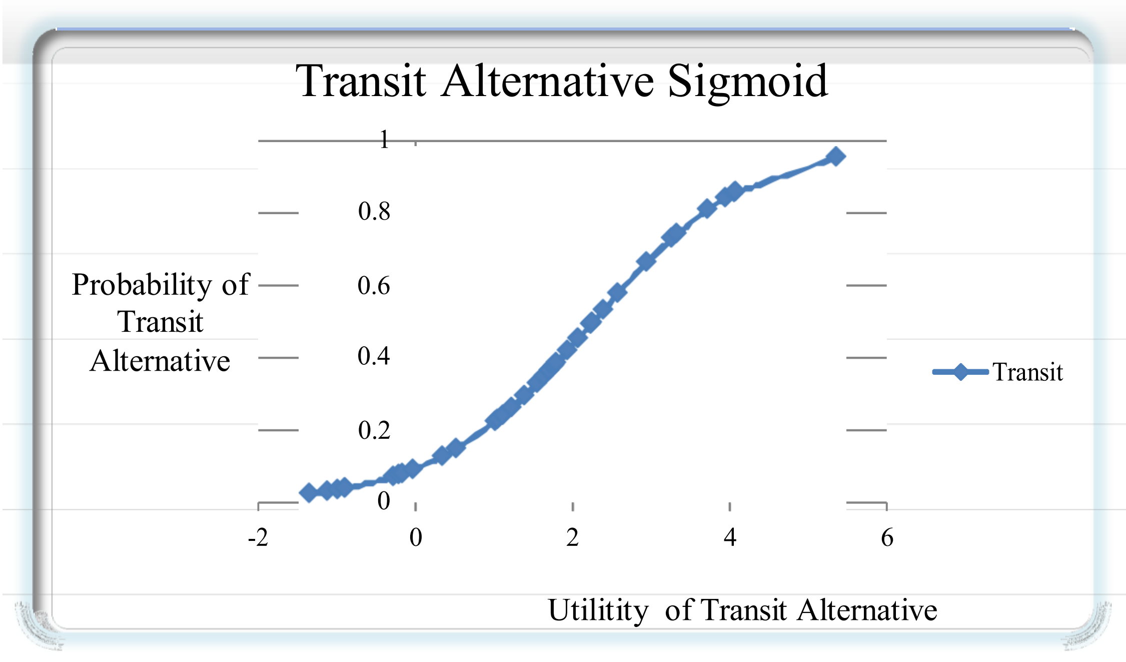


Figure 35. S Shape of MNL Probabilities

6.2.4.2. The Equivalent Difference Property

An important property of multinomial logit models is that the probability of a mode does not depend on the actual value of the utility of the mode, but on the differences between the utilities. Table 16 shows this property through the use of data and the derived utility models in previous section. The table shows two sets of utility values the difference between the utility models is a value of 1. As the table shows, the probability of modes remains constant while the values of the utilities are different by a value of one.

Table 16. MNL Equivalent Difference Property

	U	P(U)
$U_T = -0.5046\ hhveh - 0.1141inc + 0.06837TT + 1.784$	3.85	0.47
$U_{A\_D} = 0.3797\ hhveh - 0.1726inc + 0.0250TT + 3.232$	3.19	0.24
$U_{A\_P} = 0.1442\ hhveh - 0.1426inc + 0.0223TT + 1.461$	1.47	0.04
$U_W = -0.5043\ hhveh - 0.0582inc - 0.1147TT + 5.281$	3.18	0.24
$U_B = -0.4493\ hhveh - 0.0642inc + 0.0247TT - 1.012$	-2.12	0.00
	U + 1	P(U)
$U_T = -0.5046\ hhveh - 0.1141inc + 0.06837TT + 1.784$	*4.85*	*0.47*
$U_{A\_D} = 0.3797\ hhveh - 0.1726inc + 0.0250TT + 3.232$	*4.19*	*0.24*
$U_{A\_P} = 0.1442\ hhveh - 0.1426inc + 0.0223TT + 1.461$	*2.47*	*0.04*
$U_W = -0.5043\ hhveh - 0.0582inc - 0.1147TT + 5.281$	*4.18*	*0.24*
$U_B = -0.4493\ hhveh - 0.0642inc + 0.0247TT - 1.012$	*-1.12*	*0.00*

6.2.4.3. Model Validation Using Data

The utility models developed as part of this section are validated using the COG data. Initially values of 2, 5, and 30 are randomly chosen for Vehicle, Income and Travel Time respectively. The Utility models for transit, auto drive, auto passenger, walk, and bike is run for these values and probability of each is calculated. Subsequently, using the 5950 data points the probability of these values for the variables is calculated as the number of occurrence per model divided by the total number of occurrence for all modes.

Table 17 shows the results of this comparison. As shown on the table, the difference in probabilities of taking a mode in a TOD environment between what the utility models are deriving and what the actual data is showing is minimal.

Table 17. Model Validation Using Data Points

	Vehicle	Income	Travel Time	Utility	Exp	Prob. (Model)	Prob. (data)
Transit	2	5	30	2.26	9.54	0.15	0.13
Auto Drive	2	5	30	3.88	48.35	0.74	0.88
Auto Passenger	2	5	30	1.71	5.50	0.08	0.00
Walk	2	5	30	0.54	1.72	0.03	0.00
Bike	2	5	30	-1.49	0.23	0.00	0.00

As a more robust validation of the models the same procedure is repeated for 10 trials and the average of the 10 trials are taken and compared against the two results. Table 18 shows the values used for each variable. Table 19 is the average values of the ten trial runs. As the table shows there is minimal difference between the results of the utility models and the actual observed data.

Table 18. Variable Selection for Mode Choice Model Validation

Trial	Vehicle	Income	Travel Time
1	0	9	10
2	0	5	30
3	1	8	10
4	1	9	40
5	1	9	10
6	2	5	30
7	2	9	60
8	2	11	90
9	3	11	15
10	3	7	45

Table 19. Average Probability Values of 10 Trial Runs

Mode	Prob. (Model)	Prob. (Data)
Transit	0.27	0.24
Auto Drive	0.45	0.42
Car pool	0.06	0.02
Walk	0.22	0.29
Bike	0.00	0.01

6.3. Transit Utility Model

An interesting problem for transportation analysts is to assess the impact of a change in policy ensued by the number of vehicles owned by households who take transit to work. A mathematical model that shows the household's choice of how many vehicles they own will provide information about the impact of various policies for example parking policy.

A stochastic mode choice utility model is developed using multinomial logistic regression to show this relationship. This model only includes transit trips in the 0.25 mile radius of all transit stations. Average number of vehicles per household is the dependent variable which is used to determine the interaction between characteristics of the traveler with utilities of transit mode. Similar to the mode choice model presented in the previous section, home-base work trips that uses transit as the primary mode of travel is extracted from the 24-hour activity based data. Table 20 shows the sample data used to develop this model.

The attributes that represent the attractiveness (or the cost) associated with transit mode in the greater Washington area are assumed as transit travel time (min), average wait time (min), transit fare cost (dollars), and average walk time to a transit station (min).

Table 20. Transit Utility Model Sample Data

Only Work Trips in the 0.25 TAZs opurp=2(Work)								
opurp	sampn	rtripid	hhveh	incom	01 = Transit Travel Time	Average Wait Time for a train (min)	Fare Cost (based on Travel time)	Average Walk Time to Transit (min)
2	2100009	21000090203	2	9	60	3.97	5.45	5.34
2	2100027	21000270208	2	10	39	3.19	4.295	5.29
2	2100030	21000300105	4	9	30	2.89	3.8	0.29
2	2100122	21001220109	2	11	57	0.16	5.285	2.08
2	2100141	21001410110	1	8	75	1.63	6.275	0.18
2	2100154	21001540105	2	9	50	0.48	4.9	1.26
2	2100187	21001870111	1	4	57	3.91	5.285	3.35
2	2100283	21002830107	1	3	35	3.34	4.075	4.68
2	2100283	21002830305	1	3	60	2.18	5.45	1.50
2	2100295	21002950211	1	9	55	2.41	5.175	5.29
2	2100467	21004670103	2	11	20	0.04	3.25	0.27
2	2100467	21004670105	2	11	68	1.82	5.89	3.39
2	2100626	21006260204	2	9	10	2.35	2.7	0.82
2	2100734	21007340110	1	9	60	3.86	5.45	0.10

6.3.1. Travel Cost

The Metrorail fare data is obtained from the WMATA website. The website contains extensive fare tables from every transit station to all other locations. Due to insufficient data to link the station names to the TAZ data numbers which are included in the 24-hour activity based trip data, a regression equation is developed to determine the regular Metrorail fare based on miles traveled and the travel time. A random selection of 169 data points is selected. The data points pertain to traveling from a station to all other stations. The independent variables are the travel time and miles distance between the two stations. The regression equation is:

$$X = 2.0196 + 0.00167\, X_1 + 0.0210\, X_2$$

Where:

X is the Metrorail fare in dollars ($)

X_1 is miles travelling distance between the two stations, and

X_2 is travel time in seconds

The regression coefficient (R^2) is 0.88 and a P-value of close to zero which both indicate a robust regression equation. Table 21 shows these results. The derived regression equation is used as the basis to determine the Metrorail fare cost between trips stations.

Table 21. Regression Output for Metrorail Fare Calculations

SUMMARY OUTPUT *Regression Statistics*				
Multiple R	0.9378			
R^2	0.8795			
Adjusted R^2	0.8781			
Standard Error	0.2982			
Observations	169			
	Coefficients	*Standard Error*	*t Stat*	*P-value*
Intercept	2.0196	0.0647	31.2144	2.2917E-71
Miles	0.1167	0.0133	8.7937	1.77689E-15
Travel Time	0.0210	0.0043	4.8751	2.52714E-06

6.3.2. Average Transit Wait Time

For a long time the average transit wait time is simply half the headway time between train arrivals. This model is based on random arrival of passengers, and uniform arrival of trains, while passengers get on the first train that arrives (Holroyd and Scraggs,1966). This model is widely accepted until the assumption of uniform and on-time arrival of trains is questioned. If train arrival is non-uniform, then the average waiting time for the passenger is expected to be longer. Several researchers including Osuna and Newell (1972) conducted research to overcome the shortcomings of the traditional model. They developed a model for the expected waiting time W, which is a function of the average headway μ and variations in the headway s^2:

$$w = \mu * (1 + \frac{s^2}{\mu^2})/2$$

Where:

W = expected passenger waiting times,

μ = mean headways between buses,

s^2 = variances of headways between buses.

This equation is used to determine the expected wait times in the development of the transit utility model for this section.

6.3.3. Normality

While the 1660 data points ensure normality by the Central Limit Theorem ensures, a further look at the normality of independent variables is essential. The statistical process of transformation of data variables would help us derive at a normal distribution for variables that do not have a normal distribution.

Figure 23 to Figure 28 show the transformation necessary for the independent variables to maintain a normal distribution. Table 22 shows the summary of data transformation results.

Table 22. Mode Choice Model – Predictor Variable Transformation

Variable	Transformation
TT	Natural log (ln)
W_T	Identity
Cost	Inverse
WK_T	Identity

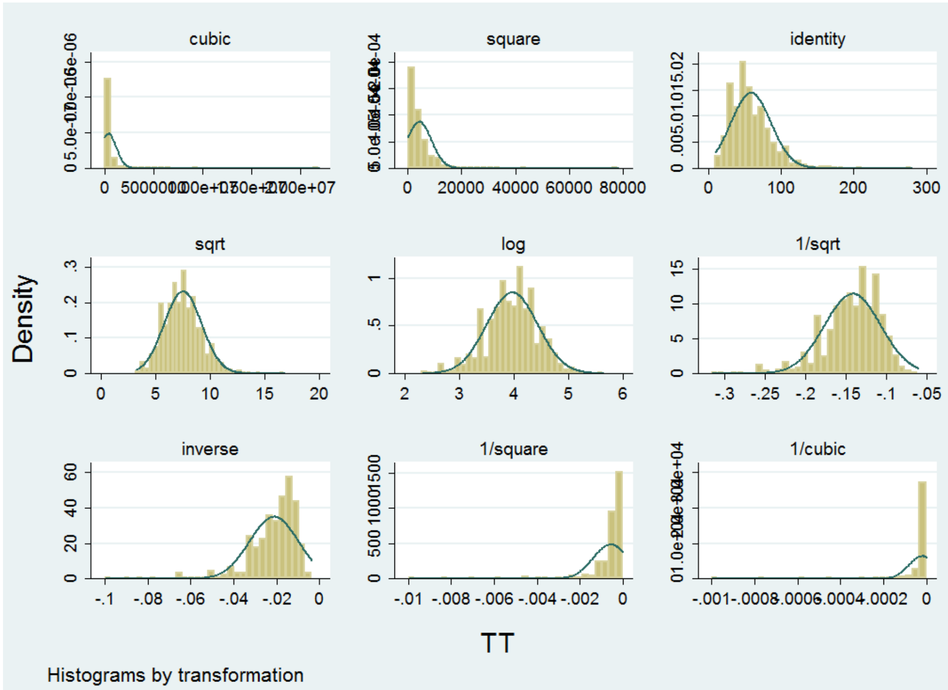


Figure 36. Regression Diagnostic Plot – Travel Time Transformation

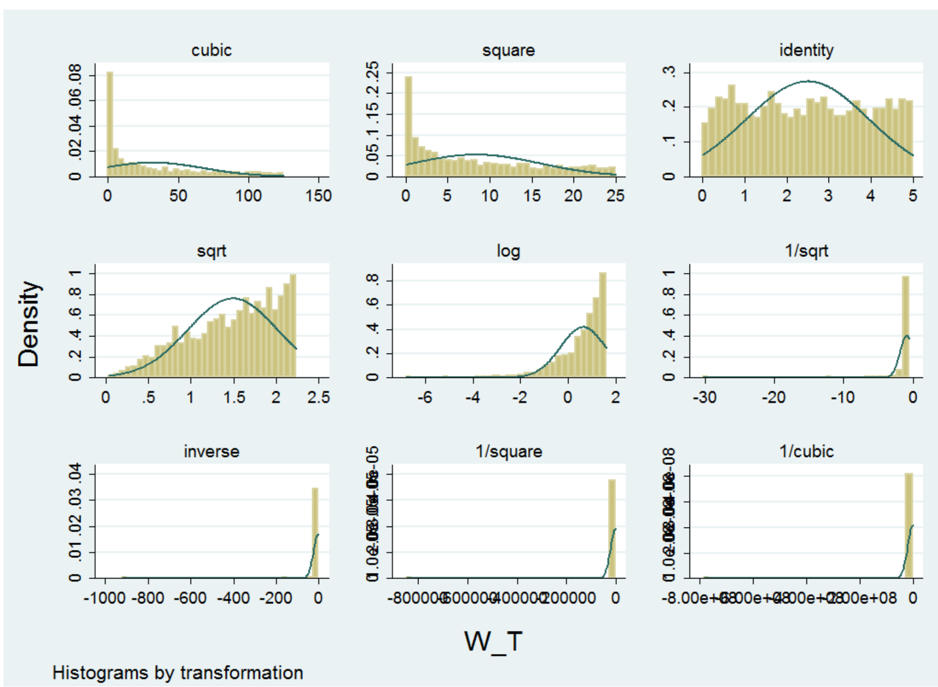


Figure 37. Regression Diagnostic Plot –Transit Wait Time Transformation

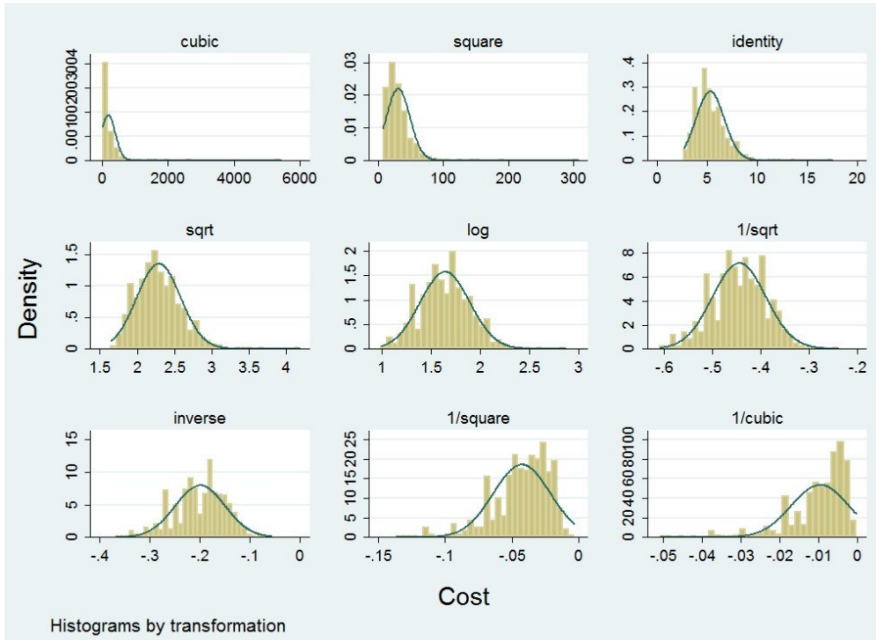


Figure 38. Regression Diagnostic Plot – Transit Fare Cost Transformation

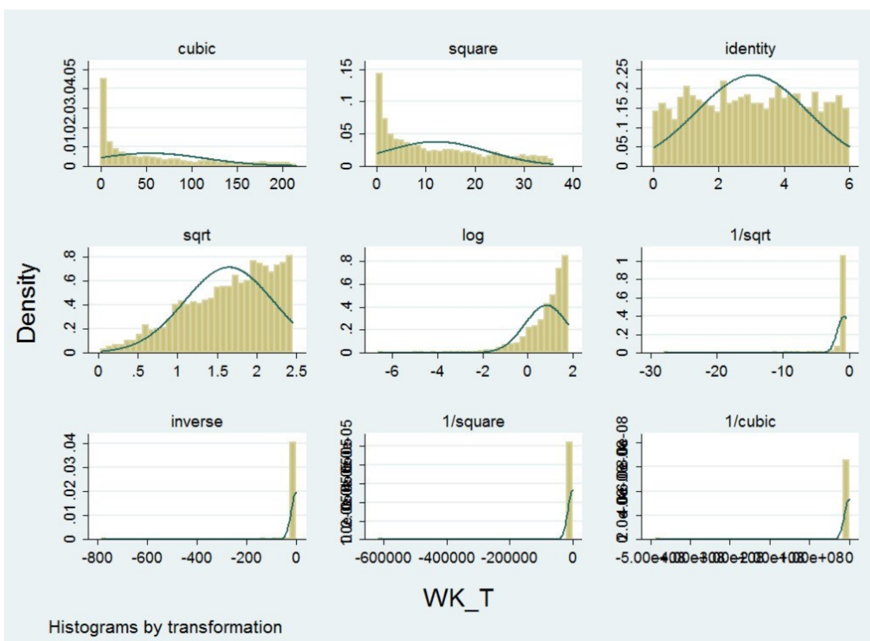


Figure 39. Regression Diagnostic Plot – Walk Time Transformation

Normality of the predictor variables are also justified by the Kernel density estimate graphs. Figure 41 thru Figure 43 shows the normality tests for transit travel time (min), average wait time (min), transit fare cost (dollars), and average walk time to a transit station (min).

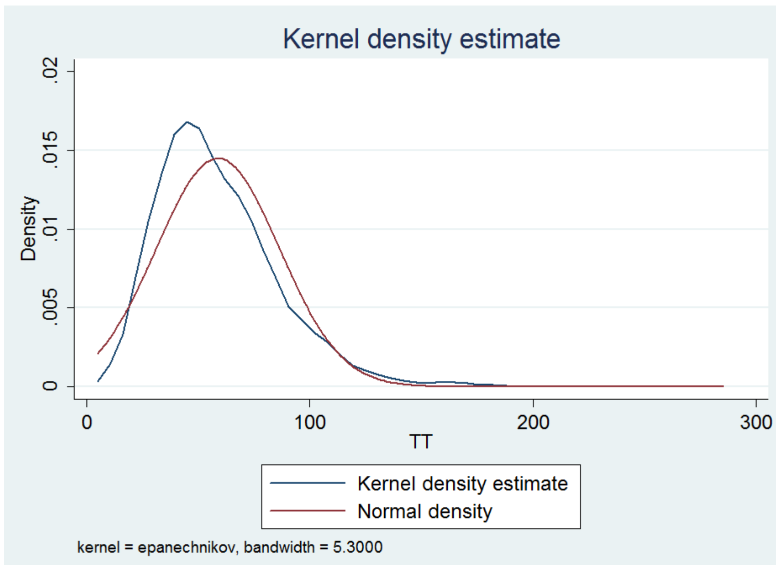


Figure 40. Kernel Density Estimate – Travel Time (min)

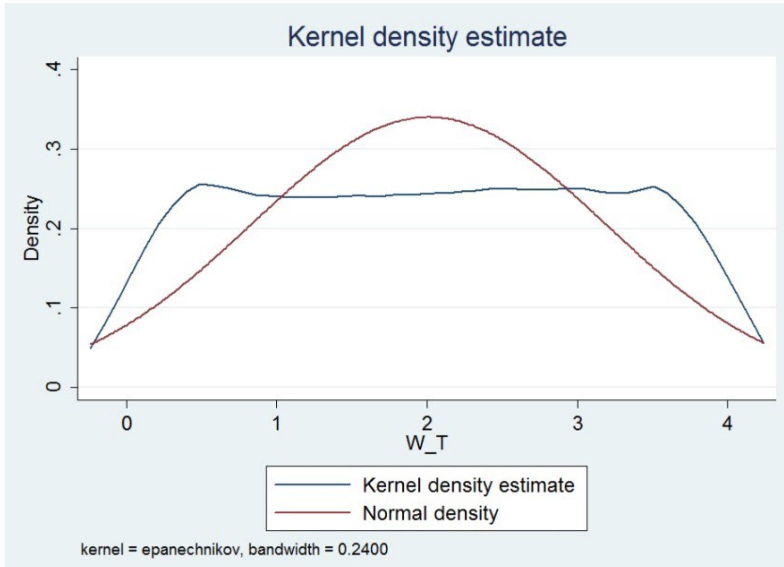


Figure 41. Kernel Density Estimate – Transit Wait Time (min)

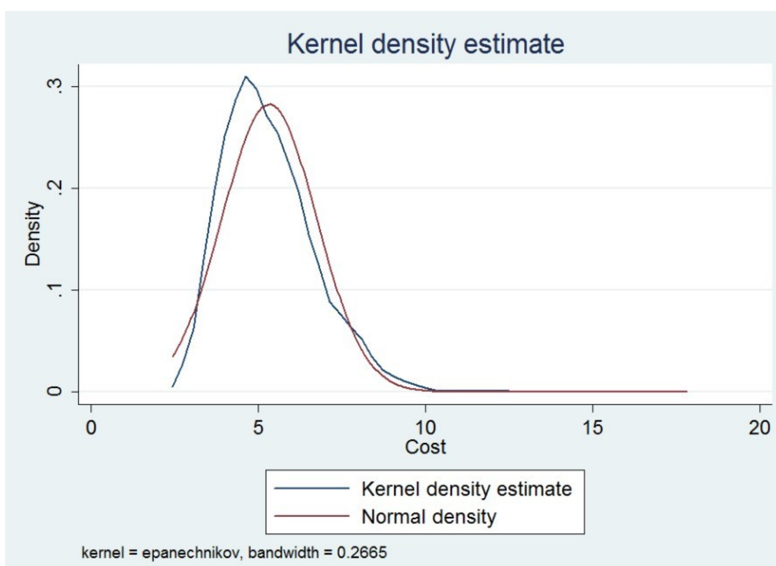


Figure 42. Kernel Density Estimate – Transit Fare Cost ($)

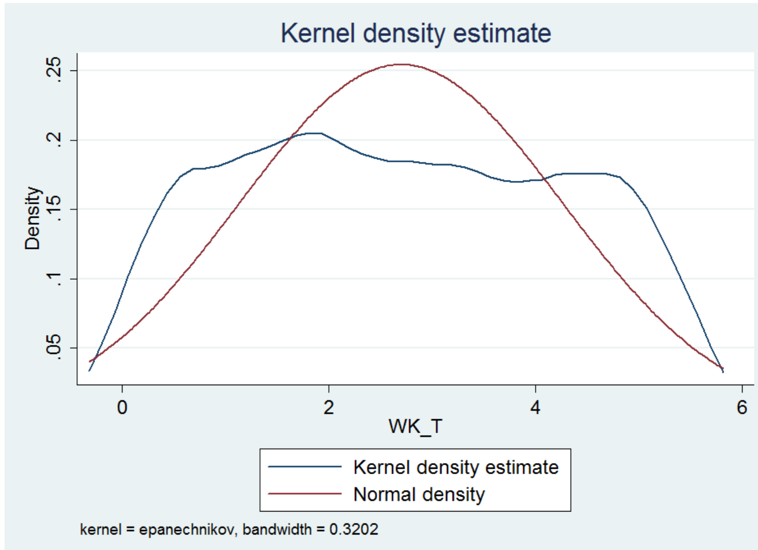


Figure 43. Kernel Density Estimate – Transit Station Walk Time (min)

6.3.4. Model Specifications

The utility models for transit trips for 0 to ≥4 vehicles per household is determined by using Stata®. The models can be shown as follows:

$U_0 = 1.16 - 0.667 ln(TT) + 0.559(W\_T) + 14.523 (Cost)^{-1} - 0.0079(WK\_T)$

$U_1 = 7.08 - 1.408 ln(TT) + 0.0923(W\_T) + 4.20 (Cost)^{-1} - 0.401(WK\_T)$

$U_2 = 4.681 - 0.7424 ln(TT) + 0.0645(W\_T) + 0.799 (Cost)^{-1} - 0.1021(WK\_T)$

$U_3 = 5.213 - 0.8478 ln(TT) + 0.0530(W\_T) - 5.230 (Cost)^{-1} - 0.0354(WK\_T)$

Where,

TT = Trip travel time (min)

W_T = Wait time (min)

Cost = Transit Fare Cost ($)

WK_T = Walk time to transit station (min)

Table 23 shows the results of the multinomial logistic regression. The iteration log show the list of log likelihood at 5 iterations until the model is converged. Multinomial log regression models use the "maximum likelihood estimation" which is an iterative process to reach minimum log likelihood. When the difference between each iteration is small, then the model is converged and no smaller value of log likelihood exists.

The likelihood ratio test (LR) uses the log likelihood to determine if a variable or a group of variables should be dropped from the logit model. The log likelihood tests the explanatory effectiveness of a variable. Therefore, if dropping a variable doesn't change the value of the log likelihood then the variable can be dropped.

The likelihood ratio test (LR) is implemented by first estimating the model with all variables. Then a second model is estimated to only include variables that are believed to have an explanatory impact. Subsequently, the value of "likelihood ratio test statistic (LR)" is determined as follows:

$$LR = 2(log\ (log\ likelihood\ of\ Model_1) - log(log\ likelihood\ of\ Model_2\ )$$

In Stata® statistical software package the Likelihood Ratio (LR) test is represented by LR chi^2 and is an indication if the model is significant. Unlike Horowitz, the LR chi^2 is simply twice the difference between the log likelihood of the current model with the intercept model. The log likelihood of the intercept model is shown at the 0^{th} iteration. This value indicates the likelihood ratio that for all equations at least one of the predictors' regression coefficient is not equal to zero.

The degree of freedom (df) for the Chi-Square distribution is also shown in Stata® and is calculated as:

df = the number of models estimated (5) × the number of predictors in the model (3)

The null hypothesis is that all of the regression coefficients across all models are equal to zero. The Prob > chi^2 is the p-value that is compared with a pre-set tolerance to accept a Type I error of $\alpha = 0.05$ would reject the null hypothesis and shows that at least one regression coefficient is not equal to zero.

The confidence interval (CI) shown on the output indicated that for a particular predictor we are 95% confident that the "true" coefficient lies between the lower and upper limit of the interval. If the CI includes zero, we'd fail to reject the null hypothesis that the regression coefficient is zero given the other independent variables are in the model.

Table 23. Transit Trips MNL Summary of Results

Number of Obs		1660			
LR chi^2 (16)		150.08			
P value		0.0000			
Pseudo R^2		0.0336			
Log Likelihood		-2158.6122			
Veh	Variable	Coef	P Value	95% Confidence Interval	
0	Travel time	-0.6674	0.526	-2.7323	1.3975
	Wait Time	0.0559	0.655	-0.1891	0.3010
	Fare Cost	14.5238	0.159	-5.6660	34.7138
	Walk Time	-0.0079	0.933	-0.1936	0.1777
	Constant	1.1607	0.851	-10.9510	13.2726
1	Travel time	-1.4085	0.150	-3.3253	0.5082
	Wait Time	0.0923	0.427	-0.1356	0.3230
	Fare Cost	4.2002	0.661	-14.601	23.0014
	Walk Time	0.0401	0.649	-0.1328	0.2131
	Constant	7.0832	0.217	-4.1595	18.3261
2	Travel time	-0.7424	0.427	-2.5759	1.0911
	Wait Time	0.0645	0.581	-0.1649	0.2941
	Fare Cost	0.7990	0.931	-17.3349	18.9331
	Walk Time	0.1021	0.250	-0.7192	0.2763
	Constant	4.6814	0.394	-6.0940	15.4569
3	Travel time	-0.8478	0.456	-3.0757	1.3800
	Wait Time	0.0530	0.684	-0.2026	0.3086
	Fare Cost	-5.2308	0.639	-27.0793	16.6176
	Walk Time	0.0354	0.720	-0.1585	0.2294
	Constant	5.2128	0.435	-7.8616	18.2874
≥4	Base Outcome				

6.3.5. Validation

The derived models are tested against the data to determine the validity. Using 40 data points in two sets of probability values are determined. The first set is what is obtained through the use of the logit model and the second set if simply the probability of occurrence of the data points in the data set. This comparison in effect provides the probability of taking transit as the primary mode of travel in a transit-oriented environment given the users are classified as having 0, 1, 2, and 3 vehicles.

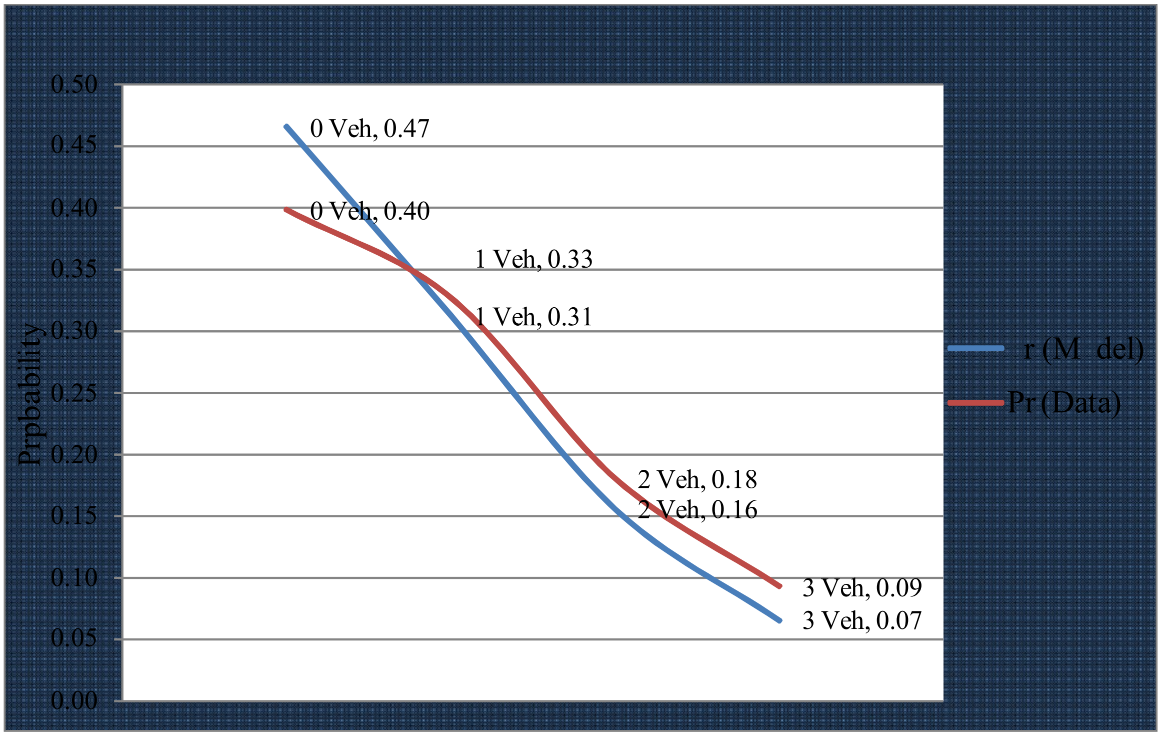
Table 24 shows the results of the comparison.

Table 24. Model Validation

Vehicle Ownership	Prob. (Model)	Prob. (data)
0	0.47	0.40
1	0.31	0.33
2	0.16	0.18
3	0.07	0.09

Similarly Figure 44 is a schematic presentation of the results which indicates that not only the use of transit decreases as the number of vehicle ownership increases, it also shows that the probability of using transit is similar between what is derived by the logit model and the observed values.

Figure 44. Average Probabilities of Transit Use - Model vs. Observed



CHAPTER 7. Conclusion

Transit Orientated Developments (TODs) have been recognized as a promising proposition for transportation policy makers and land developers to meet the challenges of urban sprawl. Recent land developments in the United States focus on creating livable and walkable communities, concentrated along transit corridors. The rapid pace with which TODs are being developed across the United States has left policy makers and transportation planners looking for methods aimed at modeling travel characteristics of TODs. The travel demand parameters necessary to predict trip generation rates, develop trip distribution tables, identify mode choice characteristics, and determine the trip assignment of TODs are yet to be fully explored.

Models are developed to assess trip generation and mode choice characteristics in transit oriented developments based on activity based 24-hour household travel survey. The activity-based survey data provides a wealth of transit-oriented corridors, and diverse land use. The use of this data mitigates loss of computational information frequently ensued by aggregate data, hence providing a more accurate quantitative forecast.

The methods will enable transportation professionals and policy analysts forecast vehicular trips and modal choice of transit oriented developments. Multinomial regression models are developed and validated relating TOD trip ends to the size of the development. Model validation is performed by checking for normality, multicollinearity and heteroscedasticity of the independent variables. Stochastic mode choice utility models using multinomial logit regression are also developed and validated to show modal split behavior in the 0.25 mile radius of transit stations in the Washington Metro area.

The literature search shows that a significant amount of research has been performed on the planning side of transit oriented developments and less on the output such as trip generation rates, ridership and traffic conditions. There is an abstract understanding of what constitutes a TOD in terms of land use and transit. Trip characteristics of TODs including levels of walking, cycling, public transit utilization and Vehicle Mile Traveled (VMT), and how these impact pollution emissions and traffic fatality rates need further examination. The literature clearly showed lack of mathematical models that accurately predicts trip generation rates and asses mode choice behavior of transit oriented developments.

Trip behavior of transit oriented developments is examined as part of this research and is compared with non-TOD environments. Results of the analysis show that home-based work, shop, and entertainment trips are mainly performed via the use of transit in TOD areas. Furthermore, walk and bike as the primary mode of travel are more prominent in TOD areas than the non-TOD areas.

Another result of the analysis which may be contrary to intuition is the use of personal vehicles in TOD area is still high. This is because while the greater Washington D.C. area has one of the best transit network systems in the nation, yet the transit network is not saturated and only serves a limited part of the geography.

The association between trip ends and gross floor area of developments along a transit-oriented corridor is shown with a linear regression model. The model has a regression coefficient of $R^2 = 0.81$. Furthermore, the p-value of close to zero, with 4 significant digits, shows the model is significant and independent variables reliably predict the dependent variable. The Rosslyn-Ballston Metro Corridor in Arlington, Virginia which exemplifies an ideal transit-oriented corridor is selected as the test site.

The linear regression model presented is further validated against two state-of-practice measures for trip prediction. The developed regression model shows a 55% trip reduction for transit oriented developments compared to a non-TOD development. This is consistent with the state of practice. The less than 10% difference in trip generation numbers between the developed regression model and the MXD methodology is another good indication of the validity of the developed model.

A multivariate regression model is developed for estimating trip generation rates associated with socio-economic factors such as household size, income, average number of drivers, workers, bikes and vehicles per household in a transit oriented development environment. Backward elimination technique is used to eliminate variables that do not significantly impact the association. The final model expressed trip rates of transit-oriented developments in terms of size, average number of vehicles and average number of workers in a household. The model is validated by checking for normality, heteroscedasticity and multicollinearity. The $R^2 = 0.7$ for the final model is a robust indication of goodness of fit.

Moreover, a stochastic mode choice utility model is developed using multinomial logistic regression to show the modal split in the 0.25 mile radius of all transit stations in the Washington Metro area. The primary focus of the mode choice model is on home-base work trips which predominantly constitute the number of trips in the 24-hour activity based data. The attributes of the primary mode of travel include transit, auto-driver, auto-passenger, walk, bike and other. The mode choice model was validated and results indicated that the values derived by the model are closely similar to observed values in the data set.

Finally, a utility function for the transit mode was developed to determine the attractiveness of using transit given vehicle ownership. The attributes that represent the attractiveness (or the cost) associated with transit mode in the greater Washington area are assumed as transit travel time (min), average wait time (min), transit fare cost (dollars), and average walk time to a transit station (min). Average household income is assumed as the characteristic of traveler.

The results indicated that not only the use of transit decreases as the number of vehicle ownership increase, but also the probability of using transit is similar when values obtained from the logit model is compared to observed values in the data set.

In the absence of a structured sensitivity analysis, it is not clear if differentiating trip generation models for TODs and other land uses will automatically lead to better results from the travel demand modeling process. However, disaggregate trip generation models are widely regarded as better model for travel demand modeling applications. Therefore, whenever travel survey data with spatial resolution are available, it is recommended that separate trip generation models be developed for TODs.

It should be pointed out, while the methodology presented in this dissertation is transferable, the models themselves is limited to greater metropolitan Washington D.C and may not be transferable to other regions of the country.

Appendix

TAZ	Area
1264	Ballston
1265	Ballston
1266	Ballston
1284	Ballston
1285	Ballston
1255	Clarendon
1256	Clarendon
1257	Clarendon
1260	Clarendon
1261	Clarendon
1262	Clarendon
1263	Clarendon
1253	Court House
1254	Court House
1256	Court House
1232	Rosslyn
1236	Rosslyn
1237	Rosslyn
1238	Rosslyn
1273	Rosslyn
1260	Virginia Square
1261	Virginia Square
1262	Virginia Square
1266	Virginia Square

Table 25. Trip Generation Regression Model – Sample Data Set

Metro Name	TAZ	Total Area (Sq. Ft.)	Area Inside (Sq. Ft.)	% Area Inside	Total Trips	% Trips	Develop’t Area (SF)
Rosslyn	1254	5028012	2157335	0.3272	18060	5909	1315442
Rosslyn	1257	2163459	113515	0.5482	10939	5997	1918633
Rosslyn	1238	3938228	1297825	0.3295	19460	6413	2814013
Rosslyn	1273	5362782	123892	0.0231	1707	39	197271
Court House	1253	6783963	2940915	0.4335	24097	10446	1709891
Court House	1255	5262207	1635	0.0003	2509	1	1226
Court House	1256	2124146	258699	0.1218	16374	1994	480375
Court House	1257	2163459	113515	0.0525	10939	574	206955
Clarendon	1255	5262207	864217	0.1642	2509	412	282223
Clarendon	1262	2518059	158380	0.0629	10624	668	108087
Clarendon	1263	3934619	244917	0.0622	9161	570	106968
Virginia Square-	1260	7089717	861852	0.1216	10939	1330	294842
Virginia Square-	1261	1824204	1428352	0.7830	7594	5946	1899096
Virginia Square-	1263	3934619	536051	0.1362	9161	1248	330437
Virginia Square-	1266	8892736	434457	0.0489	14105	689	118494
Ballston-MU	1264	5492102	2560936	0.4663	23270	10851	3697696
Ballston-MU	1265	1739246	1380024	0.7935	30216	23975	6292116
Ballston-MU	1284	8288957	310839	0.0375	14032	526	297376
Ballston-MU	1285	3976522	973969	0.2449	12365	3029	1942285

```
. regress trips area

      Source |       SS       df       MS              Number of obs =      38
-------------+------------------------------           F(  1,    36) =  306.03
       Model |  199.773832     1  199.773832           Prob > F      =  0.0000
    Residual |  23.5002649    36  .652785137           R-squared     =  0.8947
-------------+------------------------------           Adj R-squared =  0.8918
       Total |  223.274097    37  6.03443506           Root MSE      =  .80795

------------------------------------------------------------------------------
       trips |      Coef.   Std. Err.      t    P>|t|     [95% Conf. Interval]
-------------+----------------------------------------------------------------
        area |   1.096076   .0626551    17.49   0.000     .9690058    1.223147
       _cons |  -6.964918   .8270994    -8.42   0.000    -8.642353   -5.287483
------------------------------------------------------------------------------


. avplots

. mvtest normality developmentareasf

Test for multivariate normality

    Doornik-Hansen                    chi2(2) =    27.653   Prob>chi2 =  0.0000

. correlate
(obs=38)

             |    trips develo~f
-------------+------------------
       trips |   1.0000
developmen~f |   0.7921   1.0000
```

TOD Trip Generation Regression Results – Stata Output

Equation	Obs	Parms	RMSE	"R-sq"	F	P
trips	**117**	**4**	**17.01292**	**0.7115**	**92.87959**	**0.0000**

trips	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
size	**-.5249845**	**.1903792**	**-2.76**	**0.007**	**-.90216**	**-.1478089**
veh	**.8374482**	**.1261463**	**6.64**	**0.000**	**.5875296**	**1.087367**
wrkr	**.46785**	**.1032457**	**4.53**	**0.000**	**.2633016**	**.6723984**
_cons	**8.458232**	**2.315894**	**3.65**	**0.000**	**3.870028**	**13.04644**

TOD Trip Generation Prediction

. vif

Variable	VIF	1/VIF
size	**1.02**	**0.978530**
wrkr	**1.02**	**0.983140**
veh	**1.01**	**0.985799**
Mean VIF	**1.02**	

Multicollinearity – Final Cut

```
. mlogit mode hhveh incom tt, baseoutcome(9)

Iteration 0:   log likelihood = -7746.8711
Iteration 1:   log likelihood = -6259.6701
Iteration 2:   log likelihood = -5889.6884
Iteration 3:   log likelihood = -5811.9045
Iteration 4:   log likelihood = -5808.9502
Iteration 5:   log likelihood = -5808.9426
Iteration 6:   log likelihood = -5808.9426

Multinomial logistic regression                   Number of obs   =       5950
                                                  LR chi2(15)     =    3875.86
                                                  Prob > chi2     =     0.0000
Log likelihood = -5808.9426                       Pseudo R2       =     0.2502
```

mode	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
1						
hhveh	-.5046556	.1146475	-4.40	0.000	-.7293606	-.2799507
incom	-.1140957	.0475602	-2.40	0.016	-.207312	-.0208793
tt	.068377	.0057231	11.95	0.000	.0571599	.0795941
_cons	1.784721	.4525866	3.94	0.000	.8976679	2.671775
2						
hhveh	.3797315	.1088084	3.49	0.000	.166471	.592992
incom	-.1726124	.0461779	-3.74	0.000	-.2631194	-.0821054
tt	.0250269	.0055996	4.47	0.000	.0140518	.0360019
_cons	3.23263	.4411945	7.33	0.000	2.367905	4.097355
3						
hhveh	.0144207	.1274566	0.11	0.910	-.2353896	.264231
incom	-.1426872	.0527391	-2.71	0.007	-.246054	-.0393204
tt	.0223305	.006276	3.56	0.000	.0100297	.0346312
_cons	1.46156	.4974901	2.94	0.003	.4864969	2.436622
6						
hhveh	-.5043195	.1177514	-4.28	0.000	-.7351081	-.2735309
incom	-.0582983	.0484098	-1.20	0.228	-.1531798	.0365831
tt	-.1147278	.0074018	-15.50	0.000	-.1292351	-.1002206
_cons	5.281071	.4612116	11.45	0.000	4.377113	6.185029
7						
hhveh	-.4493228	.1820044	-2.47	0.014	-.8060448	-.0926008
incom	.064218	.0725223	0.89	0.376	-.0779232	.2063591
tt	.0247823	.0079606	3.11	0.002	.0091799	.0403848
_cons	-1.012126	.6927584	-1.46	0.144	-2.369908	.3456552
9	(base outcome)					

```
. mlogit veh tt w_t cost wk_t, baseoutcome(5)

Iteration 0:   log likelihood = -2233.6528
Iteration 1:   log likelihood = -2169.2629
Iteration 2:   log likelihood = -2167.4853
Iteration 3:   log likelihood = -2167.4696
Iteration 4:   log likelihood = -2167.4695

Multinomial logistic regression                   Number of obs   =       1660
                                                  LR chi2(16)     =     132.37
                                                  Prob > chi2     =     0.0000
Log likelihood = -2167.4695                       Pseudo R2       =     0.0296
```

veh	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
0						
tt	-.0117229	.0107049	-1.10	0.273	-.0327042	.0092583
w_t	.0600529	.1250287	0.48	0.631	-.1849988	.3051046
cost	-.3916827	.2155771	-1.82	0.069	-.814206	.0308406
wk_t	-.0089083	.0945566	-0.09	0.925	-.1942359	.1764193
_cons	4.128793	.7653558	5.39	0.000	2.628724	5.628863
1						
tt	-.0166284	.009562	-1.74	0.082	-.0353695	.0021127
w_t	.0978066	.1166045	0.84	0.402	-.1307339	.3263471
cost	-.2009594	.1899481	-1.06	0.290	-.5732509	.1713321
wk_t	.037779	.08824	0.43	0.669	-.1351682	.2107262
_cons	4.30272	.6899852	6.24	0.000	2.950374	5.655066
2						
tt	-.0077906	.008959	-0.87	0.385	-.02535	.0097688
w_t	.0659099	.117486	0.56	0.575	-.1643583	.2961782
cost	-.0287563	.1781493	-0.16	0.872	-.3779226	.32041
wk_t	.1003446	.0888747	1.13	0.259	-.0738467	.2745359
_cons	2.449431	.6720991	3.64	0.000	1.132141	3.766721
3						
tt	-.0091157	.011139	-0.82	0.413	-.0309476	.0127163
w_t	.0507177	.1309078	0.39	0.698	-.2058569	.3072924
cost	.1248911	.2168317	0.58	0.565	-.3000911	.5498734
wk_t	.0355476	.0990589	0.36	0.720	-.1586043	.2296996
_cons	.6436294	.7667576	0.84	0.401	-.8591879	2.146447
5	(base outcome)					

```
. mlogit veh lntt w_t invcost wk_t, baseoutcome(4)

Iteration 0:   log likelihood = -2233.6528
Iteration 1:   log likelihood = -2160.6923
Iteration 2:   log likelihood = -2158.6289
Iteration 3:   log likelihood = -2158.6122
Iteration 4:   log likelihood = -2158.6122

Multinomial logistic regression                   Number of obs   =       1660
                                                  LR chi2(16)     =     150.08
                                                  Prob > chi2     =     0.0000
Log likelihood = -2158.6122                       Pseudo R2       =     0.0336
```

veh	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
0						
lntt	-.667401	1.053571	-0.63	0.526	-2.732363	1.397561
w_t	.0559133	.1250486	0.45	0.655	-.1891774	.301004
invcost	14.52389	10.30119	1.41	0.159	-5.666081	34.71386
wk_t	-.0079342	.0947513	-0.08	0.933	-.1936434	.177775
_cons	1.16076	6.179624	0.19	0.851	-10.95108	13.2726
1						
lntt	-1.408561	.9779644	-1.44	0.150	-3.325336	.508214
w_t	.0923324	.1163183	0.79	0.427	-.1356472	.3203121
invcost	4.200249	9.592648	0.44	0.661	-14.601	23.00149
wk_t	.0401168	.0882674	0.45	0.649	-.132884	.2131177
_cons	7.08328	5.736261	1.23	0.217	-4.159586	18.32615
2						
lntt	-.7424094	.935504	-0.79	0.427	-2.575963	1.091145
w_t	.0645695	.1171105	0.55	0.581	-.1649628	.2941018
invcost	.799068	9.252227	0.09	0.931	-17.33496	18.9331
wk_t	.102189	.0888372	1.15	0.250	-.0719287	.2763068
_cons	4.681465	5.497794	0.85	0.394	-6.094013	15.45694
3						
lntt	-.8478557	1.136683	-0.75	0.456	-3.075713	1.380001
w_t	.0530276	.1304464	0.41	0.684	-.2026427	.3086979
invcost	-5.230847	11.14737	-0.47	0.639	-27.0793	16.6176
wk_t	.0354496	.0989751	0.36	0.720	-.1585381	.2294372
_cons	5.212874	6.670803	0.78	0.435	-7.861659	18.28741
4	(base outcome)					

Bibliography

Bibliography

Arrington, G.B., and Cervero, R. Effects of TOD on Housing, Parking, and Travel. TCRP Report 128. Transportation Research Board, Washington, DC, 2009.

Bhat, C.R. and V. Pulugurta (1998) "A comparison of two alternative behavioral mechanisms for household auto ownership decisions," Transportation Research, 32B, 10-24.

Bhat, C.R., A. Govindarajan and V. Pulugurta (1998) "Disaggregate attraction-end choice modeling: formulation and empirical analysis," Transportation Research Record 1645, 60-68.

Bochner, B., Hooper, K., Benjamin, S. and Dunphy, R., Enhancing Internal Trip Capture Estimation for Mixed-Use Developments. NCHRP Report 684. Transportation Research Board, Washington DC, 2011.

Cervero, R and C. Radisch, "Travel Choices in Pedestrian versus Automobile Oriented Neighborhoods," Transport Policy Vol. 3 No 3, 1996, pp. 127-141.

Cervero, R and K. Kockelman, Working Paper 674: Travel Demand and the Three Ds: Density, Diversity, and Design, University of California at Berkeley Institute of Urban and Regional Development, 1997.

Cervero, R and R. Ewing, Travel and the Built Environment-Synthesis, University of California at Berkeley Institute of Urban and Regional Development, 2002.

Cervero, R and R. Gorham, "Commuting in Transit versus Automobile Neighborhoods," Journal of the American Planning Association, Vol. 61 No 1, 1995, pp. 210-225.

Cervero, R and S. Seskin, An Evaluation of the Relationships Between Transit and Urban Form. TCRP Research Results Digest Number 7, 1995.

Cervero, R, "Built Environments and Mode Choice: Toward a Normative Framework", Transportation Research Part D, Volume 7, 2002, pp. 265-284.

Cervero, R, "Mixed Land-Uses and Commuting: Evidence from the American Housing Survey," Transportation Research-A Vol. 30 No. 5, 1996, pp. 361-377.

Cervero, R, Ridership Impacts of Transit-Focused Development in California, University of California at Berkeley Institute of Urban and Regional Development, 1993a.

Chalumuri, S. and M.M. Venigalla. (2004). TRIMM User Manual and Guidance Document. Report Submitted to the Federal Highway Administration (FHWA). March 2004.

Chalumuri, S. and M.M. Venigalla. (2004). Vehicle Activity and Personal Travel Inputs to Emission Models. Report Submitted to the Federal Highway Administration (FHWA). March 2004.

Chalumuri, S., and M.M. Venigalla. (2004). Methodology for deriving vehicle activity parameters from travel survey databases. Presented at the Transportation Research Board 83rd Annual Meeting. Washington DC. January 2004. (Also published in Transportation Research Record: Journal of the Transportation Research Board. http://trrjournalonline.trb.org/doi/abs/10.3141/1880-13).

Chalumuri, S., and M.M. Venigalla. (2004) Methodology for Deriving Vehicle Activity Parameters from Travel Survey Databases. Transportation Research Record: Journal of the Transportation Research Board, (1880), 2004, pp.108-118. (http://dx.doi.org/10.3141/1880-13).

Chatterjee A., Reddy P.M., Venigalla MM and Miller T. (1996). Operating Mode Fractions on Urban Roads Derived by Traffic Assignment. Transportation Research Record: Journal of the Transportation Research Board, (1520), 1996, pp. 97-103.

Chatterjee, A., & Venigalla, M. M. (2003). Travel Demand Forecasting for Urban Transportation Planning (Chapter 7). In M. Kutz (Ed.), Handbook of Transportation Engineering. McGraw-Hill Publications.

Chatterjee, A., E. Cadotte, N. Stamatiadis, H. Sink, M.M. Venigalla, and G Gaides. (1996). Driver-related factors involved with truck accidents. Journal of Safety Research. Elsevier, 27(1), 1996. (http://dx.doi.org/10.1016/0022-4375(96)91005-5).

Criterion Planners/Engineers and Fehr & Peers Associates, “Index 4D Method: A Quick Response Method of Estimating Travel Impacts of Land Use Changes”, United States Environmental Protection Agency.

Dunphy, R. and K. Fisher, Transportation, Congestion, and Density: New Insights, Urban Land Institute, 1993.

Ewing, R., Greenwald, M. Zhang, M., Walters, J., Feldman, M. Cervero, R., Frank, L., Thomas, J. Traffic Generated by Mixed-Use Development – A Six-Region Study Using Consistent Built Environmental Measures. Journal of the Urban Planning and Development, May, 2011.

Frank, L. and G. Pivo, "Impacts of Mixed Use and Density on Utilization of Three Modes of Travel: SOV, Transit and Walking," Transportation Research Record 1466, 1995.

HNTB Corporation. Alternative Mode (Non-Auto), Trip Reductions Database Study, Final Report. Virginia Department of Transportation, Chantilly, 2009.

Holroyd E. M. and Scraggs D. A. (1966) Waiting Times for Buses in Central London, Traffic Engineering and Control, Vol.8, No.3, 158-160.

Institute of Transportation Engineers. Trip Generation Handbook, an ITE Recommended Practice, 2nd ed. Washington, DC, 2004.

Institute of Transportation Engineers. Trip Generation, 8th Edition: An ITE Informational Report. Washington, DC, 2008.

Jolliffe J. K. and Hutchinson T. P. (1975) A Behavioral Explanation of the Association Between Bus and Passenger Arrivals at a Bus Stop, Transportation Science, Vol.9, No.4, 248-282.

Kimley-Horn and Associates, Inc. Trip-Generation Rates for Urban Infill Land Uses in California Phase 2: Data Collection, 2009. http://www.dot.ca.gov/research/researchreports/reports/2009/final_summary_report-calif._infill_trip-generation_rates_study_july_2009.pdf. Accessed December 15, 2011.

Krimmer, M.J., and M.M. Venigalla. (2006). Measuring Impacts of High-Occupancy-Vehicle Lane Operations on Light-Duty-Vehicle Emissions: Experimental Study with Instrumented Vehicles. Presentation at the Annual Meeting of the Transportation Research Board. Washington D.C. 2006.

Krimmer, M.J., and M.M. Venigalla. (2006). Measuring Impacts of High-Occupancy-Vehicle Lane Operations on Light-Duty-Vehicle Emissions: Experimental Study with Instrumented Vehicles. Transportation Research Record: Journal of the Transportation Research Board, (1987), 2006, pp. 1-10. (http://dx.doi.org/10.3141/1987-01).

Lam, S-H (1991) Multinomial probit model estimation: computational procedures and applications, Unpublished Ph.D. dissertation, Department of Civil Engineering, The University of Texas at Austin.

Lam, S-H. and H.S. Mahmassani (1991) “Multinomial probit model estimation: computational procedures and applications,” in Methods for Understanding Travel Behavior in the 1990s, Proceedings of the International Association of Travel Behavior, 229-242.

Lancaster, K. (1971) Consumer Demand: A New Approach, New York, Columbia University Press.

Lapham, Michael Transit Oriented Development – Trip Generation and & Mode Split in the Portland Region. Portland State University, March 2001.

Lawton, T. , Travel Behavior – Some Interesting Viewpoints: The Urban Environment Effects and a Discussion on Travel Time Budget, A Discussion on Selected Data from the 1994/1995 Household Survey, Portland Transportation Summit, 1998.

Lee, R., Miller, J., Maiss, R. Campbell, M., Shafizadeh, K., Niemeier, D., Handy, S., and Parker, T. Evaluation of the Operation and Accuracy of Five Available Smart Growth Trip Generation Methodologies. University of California, Davis, 2011.

Litman, T. Land Use Impacts on Transport. Victoria Transportation Policy Institute. Victoria, British Columbia. 2010.

Lund, H. , R. Cervero and R. Willson, Travel Characteristics of Transit-Oriented Development in California. California Department of Transportation. Forthcoming 2004.

Margiotta, R.; H. Cohen; G. Elkins; A. Rathi; and M.M. Venigalla "Speed Determination Models for the Highway Performance Monitoring System," Prepared for the Federal Highway Administration by Science Applications International Corporation, Oak Ridge, Tennessee. October 1993.

Margiotta, R.; H. Cohen; G. Elkins; A. Rathi; and M.M. Venigalla. (1994). Generic Vehicle Speed Model Based on Traffic Simulation: Development and Application. Proceedings of the 74th Annual Meeting of the Transportation Research Board. 1994. 10p (http://ntl.bts.gov/lib/7000/7000/7009/m96004384.pdf).

Margiotta, R.A., M.M. Venigalla, and G. Evans. (1989). "Improving Safety for Pedestrians and Bicyclists," Transportation Center, University of Tennessee, Prepared for the Tennessee Governor's Highway Safety Program, Tennessee Department of Transportation, December 1989.

Marguier, Philippe H. J. and Ceder, Avishai (1984) Passenger Waiting Strategies for Overlapping Bus Routes, Transportation Science Vol.18, NO.3 207-230.

Metropolitan Transportation Commission. Planning: Station Area Residents Survey,

2006. http://www.mtc.ca.gov/planning/smart_growth/stars/. Accessed December 15, 2011.

Metzger, D.N., A.K. Rathi and M.M. Venigalla. (1991). Evacuation Time Estimates for Anniston Army Deport and Vicinity. Oak Ridge National Laboratory, Prepared for the U.S. Department of Army and Federal Emergency Management Agency, October 1991.

Miller, E. and A. Ibrahim, "Urban Form and Vehicular Travel: Some Empirical Findings," Transportation Research Board 77th Annual Meeting, 1998.

Olaherty C. A. and Mangan D. O. (1970) Bus Passenger Waiting Time in Central Areas, Traffic Engineering and Control, Vol.11, No.9, 419-421.

Ozekici, Suleyman. (1987) Average Waiting Time in Queues with Scheduled Batch Services, Transportation Science Vol.21, No.1 55-61.

Rathi A.K., and M.M. Venigalla. Variance Reduction Applied to Urban Network Traffic Simulation. Transportation Research Record: Journal of the Transportation Research Board, (1365), 1992, pp. 133-146.

Rathi A.K., and M.M. Venigalla. (1992). Variance Reduction Applied to Urban Network Traffic Simulation. Presented at and appeared in the proceedings of the 71st Annual meeting of the Transportation Research Board, Washington, DC, January 1992.

Rathi A.K., and M.M. Venigalla. (1992). Variance Reduction Applied to Urban Network Traffic Simulation. Transportation Research Record: Journal of the Transportation Research Board, (1365), 1992, pp. 133-146. (http://trid.trb.org/view.aspx?id=371414).

Rathi, A.K, D. Metzger, M.M. Venigalla and F. Southworth. (1992). "Evacuation Time Estimates for Lexington-Blue Grass Army Depot and Vicinity." Oak Ridge National Laboratory, Prepared for the U.S. Department of Army and Federal Emergency Management Agency, 1992.

Rathi, A.K, F. Southworth, M.M. Venigalla and J. Jacobi. (1990). "Evacuation Time Estimates for Tooele Army Depot and Vicinity." Oak Ridge National Laboratory, Prepared for the U.S. Department of Army and Federal Emergency Management Agency, December 1990.

Rathi, A.K., F. Southworth, M.M. Venigalla & J. Jacobi. (1991). "Evacuation Time Estimates for Newport Army Ammunition Plant and Vicinity." Oak Ridge National Laboratory, Prepared for the U.S. Department of Army and Federal Emergency Management Agency, February 1991.

Rathi, A.K., M.M. Venigalla, Louis Chang and Sarah Jennings. (1992). "User Manual for Oak Ridge Evacuation Model (OREM)," Oak Ridge National Laboratory, June 1992.

Santosh V.K., M.M. Venigalla, and V. Isaac. (1987). "A Report on the Evaluation of Arumbakkam Sites and Services," Kirloskar Consultants Limited, Prepared for Madras Metropolitan Development Authority, December 1987.

Santosh V.K., M.M. Venigalla, and V. Isaac. (1988). "Development of Kilpauk Section of Inner Orbital Road," Kirloskar Consultants Limited, Prepared for Madras Metropolitan Development Authority, the Corporation of Madras and the World Bank, October 1988.

Santosh V.K., M.M. Venigalla, and V. Isaac. (1989). "Highway Capacity and Speed-Flow Relationship," Kirloskar Consultants Limited, Prepared for Madras Metropolitan Development Authority and the World Bank, February 1989.

Santosh V.K., M.M. Venigalla, and V. Isaac. (1990). "Improvements to Cross-Cut Road at Coimbatore," Kirloskar Consultants Limited, Prepared for the Project Management Group, Tamil Nadu Urban Development Program (Madras) and the World Bank, April 1990.

Santosh V.K., M.M. Venigalla, and V. Isaac. (1988). "Improvements to the Subway at Big Bazaar Street Intersection," Kirloskar Consultants Limited, Prepared for the Project Management Group, Tamil Nadu Urban Development Program (Madras) and the World Bank, October 1988.

Santosh V.K., M.M. Venigalla, and V. Isaac. (1988). "Traffic Management Scheme for Nungambakkam High Road," Kirloskar Consultants Limited, Prepared for Madras Metropolitan Development Authority, the Corporation of Madras and the World Bank, October 1988.

Santosh V.K., M.M. Venigalla, and V. Isaac. (1989). "Users' Perception of Different Aspects of Travel and Value of Travel Time," Kirloskar Consultants Limited, Prepared for Madras Metropolitan Development Authority and the World Bank, February 1989.

Seattle METRO (Municipality of Metropolitan Seattle). Encouraging Public Transportation Through Effective Land Use Actions (DOT-I-87-5), 1987. United States Department of Transportation, 1997.

Spillar, R. and G. S. Rutherford, “The Effects of Population Density and Income on Per Capita Transit Ridership in Western American Cities,” ITE 1990 Compendium of Technical Papers, 1990, pp. 327-331.

Still, K, S. Seskin, and T. Parker, “Chapter 3: How Does TOD Affect Travel and Transit Use,” Caltrans Statewide Transit-Oriented Development Study, pp. 46-50, 2000.

Transportation Research Board. NCHRP 08-66. Trip-Generation Rates for Transportation Impact Analyses of Infill Developments. Washington, DC, 2011b.

Trip Capture Estimation for Mixed-Use Developments. Washington, DC, 2011a. http://apps.trb.org/cmsfeed/trbnetprojectdisplay.asp?projectid=927. Accessed December 11, 2011.

U.S. Environmental Protection Agency. Smart Growth: Trip Generation Tool for Mixed-Use Developments, 2011.

Venigalla, M.M. (1987). "Modernization of Commercial Vehicle Fleet on Indian Roads," Master's Thesis Submitted to the Indian Institute of Technology, Madras, April 1987.

Venigalla M.M. (1990). "Operational Effects of Non-Traversable Medians and two-way Left-Turn Lanes: A Comparison," A Master's Thesis Submitted to the University of Tennessee, December 1990.

Venigalla, M.M. (1994). "A Network Assignment Based Approach to Modeling Mobile Source Emissions” A Dissertation Research Report Presented in Partial Fulfillment for the Award of Doctor of Philosophy in Civil Engineering, The University of Tennessee, Knoxville, Tennessee, May 1994.

Venigalla, M. M. (1996). A network assignment based approach to modeling mobile source emissions. Transportation Research Part A, 1(30), 56, 1996.

Venigalla, M.M. (2004). Household Travel Survey Data Fusion Issues. In Resource Paper, National Household Travel Survey Conference: Understanding Our Nation’s Travel (Vol. 1, No. 2), Nov 2004. (http://citeseerx.ist.psu.edu/viewdoc/summary?doi=10.1.1.120.2980).

Venigalla, M.M and D.H. Pickrell. (2002). Soak Distribution Inputs to Mobile Source Emissions Modeling: Measurement and Transferability. Journal of Transportation Research Board, Transportation Research Record: Journal of the Transportation Research Board, (1815) 2002, pp. 63-70. (http://dx.doi.org/10.3141/1815-08).

Venigalla, M.M., A. Chatterjee, and M.S. Bronzini. (1999) A specialized equilibrium assignment algorithm for air quality modeling. Transportation Research – D. Volume 4. No. 1, January 1999, pp. 19-44. (http://dx.doi.org/10.1016/S1361-9209(98)00022-4).

Venigalla, M.M. and A.K. Rathi. (1992). A Software Utility for Regional Evacuation (SURE). Proceedings of the ASCE 8th Specialty Conference on Computing in Civil Engineering, Dallas, June 7-9, 1992. pp. 25-32. (http://cedb.asce.org/cgi/WWWdisplay.cgi?76435).

Venigalla, M.M. and A.K. Rathi. (1993). Software Utilities for Network Traffic Simulation Models. Proceedings of the ASCE 4th International Conference on Microcomputers in Transportation, Baltimore, July 22-24, 1993. pp. 707-717 (http://cedb.asce.org/cgi/WWWdisplay.cgi?80343).

Venigalla, M.M. and multiple other authors. (1999). "Environmental Impact Statement for Redline Extension Study," Draft report submitted to the Cleveland Rapid Transit Authority. June 1999

Venigalla, M.M. and multiple other authors. (1999). "Intelligent Transportation Systems (ITS) Impact Assessment Framework." Report prepared for the ITS Joint Program Office of the Federal Highway Administration. Volpe National Transportation Systems Center, October 1995.

Venigalla, M.M. and multiple other authors. (1999). "Northeast Nebraska Corridor Feasibility Studies." Submitted to Nebraska Department of Roads, December 1999.

Venigalla, M.M. and multiple other authors. (2004). TMC Applications of Archived Data –ADMS (Archived Data Management System) Virginia. May 2004.

Venigalla, M.M. (2004). Household Travel Survey Data Fusion Issues. In Resource Paper, National Household Travel Survey Conference: Understanding Our Nation's Travel (Vol. 1, No. 2), Nov 2004.

Venigalla, M.M., and A. Ali. (2005). Deriving performance measures for transportation planning using ITS archived data. The Journal of Civil Engineering and Environmental Systems. 22(3), 2005, pp. 171-188. (http://dx.doi.org/10.1080/10286600500279998).

Venigalla, M.M., and B. Baik. (2007). GIS-Based Engineering Management Service Functions. Journal of Computing in Civil Engineering. Volume 21(5), 2007, pp. 331-342. (http://dx.doi.org/10.1061/(ASCE)0887-3801(2007)21:5(331))

Venigalla, M.M., and M.S. Bronzini. (2004). Arrival Sampling Without Replacement for Simulating Fixed Entity Streams in Civil Engineering Systems. ASCE Journal of Computing in Civil Engineering, 18(4), October 2004, pp. 313-321.

Venigalla, M.M., and M.S. Bronzini. (2002). Sampling Entities Without Replacement for Stochastic Simulation Using Randomized Streams. Proceedings of the IASTED International Conference on Modeling and Simulation, ACTA Press, May 2002, pp. 110-117. (https://www.actapress.com/Content_Of_Proceeding.aspx?ProceedingID=377).

Venigalla, M.M., and S. Chalumuri. (2004). Applications of TRIMM for Small and Medium Communities. Transportation Research Board conference on Tools of the Trade. Colorado Springs, CO. September 2004.

Venigalla, M.M., S. Chalumuri, and R. Mandapati. (2005). Developing Custom Tools for Deriving Complex Data from Travel Survey Databases. Transportation Research Record: Journal of the Transportation Research Board, (1917), 2005, pp. 80-89. (http://dx.doi.org/10.3141/1917-10).

Venigalla, M.M., S. Chalumuri, S., & R. Mandapati. (2005). Developing custom tools for deriving complex data from travel survey databases. Presented at the Transportation Research Board 84th Annual Meeting. Washington DC. January 2005. (Also published in Transportation Research Record: Journal of the Transportation Research Board. http://trrjournalonline.trb.org/doi/abs/10.3141/1917-10).

Venigalla, M.M., and M. Casey. (2006). Innovations in Geographic Information Systems Applications for Civil Engineering. Journal of Computing in Civil Engineering, 20(6), 2006, pp. 375–376. (http://dx.doi.org/10.1061/(ASCE)0887-3801(2006)20:6(375))

Venigalla, M.M., R. Margiotta, D.B. Clarke, and A. Rathi. (1992). Operational Effects of Non-Traversable Medians and two-way Left-Turn Lanes: A Comparison. Presented at and appeared in the proceedings of the 71st Annual meeting of the Transportation Research Board, Washington, DC, January 1992. (Also published in Transportation Research Record: Journal of the Transportation Research Board. http://trid.trb.org/view.aspx?id=370810).

Venigalla, M.M., R. Margiotta, D.B. Clarke, and A. Rathi. (1992). Operational Effects of Non-Traversable Medians and two-way Left-Turn Lanes: A Comparison. Transportation Research Record: Journal of the Transportation Research Board, (1356), 1992, pp. 37-46. (http://trid.trb.org/view.aspx?id=370810).

Venigalla, M.M., T. Miller, and A. Chatterjee. (1995). "Start Modes of Trips for Mobile Source Emissions Modeling." Presentation at the 75h Annual Meeting of the Transportation Research Board. Washington D.C. 1995. (Also published in Transportation Research Record: Journal of the Transportation Research Board. http://trid.trb.org/view.aspx?id=427193).

Venigalla, M.M., T. Miller, and A. Chatterjee. (1995). Alternative Operating Mode Fractions to the FTP Mode Mix for Mobile Source Emissions Modeling. Presentation at the 75th Annual Meeting of the Transportation Research Board. Washington D.C. 1995. (Also published in Transportation Research Record: Journal of the Transportation Research Board. http://trid.trb.org/view.aspx?id=427194).

Venigalla, M.M., T. Miller, and A. Chatterjee. (1995). Alternative Operating Mode Fractions to the FTP Mode Mix for Mobile Source Emissions Modeling. Transportation Research Record: Journal of the Transportation Research Board, (1472), 1995, pp. 35-44.

(http://trid.trb.org/view.aspx?id=427194).

Venigalla, M.M., T. Miller, and A. Chatterjee. (1995). Start Modes of Trips for Mobile Source Emissions Modeling. Transportation Research Record: Journal of the Transportation Research Board, (1472), 1995. pp. 26-34. (http://trid.trb.org/view.aspx?id=427193).

Venigalla, M.M., D.H. Pickrell, and K Black. (1999). Conformity Related Sensitivity Analysis of the CO Hot-Spot Model, CAL3QHC. Presented at Transportation Research Board Annual Meeting, January 1999.

Venigalla, M.M., F. Southworth, and C.G. Davies. (1992). "Evacuation Time Estimates for Pueblo Depot Activity and Vicinity," Oak Ridge National Laboratory, Prepared for the U.S. Department of Army and Federal Emergency Management Agency, April 1992.

Venigalla, M.M., and X. Zhou. (2008). Environmental Justice Implications of Personal Travel Related Emissions Burden. Presented at the 87th TRB Annual Meeting. Washington D.C. January 2008. Published in the TRB 87th Annual Meeting Compendium of Papers DVD. (http://trid.trb.org/view.aspx?id=848436).

Venigalla, M.M., X. Zhou and S. Zhu. (2015). Effect of Turns, Signals and Other Network Variables on Route Choice. Poster presentation. Symposium on Transportation Informatics: Big Data Analytics Transforming Transportation Operations, Management and Safety. Buffalo Niagara, NY. August 2015.

Venigalla, M.M., X. Zhou, and S. Zhu. (2016). The Psychology of Route Choice in Familiar Networks: Minimizing Turns and Embracing Signals. Journal of Urban Planning and Development, Vol. 142(3), September 2016, pp. 1-14. (http://dx.doi.org/10.1061/(ASCE)UP.1943-5444.0000364)

Walters, J. Lee, R., Feldman, M., Gray, C., Levasseur, L., Watten, M., Ruehr, E., Singleton, M.. Trip Generation for Smart Growth. San Diego Association of Governments. San Diego, Ca. 2010.

Zhang, Ming, and Chang Yi. 2006. "Can Transit Oriented Development Reduce Austin's Traffic Congestion?" Report SWUTC/06/167869-1, Center for Transportation Research, University of Texas, Austin, TX.

Zhang, Ming. 2010. "Can Transit Oriented Development Reduce Peak Hour Congestion?" Transportation Research Board 89th Annual Meeting: Washington, D.C.

Curriculum Vitae

Arsalan Faghri received his Bachelor of Science degree from York University in Toronto, Canada in 1995. He received his Master of Science in Civil Engineering from University of Delaware in 1997. He is currently senior transportation engineer with the Virginia Department of Transportation (VDOT). Prior to joining VDOT he was Senior Traffic Engineer at Jacobs Engineering. Mr. Faghri has taught graduate level courses in traffic engineering, the Highway Capacity Manual, and traffic network simulation and modeling since 2003. His areas of expertise include traffic engineering, land development engineering, and transportation planning and policy.